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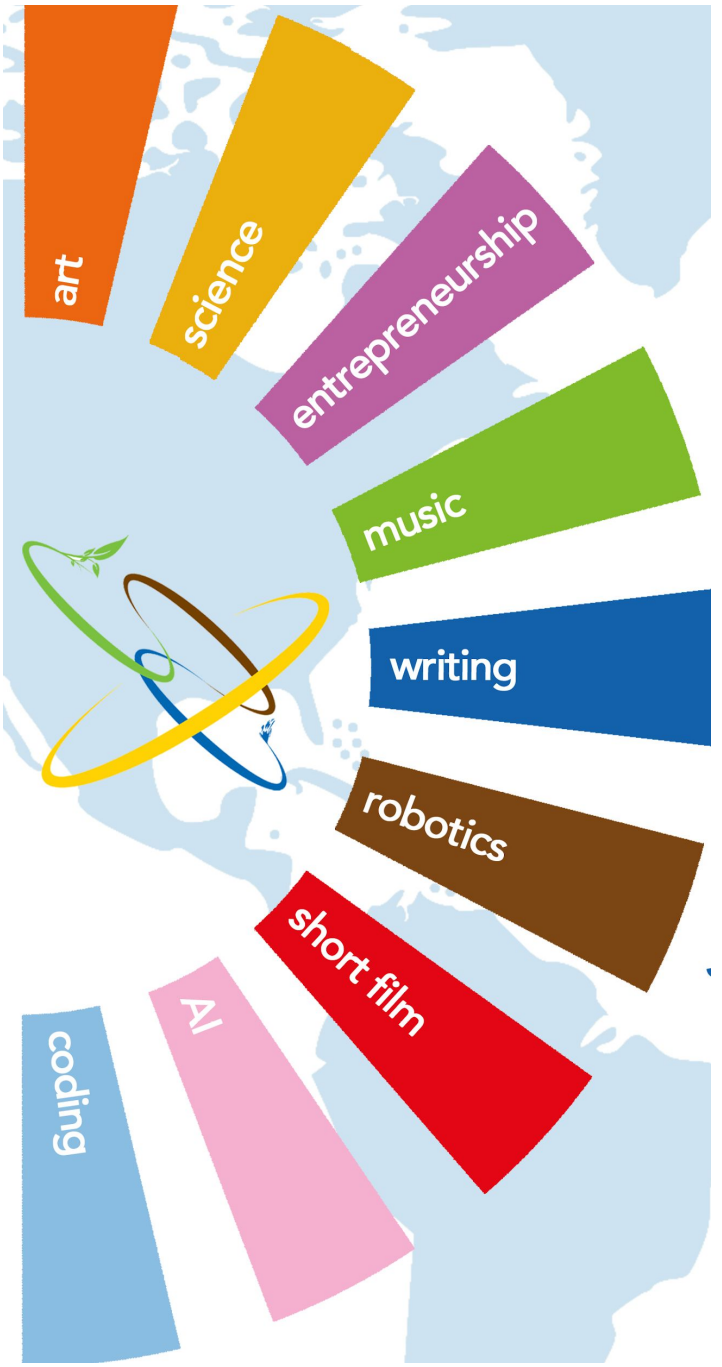

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■ LETTER FROM THE EDITOR

This issue of IJHSR features several papers that students produced for a scholarly event: Indigo Research's IRIS program, which immerses high school students in online college-level seminars. IRIS culminates in small symposia, where participating students present full-length research papers before their peers and professors. The dedicated scholars in this issue hail from both Indigo and NYAS (The New York Academy of Sciences), a prestigious global community comprising over 20,000 members, including leaders in science, industry, academia, government, and public policy.

All of the papers published in this issue underwent a rigorous single-blind peer review process, facilitated by IJHSR. Following this review, a selection of papers was accepted for further revisions, copy editing, and publication. All accepted submissions adhered to IJHSR's stringent quality standards, and the team responsible for organizing IRIS had no influence over the review process. IJHSR, Indigo Research, and the IRIS faculty are proud of the intellectual resilience that all student participants brought to the review process, whether or not their papers were accepted for this issue.

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REVIEW ARTICLE

A Review of the Post-Quantum Cryptographic Landscape

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ABSTRACT: As the development of quantum computing systems advances, the integrity of current public-key and symmetric-key cryptographic systems, such as RSA, ECC, and AES, faces unprecedented threats. These systems rely on mathematical problems like integer factorization and discrete logarithms, which quantum algorithms like Shor's can solve exponentially faster than classical ones. This review examines the vulnerability of widely used cryptographic systems and evaluates how close quantum hardware is to breaching real-world encryption. It also discusses the development of post-quantum cryptographic algorithms, specifically lattice-based, code-based, and multivariate polynomial systems designed to resist quantum attacks. This paper will also assess the strengths, limitations, and standardization progress of these post-quantum solutions to provide an understanding of the modern cryptographic landscape.

KEYWORDS: Computer Science and Software Engineering, Post-Quantum Cryptography, Quantum Computing, Shor's Algorithm, Grover's Algorithm, NIST PQC Standardization, Quantum Threats.

Introduction

Quantum computing, once thought to be a distant or theoretical concept, now threatens to unravel the mathematical foundations of modern cryptography, rendering technologies like RSA and ECC obsolete.[1] Used for over 25 years now, protocols like RSA, Advanced Encryption Standard (AES), and elliptic curve cryptography (ECC) have been the backbone of digital security systems applied to a large part of the Internet, from online banking to secure messaging, relying on the presumed impossibility of classical computers to feasibly solve integer factorization and discrete logarithm computational problems. Peter Shor's 1994 algorithm shattered these assumptions, positing that a sufficiently powerful quantum computer could solve both problems in polynomial time as a result, regulatory bodies, such as the NIST have released publications evaluating range of primitive quantum resistant systems such as lattice based, code based, multivariate, and hash based methods with the goal of replacing these vulnerable standards before they are compromised.[1,2] Proof of concept systems, such as Google's New Hope key Exchange in Chrome provides feasibility to the idea of a global switch to quantum-resistant systems.[3]

This paper thus investigates to what extent current public and symmetric key cryptographic techniques and systems are vulnerable to quantum attacks, and how emerging post-quantum algorithms are addressing these risks.

The first primary concern that this paper will address is the threat of the "harvest-now, decrypt-later" model, which suggests that malicious actors could store encrypted data today with the idea that they will be able to one day, with sufficient advances in quantum hardware, break today's encryption standards.[4]

The second issue lies with the logistical and technical complexities of transitioning to quantum-safe systems, more specifically the challenge of orchestrating mass cryptographic protocol updates across millions of devices and services while avoiding systemic failures, made all the more urgent by the fact that recent analyses show that large scale quantum attacks could become feasible within the next decade, adding a time factor to a coordinated transition to resilient cryptographic standards.[5]

This paper argues that while quantum computing poses an imminent threat to the mathematical foundations of today's cryptography standards, a pivot to post-quantum standards can help preserve and safeguard digital infrastructure. Lattice-based schemes, such as New Hope and Kyber, as well as code-based constructions, have demonstrated strong security proofs while remaining suitable for real-world deployment.[3,6] Although large-scale quantum computers, capable of breaking current encryption like RSA or ECC, are not yet fully operational, consistent advances in quantum technologies suggest that they may realistically be realized within the next decade.[6] Even today, small-scale quantum devices have proven capable of executing simplified versions of Shor's algorithm, demonstrating the feasibility of quantum attacks.[7] This paper also states that addressing the threats posed by quantum computing systems requires two steps: the first of which is establishing global consensus on standardized algorithms, and the second is managing a coordinated transition of existing cryptographic systems to quantum-resistant solutions.

Discussion

I. A brief history of quantum cryptography:

The origins of quantum cryptography can be traced back to the seminal work of Charles Bennett and Gilles Brassard, who in 1984 released their BB84 protocol, a groundbreaking framework that utilized principles of quantum mechanics, specifically the no-cloning theorem and Heisenberg's uncertainty principle, to ensure that any attempt to make a copy of information on the quantum channel would create disturbances.[2,8]

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By grounding security in the laws of quantum mechanics, the BB84 protocol laid the conceptual foundation for a new era in secure communications, though practical implementation seemed unfeasible at the time.

The need for quantum secure methods gained immense momentum with the introduction of Shor's algorithm, developed by its namesake Peter Shor in 1994, capable of factoring large integers and calculating discrete logarithms in polynomial time, revealing that public key systems such as RSA and ECC could theoretically be rendered vulnerable once sufficiently powerful quantum hardware became available.[1] Shor's algorithm has not only catalyzed research into physical layer defenses like quantum key distribution (QKD) but also prompted further exploration of post-quantum cryptographic primitives, cryptographic methods designed to remain secure against attacks from quantum computers, while being able to be implemented by classical hardware and infrastructure.[2,9]

From the late 1990s and early 2000s, discussions on quantum cryptography gradually progressed from theoretical concepts to how they could be applied and implemented in real-world settings. Research groups began demonstrating basic implementations of quantum key exchange over short distances, using fiber optic infrastructure, marking a significant milestone in validating QKD. Soon after, organizations like ETSI began releasing documentation guiding migration from classical encryption systems to quantum-safe approaches, highlighting the practical and infrastructural challenges involved in such a transition.[10] Adding to this urgency is the "harvest now, decrypt later" attack vector, which posits that malicious actors may already be capturing encrypted traffic today, with the intention of storing it until quantum computers reach a level of capability such that they would be able to decrypt it.[4]

Table 1: Key milestones in the development of quantum cryptography and quantum computing.

Year	Event	Explanation	Significance
1984	BB84 Protocol	Bennet and Brassard published the BB84 protocol, the start of quantum key distribution as a field.	The world's first quantum key distribution protocol
1991	E91 Protocol	Ekert proposes entanglement-based quantum key distribution (QKD) using Bell inequality checks.	Introduced entanglement-based QKD and applied Bell-inequality tests, showing that quantum correlations can be used to detect eavesdropping.
1992	First QKD lab demo	Bennet, Brassard, *et al.* report successful implementation of the BB84 protocol in a laboratory environment.	Demonstrated that QKD was practically feasible rather than purely theoretical.
1994	Shor's algorithm	Peter Shor publishes his algorithm proposing polynomial-time for factoring and discrete logarithm problems on an ideal quantum machine.	Illustrated that a quantum computer could solve integer factoring and discrete log problems in polynomial time, threatening classical cryptography.
1996	Grover's algorithm	Grover's algorithm was published, positing a quadratic speedup in the time taken to search an unsorted array.	Showed that even non-factorization problems benefit from quantum computing.
1998	First QEC demonstrations	The early lab demonstrations of quantum error-correcting code (QEC) were the first step towards fault-tolerant quantum computing.	Began the transition from experimentation to the development of fault-tolerant quantum architectures by showing that quantum error-correcting code could be physically realized.
2001	Shor's algorithm applied to N = 15	A nuclear magnetic resonance quantum computing device was used for the first-ever implementation of Shor's algorithm to factor the number 15.	The first physical demonstration of Shor's algorithm confirmed that quantum algorithms could be implemented rather than just theorized.
2007	QKD implemented over a 200km distance using fiber	Decoy-state BB84 QKD over 200km standard telecom fiber, demonstrating practical implementation.	A real-world scale implementation of QKD, establishing the viability of quantum cryptography in long-distance classical infrastructure.
2010	Tokyo QKD network goes live	Multi-vendor, city-wide QKD network launched, demonstrating interoperability for city-scale QKD.	Established that quantum communications could scale in urban environments with interoperability.
2017	Satellite QKD achieved	Entanglement distribution and QKD achieved over 1200km via the Micius satellite.	Demonstrated that quantum communications could be implemented globally.
2023	IBM Condor	IBM announced and operated a 1121-qubit quantum superconducting processor, marking a breakthrough in quantum hardware.	Marked the first gate-model quantum processor to surpass 1,000 qubits, setting a new benchmark for scale in quantum hardware.

Table 1 illustrates how quantum cryptography and quantum computing have evolved alongside rising cryptographic threats; in the following section, we examine the current and emerging quantum-threat landscape.

II. Survey of quantum threats:

While the advent of quantum cryptography has opened new avenues for securing information, the rapid advancement of quantum hardware simultaneously endangers the classical cryptographic systems that secure the Internet, along with all of its related infrastructure. This section reviews the algorithms and hardware developments that drive these risks and illustrates how experimentation with these algorithms is gradually moving towards practical attacks.

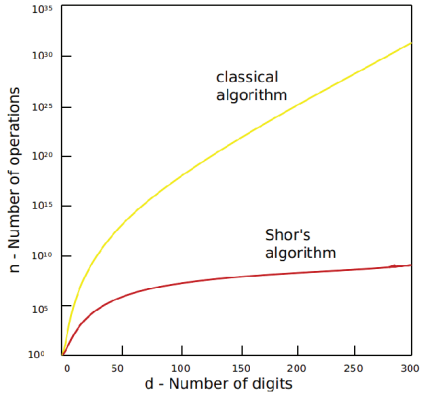

Figure 1: A visual comparison of the number of operations required by a classical algorithm in comparison to Shor's algorithm with respect to the number of digits. [11]

Even today, the primary theoretical threat to public key cryptography remains Shor's algorithm, being able to solve the integer factorization and discrete logarithm problems in polynomial time (as illustrated in Figure 1[1]). Because RSA and ECC rely on the complexity of these problems, the arrival of an amply powerful quantum computer would immediately invalidate the security that they provide. The viability of such an attack has been proven through numerous experiments in which teams have implemented a smaller-scale version of Shor's algorithm, factoring numbers such as 15 using only a small number of qubits.[5]

While Shor's algorithm targets public key cryptographic systems, Grover's algorithm, created initially to search unsorted arrays, poses a threat to symmetric ciphers by providing a quadratic speed-up of brute force key search, essentially halving the effective security of methods like AES.[12] When faced with an attack carried out by a quantum computer, a 128-bit key would be about as secure as 64 bits of security; such is the reason that bodies such as NIST and ETSI recommend doubling symmetric key sizes (e.g, moving to AES-256 from AES-128) to restore the original margin.[2,10]

In terms of hardware, progress remains incremental; quantum platforms are now reaching the low thousands of physical qubits, demonstrated by IBM's 1121-qubit Condor, the first ever quantum processor to surpass 1000 qubits, marking a significant milestone.[13] By contrast, leading superconducting and trapped ion systems from Google, Rigetti, and IonQ generally operate in the ranges of hundreds of physical qubits.[13] Despite these advances, present-day processors remain far from executing Shor's and Grover's algorithms in a way that would be threatening to modern-day cryptographic systems, largely due to their not yet supporting the levels of error correction required for cryptographic workloads. Executing Shor's algorithm, for example, on an RSA-2048 key is estimated to require thousands of highly logical qubits and trillions of tolerant gates, which implies requiring tens of millions of physical qubits running code error correction, considering today's error rates, as logical qubits are comprised of many physical qubits in order to suppress noise.[2,9,14]

Taken together, the progress in quantum computing, in addition to algorithmic breakthroughs, renders the quantum threat not only credible but time-sensitive. Even though present-day machines cannot yet crack internet-scale encryption, the demonstrated functionality of quantum attacks combined with the steady improvements in quantum hardware, as well as the ability to store encrypted data, underscores the need for immediate migration to quantum-resistant alternatives.

III. Overview of post-quantum algorithms:

This section examines the prominent examples of post-quantum algorithms, assessing their strengths, weaknesses, and current standardization status, aiming to provide a clear understanding of which algorithms are most likely to see widespread deployment as the threat of quantum attacks progresses.

Post-quantum cryptography encompasses a range of cryptographic systems, even in the presence of large-scale quantum computers.[2] The ideal goal for the systems is that they should be able to replace vulnerable public algorithms, such as RSA and ECC, as well as strengthen symmetric encryption by facilitating secure key exchange and reliable authentication.

A prominent organization involved in the standardization of post-quantum algorithms is the NIST, which evaluates PQC candidates based primarily on cost, performance, and algorithmic and implementation characteristics.[15]

The first and one of the most prominent examples of post-quantum cryptography can be seen in lattice-based schemes.[2] Relying on the computational difficulty of problems defined over high-dimensional lattices or mathematical grids, such as the learning with errors (LWE) and short integer solution (SIS) problems. An example of a lattice-based solution can be seen in the CRYSTALS-Kyber method standardized under the name ML-KEM in the NIST FIPS 203 standard.[16] ML-KEM is a method for secure key exchange on an insecure channel, using mathematical transformations based on lattice problems to ensure that only the intended participants can derive the key, which can then be used to encrypt and decrypt subsequent communications.[3,16,17]

Another post-quantum cryptographic method is the use of hash-based signatures. This method achieves security by relying on the strength of cryptographic hash functions, instead of number-theoretic ones that a quantum algorithm could crack, specifically their resistance to pre-image and collision attacks.[2] SHPINCS+, standardized in FIPS 205 as SLH–DSA, implements this idea through a stateless multi-layered tree system that generates and verifies signatures without using keys.[18] Specifically, SHPINCS+ does this by deriving one-time and few-time signing keys from a master secret seed and organizing them under a Merkle "hypertree," wherein the public key acts as the top root hash.

Code-based cryptography secures communication, not by using a number-theoretic approach like RSA or ECC, but by using the difficulty of decoding a general linear error-correcting code without knowledge of its private structure.[15] McEliece, for example, hides structured Goppa code within a large public matrix, making recovery computationally infeasible for a malicious actor. These schemes offer high-speed encapsulation and decapsulation but require extremely large public keys. In 2025, NIST selected HQC, another code-based KEM, for standardization. HQC uses a different code structure that allows for smaller public keys than McEliece, making it more practical for systems in which storage or transmission size is a concern.

Multivariate cryptography is based on the difficulty of solving large systems of quadratic equations over finite fields (also known as "the MQ problem") for which no effective quantum speed up is known (NP hard).[19] In multivariate signature schemes, the public key is a set of quadratic polynomials. The signer uses a system that can be solved efficiently and then applies masking transformations to obfuscate the solvable system from external observers. Researchers, however, demonstrated a key recovery attack on the rainbow signature scheme, revealing more vulnerability than initially anticipated, resulting in the removal of the scheme from the NIST standardization process.

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Conclusion

In summary, the advancement of quantum computing technologies presents a direct and measurable threat to the mathematical foundations of widely deployed cryptographic standards, such as RSA, ECC, and AES. While present-day quantum hardware lacks the scale and error correction capacity required to execute Shor's or Grover's algorithms, continued progress in hardware capabilities makes the eventual realization of such an attack a plausible near-future outcome. Post-quantum cryptographic schemes, including lattice–based, code-based, hash-based, and multivariate-based methods, show promise, providing viable and standardized alternatives that are capable of withstanding the quantum threat, as demonstrated by their selection and evaluation by the NIST. However, the effectiveness of these solutions depends entirely on the coordination of large-scale migration efforts globally. The successful preservation of secure communications in the post-quantum era will therefore rely both on the adoption of mathematically resilient algorithms and their implementations. The transition strategy should thus prioritize phasing out both RSA and ECC in critical infrastructure. Looking ahead, research should concentrate on how post-quantum standards can be deployed and how hybrid infrastructures can bridge the gap between existing and emerging encryption systems.

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References

1. Shor, P. W. Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer. *SIAM Review* **1996**, *41* (2), 303–332. https://doi.org/10.1137/s0036144598347011.
2. Chen, L.; Jordan, S.; Liu, Y.-K.; Moody, D.; Peralta, R.; Perlner, R.; Smith-Tone, D. Report on Post-Quantum Cryptography. *National Institute of Standards and Technology*, **2016**. https://doi.org/10.6028/nist.ir.8105.
3. Alkim, E.; Ducas, L.; Pöppelmann, T.; Schwabe, P. Post-Quantum Key Exchange—A New Hope. In *Proc. 25th USENIX Security Symposium (USENIX Security '16)*; USENIX Association: Austin, TX, 2016; pp 327-343. DOI: 10.5555/3241094.3241120.
4. DuBose, R.; Rao, M. M. *Harvest now, decrypt later: Why today's encrypted data isn't safe forever*. Hashicorp.com. https://www.hashicorp.com/en/blog/harvest-now-decrypt-later-why-today-s-encrypted-data-isn-tsafe-forever.
5. Monz, T.; Nigg, D.; Martinez, E. A.; Brandl, M. F.; Schindler, P.; Rines, R.; Wang, S. X.; Chuang, I. L.; Blatt, R. Realization of a Scalable Shor Algorithm. *Science* **2016**, *351* (6277), 1068–1070. https://doi.org/10.1126/science.aad9480.
6. Bos, J.; Ducas, L.; Kiltz, E.; Lepoint, T.; Lyubashevsky, V.; Schanck, J. M.; Schwabe, P.; Seiler, G.; Stehlé, D. "CRYSTALS-Kyber: A CCA-Secure Module-Lattice-Based KEM." *Proc. IEEE European Symposium on Security and Privacy (EuroS&P)* **2018**, 353-367. DOI: 10.1109/EuroSP.2018.00032.
7. *Quantum Threat Timeline*. Global Risk Institute. https://globalriskinstitute.org/publication/quantum-threat-timeline/.
8. Bennett, C. H.; Brassard, G. Quantum Cryptography: Public Key Distribution and Coin Tossing (Archive). *Theoretical Computer Science* **2014**, *560* (1), 7–11. https://doi.org/10.1016/j.tcs.2014.05.025.
9. *Tibbetts, J. Quantum Computing and Cryptography: Analysis, Risks, and Recommendations for Decisionmakers*; **2019**. https://cgsr.llnl.gov/sites/cgsr/files/2024-08/QuantumComputingandCryptography-20190920.pdf.
10. *Quantum-safe Cryptography and Security an Introduction, Benefits, Enablers and Challenges*; **2015**. https://www.etsi.org/images/files/ETSIWhitePapers/QuantumSafeWhitepaper.pdf.
11. Gupta, K. D.; Nag, A. K.; Rahman, Md. L.; Mahmud, M. A. P.; Sadman, N. Utilizing Computational Complexity to Protect Cryptocurrency against Quantum Threats: A Review. *IT Professional* **2021**, *23* (5), 50–55. https://doi.org/10.1109/mitp.2021.3089494.
12. Grover, L. K. A Fast Quantum Mechanical Algorithm for Database Search. *Proc. 28th Annual ACM Symposium on the Theory of Computing* (STOC '96), Philadelphia, PA, USA, July 1996; pp 212-219. DOI: 10.1145/237814.237866.
13. Gambetta, J. *IBM Quantum Computing Blog | The hardware and software for the era of quantum utility is here*. www.ibm.com. https://www.ibm.com/quantum/blog/quantum-roadmap-2033.
14. Gidney, C.; Ekerå, M. How to Factor 2048-Bit RSA Integers in 8 Hours Using 20 Million Noisy Qubits. *Quantum* **2021**, *5*, 433. DOI: 10.22331/q-2021-04-15-433.
15. Alagic, G. Status Report on the Fourth Round of the NIST Post-Quantum Cryptography Standardization Process. **2025**. https://doi.org/10.6028/nist.ir.8545.
16. Gaithersburg, MD, NIST. Module-Lattice-Based Key-Encapsulation Mechanism Standard. *Module-Lattice-Based Key-Encapsulation Mechanism Standard* **2024**. https://doi.org/10.6028/nist.fips.203.
17. Gaithersburg, MD, NIST. Module-Lattice-Based Digital Signature Standard. **2024**. https://doi.org/10.6028/nist.fips.204.
18. Gaithersburg, MD, NIST. Stateless Hash-Based Digital Signature Standard. **2024**. https://doi.org/10.6028/nist.fips.205.
19. Beullens, W. Breaking Rainbow Takes a Weekend on a Laptop. **2022**, 464–479.https://doi.org/10.1007/978-3-031-15979-4_16.

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Devyansh Lilaramani is a high school student at EISJ, Dubai, aiming to study computer science and engineering. He hopes to specialize in the fields of artificial intelligence or cybersecurity.

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RESEARCH ARTICLE

Investigating Public Online Discourse Surrounding Films About Menstruation in India

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ABSTRACT: This study investigates online public discourse surrounding menstruation-themed Indian films through the lens of computational social science. Created a dataset of over 30,000 comments sourced from Reddit and YouTube, we apply a combination of sentiment analysis, sentence embeddings, and topic modeling to explore the ways in which audience conversations differ across platforms and evolve over time. The research focuses on three prominent films: Pad Man (2018), Period. End of Sentence (2018), and Alert Condition: Red (2020). These films, released in different socio-political and cultural contexts, serve as focal points for examining public reactions to menstrual health representation in Indian media. The analysis is structured around three experiments. The first evaluates platform-specific sentiment distributions, comparing how the affordances and audience demographics of Reddit and YouTube influence emotional tone. The second identifies dominant and recurring themes in discussions, revealing how narratives around menstruation are framed, contested, or normalized in digital spaces. The third examines longitudinal sentiment trends, tracking shifts in audience attitudes over multiple years to assess the impact of changing social awareness, policy discourse, and media representation. By combining linguistic and computational approaches, the study highlights how anonymity, cultural context, and platform architecture shape menstrual health discourse, offering valuable insights into the intersection of technology, gender, and public health narratives.

KEYWORDS: Robotics and Intelligent, Machine Learning, Computational Social Science, Sentiment Analysis, Topic Modeling, Menstruation Discourse.

Introduction

Menstrual health has historically been underrepresented and often stigmatized in both public discourse and mainstream media, particularly in countries like India, where cultural taboos continue to shape public attitudes.[1-6] Although recent years have seen growth in advocacy, policy initiatives, and educational campaigns that aim to reduce stigma, menstrual health representation in film remains a relatively new and evolving phenomenon. Films such as *Pad Man* (2018), *Period. End of Sentence*. (2018), and *Alert Condition: Red* (2020) brought menstruation into the public spotlight and generated conversation that extended beyond the cinema hall into digital platforms such as YouTube and Reddit.[7-10] These platforms have become important arenas for expression where anonymity and accessibility enable candid and often polarised discussion.[7,11] Understanding discourse in these digital environments is both timely and necessary. Previous scholarship has examined menstrual representation through cultural, sociological, and feminist perspectives,[4-6] yet only a limited number of studies have used computational social science methods to analyze large-scale public reactions over time. This study contributes to the literature by combining sentiment analysis, sentence embeddings, and topic modeling to investigate how emotional tone and thematic framing differ across platforms and change in response to social, political, and media events. By integrating linguistic and computational approaches, this research provides a comprehensive, data-driven view of how digital conversation both shapes and is shaped by menstrual health narratives in India.

Early Computational Approaches to Public Discourse Analysis:

Early computational studies relied on statistical text representation methods, most notably Term Frequency Inverse Document Frequency (TF IDF).[12-15] TF IDF has been widely used for keyword extraction[13] and remains foundational in many media and communication studies.[15] Xu and colleagues demonstrated that TF IDF can reveal thematic changes in online discussions related to reproductive health policy, particularly during moments of public debate and legislative activity.[16] However, TF IDF treats documents as unordered collections of words and does not account for syntax, context, or semantics. This limitation is especially significant for menstruation discourse, where cultural nuance, metaphor, humor, and code switching carry important meaning. Neural embedding methods such as Word2Vec[17] and GloVe[18] improved upon these approaches by learning distributed representations from co-occurrence statistics. Yet these models assign a single vector to each word regardless of context, which limits their ability to handle polysemy and subtle linguistic variation. This constraint has been noted in studies of sentiment, humor, and stigma in online settings.[5,16]

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The Emergence of Transformer-Based NLP:

Transformer-based architectures transformed natural language processing through the use of self-attention mechanisms. BERT introduced contextual embeddings that capture meaning based on both preceding and succeeding words.[19] These representations significantly improved performance on sentiment classification,[20] stance detection, and other linguistic tasks that require deep contextual understanding. Sentence-level semantic modeling advanced further with Sentence BERT, which adapts BERT into a Siamese architecture to generate high-quality sentence embeddings.[21] Liu and colleagues used Sentence BERT to cluster public opinion across large social media datasets and demonstrated its effectiveness for mapping thematic discourse.[22] Subsequent model compression efforts produced faster variants such as DistilBERT[23] and MiniLM,[24] which maintain competitive performance with lower computational cost. Domain-specific models also became prominent. Twitter RoBERTa, trained on a large corpus of social media text, is particularly effective for informal spelling, emoji usage, and slang.[25] This model has been used extensively to analyze misinformation,[26,27] illicit health product advertising,[28] and pandemic-related communication.

Computational Social Science and Health Discourse:

Transformer-based models have been widely adopted in computational social science. Applications include detecting illicit product sales,[28] tracking influenza-like illness through online behavior,[3] analyzing misinformation trends,[26,27] and studying stigma surrounding reproductive and sexual health. Anonymous online spaces, in particular, have been shown to facilitate more candid and stigma-resistant expression.[11] Despite these advancements, computational work on menstruation remains limited. Existing research often focuses on menstruation as a public health concern,[3] as a human rights issue,[1] or as a topic shaped by policy campaigns.[1] Sociocultural analyses have examined how media portray menstruation, highlighting both stigma-reinforcing and stigma-challenging narratives.[4-6] However, few studies use large-scale natural language processing to compare menstruation-related discourse across platforms such as Reddit and YouTube. This gap motivates the present study.

Menstruation, Media Representation, and the Research Gap:

Menstruation in media occupies an important space at the intersection of public health communication and cultural narrative formation. Scholars have shown that media representations can challenge menstrual stigma[5] or reinforce it,[6] contributing to broader social understandings of gender and embodiment. Yet, empirical studies that examine how specific media events influence large-scale public discourse remain limited. Existing work frequently centers on textual or qualitative analysis rather than audience reception at scale. Research on online health communication has demonstrated that platform structure shapes public expression. De Choudhury and De's study of mental health discussions on Reddit illustrates how anonymity and community norms influence patterns of disclosure and support,[7] while Kaye and colleagues' systematic review of online sexual health discourse shows that algorithmic curation and audience composition drive notable differences in tone and thematic emphasis.[29] These findings suggest that social platforms produce distinct discursive environments, but this insight has not yet been extended to menstruation discourse. No menstruation-focused study to date has used multi-platform datasets to analyze thematic divergence or patterns across structurally different spaces such as Reddit and YouTube. This gap is especially notable given the emergence of films that foreground menstruation in the Indian context, including *Pad Man* (2018),[8] *Period. End of Sentence*. (2018),[9] and *Alert Condition: Red* (2020).[10] Each film generated substantial public conversation, yet no research has examined how these discussions vary across platforms or evolve over time. By analyzing more than twenty-five thousand comments related to these films, this study addresses both a methodological and substantive gap in menstrual health research by mapping cross-platform variation and temporal change in public discourse.

Methods

Dataset Curation:

The dataset was constructed to capture public discourse surrounding three films that explicitly engage with menstruation within the Indian socio-cultural context: *Pad Man* (2018),[8] *Period. End of Sentence*. (2018),[9] and *Alert Condition: Red* (2020).[10] These films were selected to represent a range of production contexts, narrative approaches, and audience reach. Pad Man is a large-scale commercial feature inspired by the work of Arunachalam Muruganantham, whose celebrity-driven narrative helped normalize public conversation on menstrual hygiene in India. Period. End of Sentence. It is an Academy Award-winning documentary that elevated global awareness of menstrual stigma. Alert Condition: Red is a grassroots short film that achieved significant engagement despite limited institutional backing, reflecting youth-driven participation in digital conversations. YouTube served as the primary source of video-based audience comments. For each film, comments were scraped from the official uploads or highest engagement versions using the Digital Methods YouTube Comment Scraper. Videos were selected based on three criteria: (1) high view count, (2) substantial engagement in the comment section, and (3) clear relevance to the film. This approach ensured that the resulting dataset reflected authentic and organic audience responses rather than peripheral or low engagement conversations.

Reddit Subreddit Selection:

Reddit data was collected via keyword-based searches across the ten most thematically and culturally relevant subreddits: (1) MovieSuggestions, (2) Mmovieaweek, (3) movies, (4) Feminism, (5) IndianDankMemes, (6) BollyBlindsNGossip, (7) India, (8) Bollywood, (9) Pakistan, (10) todayilearned. These subreddits were identified manually by testing keyword queries like "Pad Man," "Period film," or "menstruation movie" and evaluating which communities hosted the most sustained, relevant conversations. The mix spans general entertainment,

Indian pop culture, gender activism, and meme-driven commentary, enabling a diverse linguistic and ideological sample.

Preprocessing and Cleaning of the Comments:

Data preprocessing was conducted in two phases to ensure suitability for clustering, sentiment analysis, and topic modeling. In the initial phase, all comments were filtered to retain only those written primarily in English. Mixed script entries, including those containing Devanagari or Urdu characters, were removed. Language filtering was supported by established text identification approaches.[30,31] Comments containing fewer than three words were excluded to ensure minimum semantic content. Remaining entries were normalized by converting text to lowercase and removing URLs, user mentions, hashtags, emojis, punctuation, numerals, and excess whitespace. Tokenization and lemmatization were implemented using the spaCy natural language processing framework, which is widely used for large-scale text processing tasks.[32] Stopwords were removed following standard information retrieval practices.[33] This produced a clean and consistent corpus suitable for downstream computational analysis. In the second phase, cleaning focused on removing low information and irrelevant content.

Emoji-only and gibberish posts were deleted through a combination of automated filters and manual inspection. Spam, promotional material, and off-topic commentary were excluded using keyword-based heuristics informed by prior work on social media noise reduction.[26,27] Comments that retained no meaningful tokens after lemmatization and stopword removal were discarded. This two-step procedure ensured a high-quality dataset appropriate for both embedding-based representation and unsupervised modeling.

Handling Hindi Written in English (Transliterated Hindi):

A substantial subset of comments consisted of Hindi phrases written in the Latin alphabet, such as "ladkiyon ko samajhna mushkil hai." Although written using English characters, these comments do not follow English morphology or semantics and therefore fall outside the analytic scope of English language topic modeling. The prevalence of Hindi-English code switching in Indian digital spaces has been documented previously.[34] To identify and remove such entries, a manually curated list of high-frequency Hindi terms (including "hai," "nahi," "kaun," "kyun," "tum," and "kya") was used during the language filtering stage. This supplemented automated detection approaches used in multilingual environments.[30,31] While this method reduced a large portion of transliterated Hindi, complete elimination was not possible due to the fluid and hybrid nature of code switching. Following all filtering and cleaning procedures, the final dataset comprised 25,144 comments, making it one of the largest multi-platform corpora assembled for the computational study of menstruation discourse in Indian media. Reddit comments were sourced from discussions referencing the selected films, while YouTube comments were drawn from trailers and full-length uploads.

Table 1: Dataset Statistics.

Film	Platform	Raw Comments	Cleaned Comments	Avg. Words (Raw)	Avg. Words (Cleaned)
Pad Man (2018)	YouTube	30,469	18,700	8.40	8.40
	Reddit	742	579	18.69	18.69
Period. End of Sentence. (2018)	YouTube	2,237	1,770	15.19	15.19
	Reddit	3,741	3,076	13.66	13.66
Alert Condition: Red (2020)	YouTube	1,923	1,019	7.06	7.06
Total	N/A	39,112	25,144	N/A	N/A

EXPERIMENT 1: Social Media Platform Comparison Using Clustering and Sentiment Analysis:

This experiment aimed to examine whether public discourse around the film Pad Man varied significantly between social media platforms, specifically YouTube and Reddit. The analysis involved taking the raw text of user comments, translating them into numerical form (embeddings), and then exploring the patterns hidden within those numerical representations. These patterns exist in what is known as a latent space: an abstract, multidimensional representation of meaning where similar comments are positioned closer, and dissimilar comments are farther apart. The core assumption within such a latent space is that proximity equals similarity.[19,21,24] If two comments are positioned near each other in this space, it suggests they share thematic or emotional content, even if they use different words. To investigate latent differences in public discourse between Reddit and YouTube, we followed a four-stage computational pipeline: (1) Comment embedding, (2) Dimensionality reduction, (3) Clustering and statistical analysis. (4) Sentiment Analysis. While the full dataset contained over 25,000 comments across three films and multiple platforms, this experiment focused exclusively on a balanced subset of Pad Man comments: 588 from YouTube and 579 from Reddit, ensuring that the clustering analysis would not be skewed by platform size.

1. Comment Embedding:

Each comment was transformed into a dense numerical vector using three different sentence embedding models: MiniLM,[24] DistilBERT,[23] and E5[35] chosen for their balance of computational efficiency, semantic depth, and architectural diversity. MiniLM, with its compact 384-dimensional representation, offered fast processing and was ideal for clustering tasks on medium-sized datasets. DistilBERT served as a compressed yet powerful transformer-based benchmark that retained much of BERT's representational ability.[23] E5, an instruction-tuned model, provided the highest representational capacity, enabling it to capture more abstract semantic relationships. Models like SBERT were excluded to avoid redundancy with MiniLM and DistilBERT, while static word embeddings like GloVe[17] and word2vec[18] were avoided because they cannot capture contextual meaning, which is essential for understanding nuanced discourse.[4-6]

2. Dimensionality Reduction:

Embeddings from these models ranged from 384 to 1024 dimensions, far too high to visualize directly. To make the structure interpretable, we projected them into two dimensions

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using both Principal Component Analysis (PCA)[36] and t-distributed Stochastic Neighbor Embedding (t-SNE).[37] PCA is a linear technique that preserves global variance and highlights broad trends, while t-SNE is a non-linear approach that focuses on preserving local neighborhoods, making it better suited for revealing fine-grained clusters. By comparing results from both techniques, we could verify whether observed groupings were robust patterns in the data rather than artifacts of a single projection method.

3. Clustering and Statistical Analysis:

After dimensionality reduction, I applied KMeans clustering (k = 2) to each of the six 2D embedding spaces (MiniLM, DistilBERT, and E5, each reduced via PCA and t-SNE).[38] Although the sentiment model used later assigns three possible labels (positive, neutral, negative), the clustering itself remained fully unsupervised and was not informed by sentiment. Choosing k = 2 ensured consistent analysis across models and allowed for straightforward comparison of cluster composition. This approach aimed to assess whether natural groupings in the embedding space aligned with platform differences, sentiment distributions, or both.

4. Sentiment Analysis:

To evaluate the emotional tone of user discourse, I applied sentiment analysis to all English-language comments across platforms and embedding models. The objective was to assign each comment a sentiment label POSITIVE, NEGATIVE, or NEUTRAL and later examine how these distributions aligned with latent clusters and platform categories. For sentiment classification, I used the CardiffNLP 'twitter-roberta-base-sentiment' model,[25] a transformer trained on social media data for multi-class sentiment detection. The model predicts one of three classes: LABEL_2 (POSITIVE), LABEL_1 (NEUTRAL), or LABEL_0 (NEGATIVE). After detecting language, I filtered for English comments and mapped these predicted labels to consistent sentiment categories across datasets.[40,41,42] including NEUTRAL sentiment, which was critical. Neutral comments represented a large share of the dataset, particularly on platforms like YouTube and Reddit. Excluding them would have skewed both the sentiment distribution and its relationship with clustering patterns. This sentiment analysis provided the foundation for evaluating whether emergent clusters corresponded to underlying emotional tones, a key question for assessing whether user discourse patterns were shaped by sentiment or other latent factors. To examine whether emotional tone aligned with platform-specific discourse structures, I analyzed sentiment distributions within clusters for Reddit and YouTube separately. The results revealed a recurring trend: clusters with a higher proportion of Reddit comments tended to skew more negative, while clusters with more YouTube comments showed a greater share of positive sentiment.

EXPERIMENT 2: Topic Modeling Using LDA:

Building on the sentiment analysis conducted in Experiment 1, which focused exclusively on Pad Man and compared sentiment across platforms, this second experiment shifts both the analytical lens and the scope of study. The objective here is to explore how the themes within online discourse around menstruation-related films have evolved. Moving beyond sentiment polarity, this experiment applies unsupervised topic modeling techniques to user comments to identify recurring discussion topics and track their prominence in the months following each film's release. Three films form the dataset for this study: Pad Man (2018), Period. End of Sentence (2018), and Alert Condition: Red (2020), all of which address menstruation, albeit through differing cinematic approaches and social contexts. By analyzing audience commentary on these films, the experiment investigates whether particular themes such as stigma, education, activism, or humor persist, diminish, or emerge across different points in time.[1-6] The key distinction of this experiment lies in its temporal focus. This experiment aims to provide a longitudinal perspective on public discourse surrounding menstruation in digital spaces. Rather than listing all emerging topics, it specifically identifies the most prominent topic in each six-month window following each film's release. This allows the analysis to capture dominant narratives over time, comparing how discussion priorities vary not just within a single film's trajectory, but also across different films. By focusing on these peak themes per period, the study surfaces the core concerns that resonated most strongly with audiences in each temporal context. Ultimately, this experiment aims to provide a longitudinal perspective on public discourse surrounding menstruation in digital spaces. It moves from identifying what people felt- the focus of Experiment 1 to understanding what they discussed, how these discussions evolved, and whether certain narratives gained or lost traction over time. For the following experiment, we followed a six-stage computational pipeline: (1) Temporal Binding, (2) Vectorization, (3) Topic Modeling, (4) Thematic Label Assignment, (5) Temporal Evolution of Themes, (6) Tracking Shifts in Public Discourse.

1. Temporal Binding:

To examine the evolution of public discourse surrounding menstruation-focused films over time, each dataset was temporally segmented based on the timestamp associated with each comment. This binning was crucial for enabling longitudinal topic modeling that tracks how dominant themes or concerns changed in public conversations during the two years following each film's release. Each raw comment collected from YouTube and Reddit included an associated timestamp (e.g., 2021-03-14T12:30:45Z), which denoted the precise date and time the comment was posted. Each dataset was anchored to the official release date of its corresponding film, treated as time zero (t = 0):

The absolute timestamp of each comment was converted into a relative offset in days from the release date of its film. This transformation allowed consistent binning regardless of the platform (YouTube or Reddit) or time zone inconsistencies. Comments were assigned to one of four six-month temporal bins post-release: Bin 1 (0-6 months), Bin 2 (7-12 months, Bin 3 (13-18 months), Bin 4 (19-24 months). For each of the four bins, a subset CSV file was generated per film

containing only the preprocessed comment text and relevant metadata (timestamp, platform, etc.). These bin-specific files became the direct input to the subsequent LDA-based topic modeling pipeline, allowing a per-bin topical analysis across time slices.

2. Vectorization:

Following the temporal binning of comments into six-month intervals based on film-specific release dates, each bin was transformed into a vectorized representation suitable for topic modeling using the Term Frequency Inverse Document Frequency (TF IDF) method.[12-15] TF IDF balances local and global importance by combining term frequency, which reflects how often a word appears within a given six-month bin, with inverse document frequency, which penalizes words that appear across many bins and therefore lack temporal distinctiveness. This weighting scheme enabled the model to downweight uninformative words while preserving terms that signal contextual or chronological shifts in discourse, such as "taboo," "education," or "SRHR." Each bin was treated as a standalone document created by concatenating all comments from that period, from which a document term matrix was constructed with rows representing time bins and columns representing unique vocabulary items. To ensure topic interpretability, vocabulary pruning was conducted by removing words that appeared in fewer than five comments across the entire dataset, as these rare terms often reflected typos or hyper-specific references, and excluding words present in more than eighty percent of bins, which functioned as secondary stopwords and hindered topic separability. This two-step filtering procedure reduced dimensionality, improved computational efficiency, and heightened the semantic clarity of the resulting topics. Both unigrams and bigrams were retained to capture meaningful collocations such as "menstrual hygiene" and "sanitary pad," ensuring that the final vectorization captured the evolving lexical landscape of menstruation discourse over time.

3. Topic Modeling:

To uncover latent thematic structures[39] in temporally grouped comments, Latent Dirichlet Allocation (LDA) was employed on the TF-IDF-weighted document-term matrices (DTMs) generated for each 6-month bin. LDA is a generative probabilistic model that assumes each document (in this case, a bin of comments) is a mixture of various topics, and each topic is a distribution over words. This unsupervised technique was used to identify evolving discursive themes over time. Each DTM bin was treated as a distinct "document," enabling the model to infer topics that are not static but evolve across the public discourse timeline. The number of topics was set to k = 5 per film (after empirical tuning), with hyperparameters optimized to balance topic coherence and separation. Two topics per interval reduce redundancy and enable clearer tracking of macro-level thematic shifts over time. This approach is particularly effective when analyzing multi-film, multi-platform datasets across a prolonged period, where interpretability and visual clarity are crucial. The resulting topics were characterized by their top 10 most representative terms, determined by term probability within each topic.

4. Thematic Label Assignment:

After extracting five topics per 6-month bin per film using LDA, the next step involved interpreting these topic-word distributions to assign higher-order thematic labels that could unify and summarize recurring patterns in the discourse. Since LDA outputs topics as distributions over words without any semantic labels, a human-in-the-loop approach was essential to meaningfully interpret and standardize the thematic coding across bins, platforms, and films. To address this, I utilized ChatGPT-4o, a large language model fine-tuned for interpretability and iterative reasoning, as a domain-assistive tool. This decision was motivated by the need for a consistent, scalable, and semantically aware process to handle the large volume of topic outputs while preserving thematic coherence across the dataset. Manual coding alone would have been prone to subjectivity, inconsistency, and fatigue-related error, especially given the volume (over 100 topics across 3 films and multiple time bins).[1,4,40-42] Rather than direct label generation, I employed chain-of-thought prompting, a method wherein the model is guided step-by-step through reasoning processes. Specifically, I provided ChatGPT with the following prompt:

"*I have performed LDA topic modeling on comment data about menstruation-related films, split across 6-month time bins. For each bin, 5 topics have been extracted, each represented by the top 10 keywords.*

Your task is to: Identify consistent overarching themes based on topic keywords across all bins and movies, assign each topic to one of these themes by interpreting the keywords, and use the same set of themes across all bins and films. Do not invent new ones for each time bin, and return your answer in a downloadable CSV file with the following columns:

(1) Movie Name (2) Time Bin (3) Topic Number (4) Top Keywords (5) Assigned Theme

I have attached the table for analysis."

This prompt was curated in such a way as to ensure that Chat-GPT did not stray from the task of assigning themes to the time bins. There was also no mention of the limit of themes Chat-GPT could assign as many themes as it deemed fit, instead of restricting it.

5. Temporal Evolution of Themes:

After assigning high-level thematic labels to the extracted LDA topics, the next analytical step was to examine how the prominence of these themes evolved for each film. This approach aimed to move beyond static topic interpretation, instead focusing on the temporal dynamics of discourse, identifying which themes gained traction, persisted, or declined in the months following each film's release. For each film, I calculated the relative prevalence of each theme within every six-month time bin. This was done by computing the proportion of LDA topics within a bin assigned to each theme. For example, if a time bin yielded five topics and two were categorized under "Menstrual Awareness," the theme's prevalence for that bin was recorded as 40%. This method allowed for

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a normalized comparison across time intervals and films, regardless of absolute topic counts. Thematic prevalence trends were then visualized using line charts and heatmaps, capturing longitudinal patterns of audience discourse. These visualizations highlighted how audience focus shifted in response to the film's release, public discussions, and possibly wider socio-political events.[1,4,40-42]

EXPERIMENT 3: Sentiment Polarity Over Time:

This experiment examines how the emotional tone of audience responses to menstruation-related films has evolved. Unlike Experiment 1, which investigated sentiment distributions within latent semantic clusters, and Experiment 2, which identified recurring themes through topic modeling, this analysis treats sentiment as an independent variable and tracks its trajectory across time. By aggregating sentiment labels across all comments and grouping them by year, this experiment aims to reveal whether public sentiment toward menstruation-themed media has become more positive, more negative, or remained stable over the past decade. The motivation for this analysis lies in the recognition that public attitudes toward menstruation are not fixed. As social awareness, media representation, and policy discourse surrounding menstrual health have shifted, audience reactions may reflect corresponding affective changes. For example, the release of government schemes, social media campaigns, or educational content may coincide with periods of increased positivity, while political controversies or backlash against feminist narratives may produce negativity spikes. By capturing the temporal dynamics of sentiment, this experiment offers insight into how menstruation discourse in digital spaces aligns with broader sociocultural shifts. This time-based sentiment analysis serves two key purposes. First, it provides a longitudinal perspective on emotional framing, helping to determine whether public discourse is growing more affirmational or resistant over time. Second, it complements the structural insights of the previous experiments by situating sentiment within a historical arc. In doing so, it supports the overarching goal of this study: to understand not just what is being said about menstruation in public forums, but how its emotional framing is evolving alongside cultural and political developments. For the following experiment we followed a five-stage computational pipeline: (1) Timestamp Join & Year Extraction (2017-2025) (2) Consolidation Across Models/Sources (3) Film-Level Segmentation (Pad Man / Period End of Sentence. / Alert Condition Red) (4) Stacked-Bar Visualization (5) Event Alignment & Interpretation (releases, awards, campaigns).

■ Results and Discussion

EXPERIMENT 1:

Dimensionality Reduction:

With MiniLM, PCA produced a clean, axis-aligned split between Reddit and YouTube, showing that even a linear projection captures big platform-specific lexical and topical differences. t-SNE further sharpened this divide into two dense, non-overlapping neighborhoods, indicating that the platforms' discourse differences are deeply encoded in MiniLM's semantic space. E5 showed weaker linear separation. Under PCA, Reddit and YouTube formed curved, partially overlapping clusters, suggesting that platform variance in E5 is more complex and less linearly expressed. t-SNE improved separation but still left fuzzy boundaries and mixed regions, implying that some cross-platform comments share similar semantic traits. DistilBERT, like MiniLM, showed strong linear separability under PCA and produced two tight, well-separated clusters under t-SNE. This consistency across methods suggests that DistilBERT also embeds clear platform-level distinctions despite being less sentiment-sensitive. Overall, MiniLM and DistilBERT display robust platform segregation, while E5 encodes platform differences more diffusely, becoming clearer only under non-linear reduction.

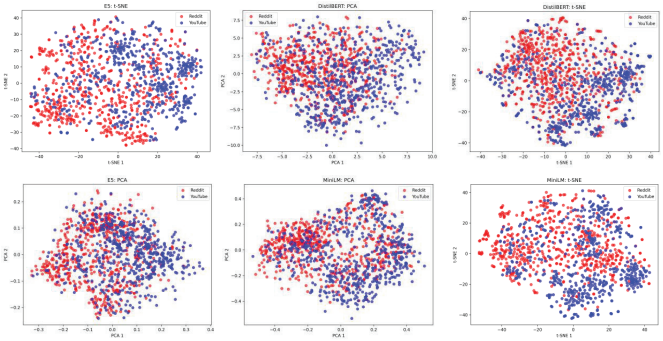

Figure 1: Two-dimensional projections of Pad man comments using PCA and t-SNE. MiniLM and DistilBERT show clear platform separation across both PCA and t-SNE. E5 shows more overlap, indicating shared semantics across platforms.

Clustering and Statistical Analysis:

Table 2: Platform distribution (YouTube vs. Reddit). Cluster membership shows no statistically significant association with platform. This suggests that any visual separation does not translate into meaningful platform-driven clustering.

Model	Cluster	% of Total	%Reddit	%YouTube	χ^2 (Platform)	p-value	Cramér's V (Platform)
MiniLM_PCA	0	44.97%	48.26%	**51.74%**	1.01	0.3140	0.030
	1	55.03%	**51.42%**	48.58%	1.01	0.3140	0.030
MiniLM_tSNE	0	48.09%	49.82%	**50.18%**	0.00	0.9530	0.002
	1	51.91%	**50.17%**	49.83%	0.00	0.9530	0.002
E5_PCA	0	46.61%	48.79%	**51.21%**	0.50	0.4785	0.021
	1	53.39%	**51.06%**	48.94%	0.50	0.4785	0.021
E5_tSNE	0	49.05%	49.03%	**50.97%**	0.35	0.5556	0.017
	1	50.95%	**50.94%**	49.06%	0.35	0.5556	0.017
DistilBERT_PCA	0	47.31%	**52.29%**	47.71%	2.01	0.1567	0.042
	1	52.69%	47.94%	**52.06%**	2.01	0.1567	0.042
DistilBERT_tSNE	0	51.74%	49.66%	**50.34%**	0.03	0.8596	0.005
	1	48.26%	**50.36%**	49.64%	0.03	0.8596	0.005

The X^2 tests across all models and dimensionality reduction combinations indicate no statistically significant association between platform (Reddit vs. YouTube) and cluster membership, as all p-values are well above the conventional 0.05 threshold. For instance, MiniLM with PCA produced two clusters that split the dataset into 44.97% and 55.03% of total comments, with a X^2 value of 1.01 ($p = 0.3140$) and a very small Cramér's V of 0.030, indicating negligible association strength. Similarly, MiniLM with t-SNE yielded an almost

perfectly balanced cluster distribution (48.09% vs. 51.91%) and an effectively zero association ($X^2 = 0.00$, $p = 0.9530$, Cramér's $V = 0.002$). E5 models also showed weak platform-cluster associations. E5 with PCA produced clusters of 46.61% and 53.39%, with $X^2 = 0.50$ ($p = 0.4785$) and Cramér's $V = 0.021$. E5 with t-SNE had an even more balanced split (49.05% vs. 50.95%) and equally low association ($X^2 = 0.35$, $p = 0.5556$, Cramér's $V = 0.017$). DistilBERT followed the same trend, with PCA-based clustering yielding 47.31% and 52.69% cluster shares, $X^2 = 2.01$ ($p = 0.1567$), and a slightly higher but still negligible Cramér's V of 0.042. DistilBERT with t-SNE again showed a near-even split (51.74% vs. 48.26%) and virtually no platform-cluster relationship ($X^2 = 0.03$, $p = 0.8596$, Cramér's $V = 0.005$). Overall, while visual inspection of PCA and t-SNE projections suggested that some models, particularly MiniLM and DistilBERT, produced relatively distinct platform-specific clusters, the statistical tests demonstrate that these apparent separations are not reflected in a strong, quantifiable relationship between platform identity and cluster membership. This indicates that while embeddings capture subtle semantic differences between Reddit and YouTube discourse, these differences do not translate into sharply segregated groups under unsupervised clustering.

Sentiment Analysis:

Table 3: Sentiment distribution across clusters. Cluster membership shows a statistically significant association with sentiment across all models with small to moderate effect sizes. This indicates that sentiment meaningfully influences clustering, but is not the sole driver.

Model	Cluster	% of Total	% Positive	% Negative	% Neutral	χ^2 (Sentiment)	p-value	Cramér's V (Sentiment)
MiniLM_PCA	0	44.97%	34.17%	12.93%	52.90%	62.82	0.00000	0.234
	1	55.03%	14.67%	20.66%	64.67%	62.82	0.00000	0.234
MiniLM_tSNE	0	48.09%	10.47%	20.04%	69.49%	100.02	0.00000	0.295
	1	51.91%	35.45%	14.55%	50.00%	100.02	0.00000	0.295
E5_PCA	0	46.61%	29.42%	17.88%	52.70%	23.20	0.00001	0.142
	1	53.39%	18.21%	16.59%	65.20%	23.20	0.00001	0.142
E5_tSNE	0	49.05%	34.69%	8.85%	56.46%	106.34	0.00000	0.304
	1	50.95%	12.61%	25.21%	62.18%	106.34	0.00000	0.304
DistilBERT_PCA	0	47.31%	33.76%	21.28%	44.95%	93.37	0.00000	0.285
	1	52.69%	14.17%	13.51%	72.32%	93.37	0.00000	0.285
DistilBERT_tSNE	0	51.74%	16.78%	17.95%	65.27%	31.01	0.00000	0.164
	1	48.26%	30.58%	16.37%	53.06%	31.01	0.00000	0.164

In contrast to the platform, clustering showed a statistically significant association with sentiment across all models and reductions, with chi-square tests consistently yielding p-values below 0.00001. This indicates a non-random relationship between cluster membership and sentiment distribution. However, the strength of this association, as measured by Cramér's V, ranged from 0.142 to 0.304 values that fall within the small to moderate effect size range. This suggests that while sentiment does influence cluster formation, it is not the sole or dominant driver of clustering outcomes. Models like MiniLM with t-SNE and E5 with t-SNE showed the strongest sentiment-cluster alignment (Cramér's $V \approx 0.30$), while others like E5 PCA and DistilBERT t-SNE exhibited weaker associations. Overall, this analysis suggests that semantic embeddings capture sentiment cues to a meaningful but moderate extent, supporting their use in sentiment-sensitive discourse analysis. Yet, the moderate effect sizes also caution against overinterpreting clusters as purely sentiment-driven; other latent factors likely contribute to cluster formation.

Conclusion:

Table 4: Overall distribution of positive and negative sentiment per platform. MiniLM (PCA) and E5 (t-SNE) show the most consistent patterns, with clearer splits across clusters.

Model	Cluster	Dominant Platform	Dominant Sentiment **(Ignoring Neutral)**
MiniLM PCA	0	**YouTube**	**Positive**
	1	**Reddit**	**Negative**
MiniLM tSNE	0	YouTube	Negative
	1	Reddit	Positive
DistilBERT PCA	0	Reddit	Positive
	1	**YouTube**	**Positive**
DistilBERT tSNE	0	YouTube	Negative
	1	Reddit	Positive
E5 PCA	0	**YouTube**	**Positive**
	1	Reddit	Positive
E5 tSNE	0	**YouTube**	**Positive**
	1	**Reddit**	**Negative**

MiniLM showed the clearest alignment between sentiment and cluster structure. Under PCA, YouTube-dominant clusters were far more positive (34.17 percent) than Reddit-dominant ones (14.67 percent), while Reddit clusters showed higher negativity. The association was statistically significant with a moderate effect size ($X^2 = 62.82$, Cramér's $V = 0.234$). MiniLM with t-SNE also produced significant results ($X^2 = 100.02$, Cramér's $V = 0.295$), although the polarity inverted, reflecting t-SNE's tendency to prioritize local structure and sometimes distort global trends. These results show that MiniLM encodes sentiment well, but dimensionality reduction strongly shapes how these distinctions surface. E5 behaved similarly in the t-SNE configuration. The YouTube-dominant cluster was strongly positive (34.69 percent) and minimally negative, whereas the Reddit-dominant cluster was markedly more negative (25.21 percent). This setting produced the largest effect size (Cramér's $V = 0.304$), indicating high sensitivity to sentiment. E5 PCA, however, mixed sentiment across clusters and showed a weaker association ($X^2 = 23.20$, Cramér's $V = 0.142$), suggesting that PCA suppresses E5's finer sentiment cues. DistilBERT produced the weakest and most inconsistent patterns. Both PCA and t-SNE failed to reveal stable sentiment–cluster alignment, and some distributions contradicted expected trends. Effect sizes remained small, indicating that DistilBERT embeddings do not reliably encode sentiment within noisy or code-mixed social media text. Overall, only MiniLM PCA and E5 t-SNE generated coherent, interpretable sentiment–platform patterns, underscoring that both embedding choice and reduction method are critical for sentiment-sensitive clustering.

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EXPERIMENT 2: LDA Topic Modeling:

Table 5: Alert Condition: Red. Discourse is dominated by film reviews and menstrual awareness, with low engagement in gender or social impact themes.

Time Bin	Film Review	Gender Roles & Equality	Menstrual Awareness	Social Change / Impact
2017-12	60.0	40.0	0.0	0.0
2018-06	40.0	20.0	40.0	0.0
2018-12	20.0	20.0	40.0	20.0
2019-06	60.0	0.0	40.0	0.0
2019-12	60.0	20.0	20.0	0.0
2020-06	40.0	0.0	60.0	0.0
2020-12	60.0	0.0	40.0	0.0
2021-06	20.0	20.0	60.0	0.0
2021-12	60.0	0.0	40.0	0.0

The temporal analysis of *Alert Condition: Red* (Table 5) shows that audience discourse was dominated by review-focused commentary across most periods, with Film Review accounting for the largest share of topics in multiple bins. Menstrual Awareness appeared consistently and ranged from 20% to 60% over time, indicating steady engagement with menstrual themes without a clear upward or downward trend. By contrast, Gender Roles and Equality appeared only sporadically and never exceeded 40%, reflecting limited public focus on gendered discourse despite the film's subject matter.[1,4,5] Social Change or Impact was almost absent across bins, suggesting that this short film did not catalyze activist-oriented or policy-driven discussion.[2] Overall, discourse surrounding *Alert Condition: Red* remained centered on reviews and basic menstrual-awareness commentary rather than deeper socio-political engagement.

Table 6: Period. End of Sentence. Discourse consolidates around menstrual awareness over time, with other themes largely disappearing after the early periods.

Time Bin	Film Review	Gender Roles & Equality	Menstrual Awareness
2020-04	40.0	20.0	40.0
2020-10	20.0	0.0	80.0
2021-04	0.0	0.0	100.0
2021-10	0.0	0.0	100.0
2022-04	0.0	40.0	60.0
2022-10	0.0	20.0	80.0
2023-04	20.0	0.0	80.0
2023-10	0.0	0.0	100.0
2024-04	0.0	0.0	100.0
2024-10	0.0	0.0	100.0
2025-04	0.0	0.0	100.0
2025-10	20.0	40.0	40.0

The thematic evolution of Period. End of Sentence. (Table 6.) differs sharply from the other films. Menstrual Awareness increased steadily over time and became the exclusive topic in multiple bins from 2021 onward, reflecting the documentary's strong and enduring influence on menstrual-health discourse.[1,3,4] Film Review declined sharply after the documentary's Oscar win[40-42] and disappeared entirely after 2023 as viewers shifted toward deeper engagement with menstruation rather than cinematic critique. Gender Roles and Equality appeared only in isolated intervals with minimal prominence.[5,6] This sustained rise in Menstrual Awareness suggests that the film generated long-term issue-focused engagement, reinforcing observations in menstrual-health scholarship that visibility can influence public discourse even after media attention decreases.[3,4] Overall, the film shows a clear trajectory from mixed early commentary to near-complete thematic consolidation around menstrual awareness.

Table 7: Padman. Discourse shifts from actor and review-driven early engagement to menstrual awareness over time, with limited focus on gender themes.

Time Bin	Actor Appreciation	Film Review	Gender Roles & Equality	Menstrual Awareness
2017-12	40.0	60.0	0.0	0.0
2018-06	40.0	0.0	0.0	60.0
2018-12	20.0	40.0	0.0	40.0
2019-06	60.0	20.0	0.0	20.0
2019-12	60.0	0.0	0.0	40.0
2020-06	20.0	20.0	20.0	40.0
2020-12	40.0	20.0	0.0	40.0
2021-06	20.0	20.0	0.0	60.0
2021-12	40.0	0.0	20.0	40.0
2022-06	40.0	20.0	20.0	20.0
2022-12	100.0	0.0	0.0	0.0
2023-06	60.0	40.0	0.0	0.0
2023-12	0.0	0.0	0.0	100.0
2024-06	0.0	100.0	0.0	0.0
2024-12	40.0	0.0	0.0	60.0
2025-06	0.0	0.0	0.0	100.0

For *Pad Man* (Table 7), early discourse from 2017 to 2020 was dominated by Actor Appreciation and Film Review, reflecting Akshay Kumar's celebrity influence and the film's mainstream visibility at release.[40,41,43] Over time, particularly after 2021, Menstrual Awareness became increasingly prominent and eventually reached 100% dominance in 2023 and 2025, indicating a delayed but deepening public engagement with menstrual-health themes. Although Film Review resurged briefly in 2024, gender-focused discussions remained marginal throughout, with Gender Roles and Equality appearing infrequently and never gaining thematic traction.[5,6] Actor Appreciation declined sharply after 2022, suggesting a long-term shift away from celebrity-centric discourse toward issue-centric conversations. This pattern indicates that *Pad Man*, although initially interpreted through the lens of star power, gradually seeded more substantive discussions on menstrual awareness.

EXPERIMENT 3:

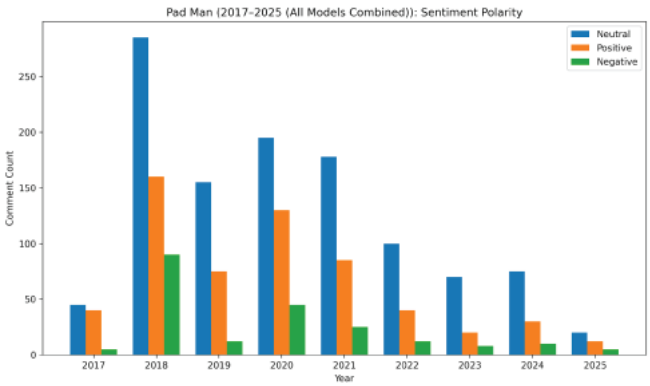

Figure 2: Sentiment polarity over time for Pad Man. Sentiment is largely neutral and event-driven.

The bar chart (Figure 2) shows how sentiment toward menstruation-themed films shifted between 2017 and 2025. Neutral sentiment dominates across the entire period, indicating that most commentary is explanatory or observational, consistent with prior work showing that menstrual discourse online often adopts an informational tone when addressing stigma, education, or hygiene access.[1,3,4] A sharp rise in sentiment activity appears in 2018, driven by the release of Pad Man in February 2018.[7,41,43] The film generated extensive online discussion, supported by campaigns such as the #PadManChallenge, and produced high positive sentiment reflecting public support for its awareness message.[4,5] The simultaneous negative sentiment reflects critiques of its narrative framing and gender representation, issues commonly noted in feminist analyses of menstrual media.[5,6] A second major increase occurs in 2020 with the visibility of the period. End of Sentence, whose Academy Award win renewed attention to menstrual equity.[40,42] Positive sentiment reflects celebratory responses, while negative sentiment reflects concerns about Western framing and simplified portrayals of stigma, consistent with broader debates on representation.[1,4,6] A smaller rise in 2021 aligns with pandemic-era discussions of menstrual health, including period poverty and policy initiatives.[44,45] Many comments during this time revisited earlier films as reference points within activism and public health conversations.[3,4] From 2022 onward, sentiment activity declines sharply, reflecting reduced engagement in the absence of major releases or public events. Neutral sentiment remains dominant, indicating that discourse continues mostly in analytical or educational contexts, mirroring the long tail of advocacy-oriented media.[46] Overall, sentiment trends show that engagement with menstruation-themed films is highly event-driven, with peaks around major releases and sociopolitical moments. Pad Man and Period. End of Sentence. shaped public discourse beyond their release years, but declining activity after 2021 underscores the limited durability of widespread attention to menstrual health.

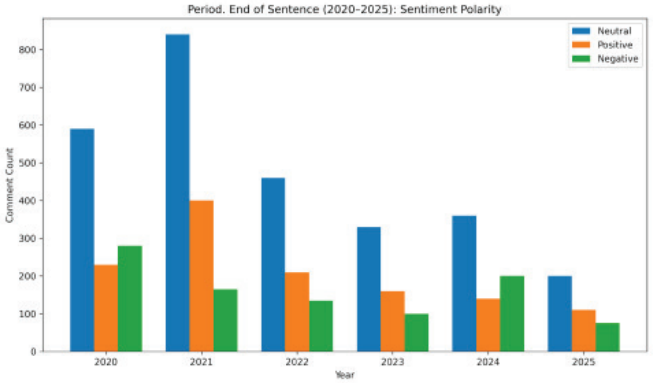

Figure 3: Sentiment polarity over time for the period. End of Sentence. Sentiment peaks around the Oscar win and early pandemic period, then declines steadily.

The documentary Period. End of Sentence, which premiered on Netflix and later won the Academy Award for Best Documentary Short, marked a pivotal moment in global media engagement with menstrual equity.[40,42] The sentiment chart (Figure 3) shows how public reactions shifted between 2020 and 2025 in response to media cycles, award recognition, and broader sociopolitical developments. In early 2020, comment volume was modest, yet sentiment skewed strongly positive, with viewers praising the documentary's portrayal of menstrual stigma, its focus on rural India, and its amplification of marginalized women's voices.[1-4] A smaller negative response reflected concerns about Western framing, brevity, and the risk of oversimplifying culturally embedded issues.[5,6] Neutral commentary consisted largely of descriptive summaries typical of early-viewer engagement. The strongest surge in sentiment occurred following the Oscar win, which amplified global attention to menstrual health.[40,42] Positive reactions expressed pride in the international recognition, while negative sentiment grew as viewers questioned whether a Western-produced documentary could authentically represent Indian experiences, reflecting a tension noted in menstrual health scholarship between visibility and representation.[1,4-6] Sentiment remained elevated into 2021 during a period of expanding menstrual equity initiatives and discussions of period poverty amid the COVID-19 pandemic.[44,45] Many comments referenced the documentary as a symbolic touchpoint rather than a standalone media object, and neutral sentiment dominated as viewers contextualized it within ongoing activism and policy efforts.[1-3] From 2022 onward, engagement declined sharply, consistent with the lifecycle of advocacy-driven media that lose visibility without continued institutional or cultural reinforcement.[46] Later comments were largely reflective, subdued, or folded into broader conversations about documentary impact and gender-focused media.[4,6] Overall, the sentiment trajectory reveals a familiar pattern: an initial burst of enthusiasm, critical revaluation, symbolic longevity, and eventual attenuation.[1,3,4] While Period. End of Sentence sparked global interest in menstrual health, sustained public discourse required continued policy action, educational engagement, and follow-up media efforts.

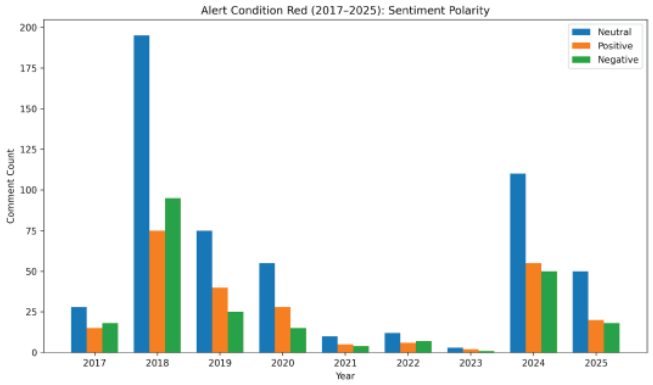

Figure 4: Sentiment polarity over time for Alert Condition Red. Sentiment remains low and mostly neutral throughout, with brief early peaks.

The bar graph (Figure 4) traces sentiment toward Alert Condition Red across nearly a decade, revealing modest engagement but a stable pattern of discourse. Early peaks in 2017 and 2018 reflect its initial circulation in academic and activist spaces, where menstruation-themed media often first gain traction.[4,5] Neutral sentiment dominates these early years, indicating largely descriptive or informational responses consistent with typical viewer engagement with education-

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al menstrual health content.[1,3] Positive sentiment appears in smaller proportions, aligning with viewers who appreciated the film's metaphor-driven narrative style, noted in feminist media studies.[6] Negative sentiment reflects critiques of abstraction and narrative opacity, echoing broader discussions of menstrual stigma representation.[5] Engagement declines sharply after 2018 due to the film's limited mainstream distribution and absence of media scaffolding compared to Pad Man or Period. End of Sentence.[30,42] A small resurgence in 2021 coincides with heightened pandemic-era discussions of menstrual equity, period poverty, and digital activism.[44,45] Neutral sentiment remains dominant, suggesting the film functioned mainly as a pedagogical reference within these conversations.[4,6] From 2022 to 2025, sentiment activity remains minimal, with occasional mentions likely emerging from classrooms, NGO training, or academic contexts, reflecting the film's transition into a long tail archival role typical of low-budget menstrual health media.[1,3,46] Overall, Alert Condition Red did not generate widespread enthusiasm but maintained an enduring presence as a niche resource revisited within educational and advocacy settings.[4,6]

Conclusion

Across approximately twenty-five thousand Reddit and YouTube comments, the findings show that public engagement with menstruation is episodic, driven primarily by media events rather than stable cultural attention. Experiment 1 demonstrates that while platform-based patterns are visually detectable in embedding space, platform identity does not meaningfully structure cluster formation. Instead, sentiment is the dominant organizing force, with strong statistical associations and clear separation between more positive YouTube-leaning clusters and more negative Reddit-leaning ones. Experiment 2 shows that thematic attention shifts over time in response to film releases, discussions of stigma, and moments of advocacy, but that these shifts lose momentum as visibility fades. Experiment 3 confirms that neutral sentiment dominates overall and that spikes in engagement correspond to specific cultural triggers, such as Pad Man in 2018, Period. End of Sentence in 2020, and pandemic era conversations in 2021. Across all analyses, the central pattern is clear: menstrual discourse online is reactive, sentiment-driven, and highly sensitive to external visibility. Without new media or policy signals, public attention dissipates quickly, suggesting that the sustainability of menstrual health conversations in digital spaces depends on repeated moments of renewed cultural activation.

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References

1. Winkler, I.; Roaf, V. Taking the Bloody Linen Out of the Closet: Menstrual Hygiene as a Priority for Achieving Gender Equality. *Cardozo J. Law Gender* **2014**, *21* (1), 1-37.
2. House, S.; Mahon, T.; Cavill, S. *Menstrual Hygiene Matters: A Resource for Improving Menstrual Hygiene around the World*; WaterAid: London, **2012**.
3. Sommer, M.; Hirsch, J. S.; Nathanson, C.; Parker, R. Comfortably, Safely, and Without Shame: Defining Menstrual Hygiene Management as a Public Health Issue. *Am. J. Public Health* **2015**, *105* (7), 1302-1311.
4. Bobel, C. *The Managed Body: Developing Girls and Menstrual Health in the Global South*; Palgrave Macmillan: Cham, **2019**.
5. Johnston-Robledo, I.; Chrisler, J. C. The Menstrual Mark: Menstruation as Social Stigma. *Sex Roles* **2013**, *68* (1-2), 9-18.
6. Sasser, J. S. Cycles of Shame: Menstrual Stigma in Media and Popular Culture. *Fem. Media Stud.* **2014**, *14* (2), 146-161.
7. De Choudhury, M.; Counts, S.; Horvitz, E. Social Media as a Measurement Tool of Depression in Populations. *Proc. ACM WebSci* **2013**, 47-56.
8. Pad Man. Directed by R. Balki; Sony Pictures India: Mumbai, **2018**.
9. Period. End of Sentence. Directed by R. Zehtabchi; Netflix: Los Angeles, **2018**.
10. Alert Condition: Red. Menstrual Hygiene Short Film; YouTube: **2020**.
11. Haimson, O. L.; Andalibi, N.; De Choudhury, M.; Hayes, G. R. Relationship Breakups on Social Media: Uncertainty, Immediacy, and Support Seeking. *Proc. CSCW* **2018**, 1-22.
12. Salton, G.; McGill, M. J. *Introduction to Modern Information Retrieval*; McGraw-Hill: New York, **1983**.
13. Jones, K. S. A Statistical Interpretation of Term Specificity and Its Application in Retrieval. *J. Doc.* **1972**, *28* (1), 11-21.
14. Ramos, J. Using TF-IDF to Determine Word Relevance in Document Queries. *Proc. First Instructional Conf. Machine Learning*, Rutgers University, **2003**.
15. Aizawa, A. An Information-Theoretic Perspective of TF-IDF Measures. *Inf. Process. Manag.* **2003**, *39* (1), 45-65.
16. Sarker, A.; DeRoos, A.; Perrone, J. Mining Social Media for Prescription Medication Abuse Monitoring: A Review and Proposal for a Data-Centric Framework. *J. Am. Med. Inform. Assoc.* **2020**, *27* (2), 315-329.
17. Mikolov, T.; Chen, K.; Corrado, G.; Dean, J. Efficient Estimation of Word Representations in Vector Space. *arXiv* **2013**, arXiv:1301.3781.
18. Pennington, J.; Socher, R.; Manning, C. D. GloVe: Global Vectors for Word Representation. *Proc. EMNLP* **2014**, 1532-1543.
19. Devlin, J.; Chang, M.-W.; Lee, K.; Toutanova, K. BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. *Proc. NAACL-HLT* **2019**, 4171-4186.
20. Sun, C.; et al. How to Fine-Tune BERT for Text Classification? *China Natl. Conf. Chinese Comput. Linguistics* 2019, 194-206.
21. Reimers, N.; Gurevych, I. Sentence-BERT: Sentence Embeddings Using Siamese BERT Networks. *Proc. EMNLP* **2019**, 3982-3992.
22. Gao, T.; Yao, X.; Chen, D. SimCSE: Simple Contrastive Learning of Sentence Embeddings. *Proc. EMNLP* **2021**, 6894-6910.
23. Sanh, V.; Debut, L.; Chaumond, J.; Wolf, T. DistilBERT, a Distilled Version of BERT: Smaller, Faster, Cheaper and Lighter. *arXiv* **2019**, arXiv:1910.01108.
24. Wang, W.; Wei, F.; Dong, L.; Bao, H.; Yang, N.; Zhou, M. MiniLM: Deep Self-Attention Distillation for Task-Agnostic Compression of Pre-trained Transformers. *Adv. Neural Inf. Process. Syst.* **2020**, 33, 5776-5788.

25. Barbieri, F.; Camacho-Collados, J.; Espinosa-Anke, L.; Neves, L. Tweeteval: Unified Benchmark and Comparative Evaluation for Tweet Classification. *Findings EMNLP* **2020**, 1644-1654.
26. Banda, J. M.; Tekumalla, R.; Wang, G.; Yu, J.; Liu, T.; Ding, Y.; Artemova, E.; Tutubalina, E.; Chowell, G. A Large-Scale COVID-19 Twitter Chatter Dataset for Open Scientific Research. *Epidemiologia* **2021**, *2* (3), 315-324.
27. Cotfas, L.-A.; Delcea, C.; Roxin, I.; Ioanăş, C.; Gherai, D. S.; Tajariol, F. The Longest Month: Analyzing COVID-19 Misinformation on Twitter. *Healthcare* **2021**, *9* (1), 82.
28. Mackey, T. K.; Li, J.; Purushothaman, V.; et al. Big Data, Natural Language Processing, and Deep Learning to Detect and Characterize Illicit COVID-19 Product Sales. *JMIR Public Health Surveill.* **2020**, *6* (2), e20794.
29. Andalibi, N.; Haimson, O. L.; Choudhury, M. D.; Forte, A. Understanding Social Media Disclosures of Sexual Abuse Through the Lenses of Support Seeking and Anonymity. *Proc. CHI Conf. Hum. Factors Comput. Syst*. **2016**, 3906-3918.
30. Joulin, A.; Grave, E.; Bojanowski, P.; Mikolov, T. Bag of Tricks for Efficient Text Classification. *Proc. 15th Conf. Eur. Chapter Assoc. Comput. Linguistics (EACL)* **2017**, 427-431.
31. Shuyo, N. *Language Detection Library for Java*. arXiv **2010**, arXiv:1007.1518.
32. Honnibal, M.; Johnson, M. *An Improved Non-monotonic Transition System for Dependency Parsing*. In Proceedings of the 2015 Conference on Empirical Methods in Natural Language Processing; Association for Computational Linguistics: Lisbon, **2015**; pp 1373-1378.
33. Manning, C. D.; Raghavan, P.; Schütze, H. *Introduction to Information Retrieval*; Cambridge University Press: Cambridge, **2008**.
34. Solorio, T.; Blair, E.; Maharjan, S.; Bethard, S.; Diab, M.; Ghoneim, M.; Hawwari, A.; AlGhamdi, F.; Hirschberg, J.; Chang, A.; Fung, P. Overview for the First Shared Task on Language Identification in Code-Switched Data. *Proc. First Workshop on Computational Approaches to Code Switching* **2014**, 62-72.
35. Wang, L.; Yang, N.; Huang, X.; Jiao, B.; Yang, L.; Jiang, D.; Majumder, R.; Wei, F. Text Embeddings by Weakly-Supervised Contrastive Pre-training. *arXiv* **2022**, arXiv:2212.03533.
36. Jolliffe, I. T. *Principal Component Analysis*, 2nd ed.; Springer: New York, **2002**.
37. van der Maaten, L.; Hinton, G. Visualizing Data Using t-SNE. *J. Mach. Learn. Res*. **2008**, *9*, 2579-2605.
38. MacQueen, J. B. Some Methods for Classification and Analysis of Multivariate Observations. *Proc. Fifth Berkeley Symp. Math. Stat. Prob*. **1967**, *1*, 281-297.
39. Blei, D. M.; Ng, A. Y.; Jordan, M. I. Latent Dirichlet Allocation. *J. Mach. Learn. Res*. **2003**, *3*, 993-1022.
40. The Guardian. Period. End of Sentence. Wins Oscar for Best Documentary Short. *The Guardian*, Feb 25, **2019**.
41. Indian Express. How Pad Man Started a Conversation on Menstrual Hygiene. *Indian Express*, Mar 2018.
42. BBC News. Period. End of Sentence: The Oscar-Winning Documentary about Menstrual Taboos. *BBC News*, Feb 2019.
43. The Times of India. Pad Man Review: A Film That Breaks Taboos. *The Times of India*, Feb 9, **2018**.
44. Kuhlmann, A. S.; Bergquist, E. P.; Danjoint, D.; Wall, L. L. Unmet Menstrual Hygiene Needs Among Low-Income Women. *Obstet. Gynecol*. **2019**, 133 (2), 238-244.
45. Lindberg, L. D.; VandeVusse, A.; Mueller, J.; Kirstein, M. Early Impacts of the COVID-19 Pandemic: Findings from the 2020 Guttmacher Survey of Reproductive Health Experiences. Perspect. *Sex. Reprod. Health* **2020**, *52* (4), 189-198.
46. Syred, J.; Naidoo, C.; Woodhall, S. C.; Baraitser, P. Would You Tell Everyone This? Facebook Conversations as Health Promotion Interventions. *J. Med. Internet Res*. **2014**, *16* (4), e108.

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REVIEW ARTICLE

Prompt Engineering and Context Engineering: Reducing AI Hallucinations in Large Language Models

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ABSTRACT: Large Language Models (LLMs) are widely used in today's world for a variety of tasks. They are known for generating confident and convincing content; however, these outputs are not always accurate. Such inaccuracies, commonly referred to as *hallucinations*, present a growing concern as individuals and organizations are increasingly relying on LLMs for content creation and augmentation. To address this concern, researchers and AI scholars have been exploring methods to design prompts and structure the context to improve the accuracy of the LLM responses. This research paper examines how prompt engineering and context engineering are being used to reduce hallucinations in LLMs, which techniques are effective, and whether all hallucinations should be considered detrimental. Most studies examined different approaches to prompt formulation, context structuring, and the use of tools such as Retrieval-Augmented Generation (RAG) to enhance the output. This paper posits that no single solution is universally applicable; there are specific techniques that work best for particular fields. However, context structure will be a key factor in reducing hallucinations and ensuring the accuracy of the output. Context engineering is expected to be as important as prompt engineering, and leveraging the two approaches together helps reduce hallucinations. This research is very important because LLMs are deeply integrated into our daily lives. Humans are becoming more reliant on and attached to AI. It is incredibly important to get accurate results from them, particularly as LLMs are increasingly utilized in critical fields such as medicine and finance.

KEYWORDS: Artificial Intelligence, Large Language Models (LLMs), Prompt Engineering, Context Engineering, AI Hallucinations.

Introduction

Large Language Models (LLMs) are advanced neural networks, trained on vast text datasets, and are capable of generating human-like output. In recent years, humans have become more reliant on LLMs such as GPT, Google's Gemini, Anthropic's Claude, X's Grok, and Meta's LLaMa models. These models perform a large variety of natural language processing (NLP) tasks - from summarization and question answering to writing code and making decisions. However, there is one serious issue with these LLMs: *hallucinations*. LLM hallucinations are generated responses that are not supported by factual truth, and are something the LLM, in other words, guesses. These inaccurate outputs can mislead users, especially in high-stakes domains.[1] Hallucinations in LLMs raise important questions regarding trust, safety, and responsibility. For example, an incorrect analysis of a medical report could endanger a patient, or an incorrect citation in a student's paper could undermine academic integrity. There are many studies that document LLM hallucinations in casual chats, and professional tools like customer service bots, writing assistants, and platforms used for drafting legal documents.[2] As LLMs continue to evolve and individuals and organizations become more reliant on them, the need to reduce LLM hallucinations becomes more urgent. To address this underlying challenge, researchers have turned to two approaches: 1) Prompt Engineering, which modifies the phrasing, structure, or reasoning steps of the input to improve its reliability using linguistic tuning, Chain-of-Thought reasoning, and rewriting tools such as DecoPrompt. 2) Context Engineering, which supplies the model with additional background information it needs using RAG and graph-based inputs. Prompt Engineering revolves around the structuring, phrasing, and crafting of the user input.[3] Context engineering focuses on supplying the model with relevant, structured, and task-specific background information, often through the context provided in the input.[4] These techniques aim to reduce hallucinations by providing context and clarifying the user's intent, so the model's prediction is more accurate.

This paper explores the effectiveness of prompt engineering and context engineering in reducing LLM hallucinations across various tasks. It is structured into 4 sections: Section 1: Prompt Engineering and Context Engineering: Distinctions and Definitions; Section 2: Prompt Engineering Strategies for Hallucination Mitigation; Section 3: Context Engineering Strategies for Hallucination Mitigation; Section 4: Hallucinations: Causes and Mitigations.

This paper uses a review-based approach, comparing findings from recent LLM hallucination studies. It analyzes secondary data drawn from benchmark experiments, prompt design evaluations, and task-specific performance reports. It reviews prompting strategies such as Chain-of-Thought, DecoPrompt, Linguistic tuning, and context engineering strategies like Retrieval-Augment Generation (RAG) and graph-based input structuring. It also provides an insight into common hallucination causes. Ultimately, this paper argues that neither prompting nor context engineering alone is sufficient in reducing hallucinations. Rather, there should be a hybrid approach

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that is tailored to every field and task. This is the most effective way of reducing hallucinations. Moreover, the paper suggests that not all hallucinations are bad. It suggests that some hallucinations may be guided or filtered[5] paving the path for new directions for future research into productive and controlled hallucinations.

Discussion

1. Prompt Engineering and Context Engineering: Distinctions and Definitions:

1.1. Distinguishing Prompt Engineering and Context Engineering:

Prompt engineering and context engineering are related, but separate fields. Clarifying the boundaries of each field aids in evaluating their specific contributions toward reducing AI hallucinations. When users interact with an LLM, two key factors determine the quality of the output: how the input is phrased and what information is in the input for the LLM to use. Prompt engineering focuses on phrasing, structuring, and formatting inputs. This includes length, tone, and word choice. Meanwhile, context engineering concerns the information provided to the model for analysis and integration into its output. This information ranges from providing word definitions all the way to providing information graphs. These two fields are frequently employed in conjunction, leading to common misinterpretations of their distinct roles. However, recent findings suggest that they have their own benefits when it comes to reducing hallucinations. By clearly delineating them, the effectiveness of various approaches can be evaluated by examining different use cases.

1.2. Prompt Engineering:

Prompt engineering is essentially the process of optimizing interactions with an LLM to elicit the most accurate and useful output. You guide the model using carefully written prompts.[6] Researchers have found that the wording, length, and structure of a prompt can make a difference in the quality of the response.[1,7] Prompt engineering is not a recent topic; however, it has been evolving since 2015, when attention mechanisms were introduced to bring more importance to the context of a prompt.[8] There are many prompt engineering approaches, some being instruction-based prompts, metaphorical prompts, and even information-based prompts.[7] However, the goal remains the same throughout these different strategies: improve the model's output on a plethora of tasks like translation, summarization, question answering, and overall text generation.

1.3. Context Engineering:

Context engineering involves providing an LLM with appropriate context or background information to enable improved and more accurate predictions. The quality of the output depends a lot on the context it is given in.[4] The optimal method for obtaining context involves this process: 1) Retrieve information from a database. 2) Generate supporting details. 3) Process the information. 4) Feed it to the LLM via user input.[4] This approach is known as Retrieval-Augmented Generation, otherwise known as RAG. The approach previously outlined resembles human information processing, and RAG indeed follows the same approach. RAG interacts with external data available online and works with other models through a multi-agent system. Essentially, the purpose of context engineering is to create a more context-aware LLM through the inputs, to ensure the LLM possesses relevant, accurate information during response generation.

1.4. Distinctions and Effectiveness towards Hallucination Reduction:

Although prompt engineering and context engineering are related through their shared involvement in prompt modification, they constitute distinct fields with differing objectives. However, researchers have found that context engineering often outperforms prompt engineering due to its provision of a structured framework for the model to operate within.[9] This may sound confusing because prompt engineering is all about providing a structured input to the LLM. Prompt engineering focuses on refining instructions, so the model is less likely to hallucinate.[1,10] For example, adjusting prompts for ChatGPT, Gemini, and Claude makes the answers from the LLMs more reliable.[11] Some techniques, like Chain-of-Thought reasoning patterns and grammar-aware prompts, improve consistency and reduce the need for the LLM to hallucinate.[12,13] Context engineering focuses on providing the models with relevant outside information to use, really effective when using methods like RAG.[14,15] The purpose of this is to fill in the model's knowledge gap, so it would not hallucinate. Research shows that adding structured tags to this context reduces hallucinations by a staggering 99.88%.[16] The subsequent section will delve into specific prompt engineering strategies.

2. Prompt Engineering Strategies for Hallucination Mitigation:

2.1. Overview of Prompt Engineering for Hallucination Reduction:

Prompt engineering can reduce hallucinations by clarifying the input's intent, controlling the formality, and restructuring misleading or broad tasks. Many studies show that minor alterations in how a prompt is structured can lead to significant differences in the LLM output.[17] These subtle changes range all the way from small word changes to complete prompt-rewriting tools like DecoPrompt.[18] Hallucinations have remained a major barrier in ensuring accuracy in AI. As a result, prompt engineering has become its own field in trying to put a stop to this spreading concern. Prompt engineering solely relies on designing the instructions given to the LLM, making sure not to alter any of the LLM's core features.[19]

2.2. Linguistic Tuning:

Word choice and sentence structure influence hallucination rates in LLMs. Research shows that prompts characterized by formal word choice and concreteness reduce hallucinations.[18] This aligns with effective prompt design, which relies on principles such as clarity, contextual framing, and instructional phrasing; all of which contribute towards guiding LLMs in the right direction, away from hallucinations.[20] These im-

portant input elements help LLMs output more accurate and factual responses. Vague or ambiguous prompts increase the likelihood of hallucinations occurring because they prompt the LLM to extract information from the biases in its training data.[1] This makes the crafting of prompts important because it requires not only attention to vocabulary, but also the sentence structure, readability, and phrasing. All of these factors contribute to the accuracy of the LLM output.[18] Prompts with lower readability, concreteness, and formality cause challenges for LLMs, leading them to hallucinate.[18]

2.3. DecoPrompt:

One way to mitigate hallucinations is to completely rewrite the prompt.[21] Reformulated prompts provide more context and modify a model's answer to a more accurate and less confusing one.[17] One of these rewriting tools is called DecoPrompt. DecoPrompt is designed to mitigate hallucinations.[3] DecoPrompt, as suggested in the title, gives LLMs the ability to decode false prompts and encode them to be specific, concrete, and straightforward prompts.[3] This approach is inspired by the observation of the randomness of false-premise prompts being related to the likelihood of producing hallucinations.[3] Furthermore, the two experiments conducted on behalf of DecoPrompt have exemplified that DecoPrompt can effectively reduce hallucinations. DecoPrompt also allows for cross-model transferability, making it more usable for applications involving LLMs on a large scale.[3]

2.4. Chain-of-Thought:

Chain-of-Thought (CoT) prompting improves the output reliability by returning its output in step-by-step instructions. The reason for the step-by-step instructions is to guide the model through a logical sequence, allowing the model to correct its own mistakes.[22] While having well-structured inputs, with formal word choices, does reduce hallucinations, guiding the LLM through reasoning steps with CoT can further enhance mitigation against hallucinations.[22] But even well-designed prompts will fail if they are not matched with relevant context by the model. Therefore, prompt engineering must be partnered with a resource useful for retaining contextual information from the prompt given to maximize the accuracy of the LLM's output.[19]

2.5. Section Summary:

Prompt engineering offers many branches for reducing hallucinations in LLMs. Techniques like linguistic tuning, DecoPrompt, and Chain-of-Thought reasoning each address different causes of hallucinations: ambiguity to faulty processing. However, prompt engineering alone would not mitigate hallucinations. Hallucination mitigation will be most effective when prompt engineering is combined with context retrieval mechanisms (ie, Context Engineering) to generate the most accurate and hallucination-free response.

3. Context Engineering Strategies for Hallucination Mitigation:

3.1. Overview of Context Engineering for Hallucination Reduction:

Context engineering reduces hallucinations by providing relevant and organized information to the LLM, thereby supplying valid factual bases. Many studies conclude that LLMs struggle with accuracy when relying solely on their original training data, which, as previously discussed, can become outdated. Context engineering solves this problem by using methods like Retrieval Augmented Generation (RAG) and graph-based inputs. By grounding the LLM's output with reliable information, context engineering makes it more accurate.[23]

3.2. Retrieval Augmented Generation (RAG):

RAG is the most common context engineering method. It works by retrieving information from external documents and letting LLMs use that information while they are generating responses. Instead of LLMs relying solely on their training data, RAG enables access to up-to-date external sources, which collectively lowers the incidence of hallucinations.[1] However, RAG depends on the quality of the documents it finds, which can be a slight problem. If the retrieval step yields inaccurate information, RAG itself cannot discern its veracity, leading the LLM to incorporate it and consequently generate fabricated responses.[24] To fix this, there are methods like Corrective Retrieval-Augmented Generation (CRAG), which check the quality of the retrieved documents and decide whether they are accurate or not.[24] RAG is multimodal, meaning it applies to texts, images, audio, and video, but these create unnecessary challenges as well.[23] RAG has long supported LLMs with accurate information.

3.3. Graph-Based and Structured Input:

Graph-based input methods guide LLMs by organizing information into a clear format.[25,26] Knowledge graphs store facts and help reduce hallucinations through a method called Knowledge Graph-based Retrofitting (KGR).[27] KGR compares the knowledge graph with the initial LLM output and modifies the output to match the facts from the knowledge graph.[27] Graphs can also be used to detect hallucinations by looking at and comparing the relationship between several generated answers. Graph Attention Networks (GANs) identify patterns that separate facts from hallucinations.[28] Graph-based methods are used for tasks that require structured data. These tasks include writing code, research, and even government tasks like planning events, showing how versatile graph-based prompts and graphs are in reducing errors.[29]

3.4. Section Summary:

Context engineering provides LLMs with essential background information, enabling them to answer user prompts with greater accuracy. Techniques like RAG and graph-based inputs each address different problems. RAG addresses the outdated information and provides up-to-date information, while graph-based inputs focus on making sure the data is

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structured and understandable, and use it to improve the accuracy of the output generated by the LLM. The subsequent section will discuss hallucinations and their causative factors.

4. Hallucinations: Causes and Mitigations:

4.1. Overview of Hallucination Causes:

Hallucinations occur when an LLM tries to generate an output not grounded in evidence. But there are many ways for hallucinations to happen, including missing or biased data within the training set, internal model reasoning errors, or a misinterpretation of the user's intent.[30] By examining these causes, we can gain a deeper understanding of why hallucinations occur and maybe even how to prevent them. Hallucinations generally pose a significant threat, impeding the trustworthiness of LLMs as their integration expands into critical fields such as healthcare, law, and education.

4.2. Training Data Limitations:

Many hallucination cases originate from problems within the data used to train LLMs.[29] If bias exists in the training data or if it is incomplete, the model will produce incorrect answers.[29] A study found that the standard knowledge conversation benchmark consisted of 60% hallucinated responses, which allowed LLMs to train on them and carry on the misinformation.[31] The quality of the training data directly impacts hallucination rates in LLMs, with issues like incompleteness or misinformation contributing to the problem. Furthermore, if the training data is outdated, the model's response will lack factual support, as it relies on old rather than current information. This was exemplified by earlier versions of ChatGPT, whose training data had not been updated since 2021.[32] Any biases in the training data are carried over to the LLM's output, affecting its factual reliability. These limitations highlight the need for updated, accurate, and unbiased training data to make LLM outputs more accurate and reduce the rate of hallucinations.[32]

4.3. Prompt Misinterpretation:

Hallucinations often occur when the LLM has trouble understanding the user query, leading to confident but inaccurate answers.[33] This typically occurs when the user provides ambiguous input to the LLM, prompting it to independently infer missing information.[34] LLMs may also prioritize the aesthetic presentation.[34] Ambiguity is definitely an issue, with more people thinking LLMs are smart enough to understand what the user is saying. This is why there are tools like DecoPrompt that exist, to remove the ambiguity and lack of clarity from the user inputs. When LLMs are presented with false information in a user query, they often assume the information is correct and proceed to generate misleading output that reinforces the false input. This is especially applicable in fields like biomedicine, where LLMs struggle to generate accurate responses, as many users simply paste reports or other material directly into the input.[34]

4.4. Valuable Hallucinations:

Valuable hallucinations in LLMs can be formally defined and analyzed using systematic approaches.[5] Rather than dismissing all hallucinations as flaws, recent work provides clear representations and manual judgments for hallucinations that are realizable and constructive under particular conditions. These propositions are not factual, but could be achieved in the future or in specific scenarios, distinguishing them from otherwise unfaithful, fabricated content. Prompt engineering techniques, such as ReAct prompting with reasoning, self-confidence assessment, and answer verification, make it possible to control and optimize the frequency and type of hallucinations produced by LLMs. Experiments using the Qwen2.5 model and the HalluQA dataset show that systematic control can reduce overall hallucinations by 5.12% and increase the proportion of valuable hallucinations from 6.45% to 7.92%.5 This demonstrates that direct intervention in the model's generative process leads to more outputs that have creative or practical utility, such as ideas for scientific or technological innovation, without introducing unhelpful or misleading information.

4.5. Section Summary:

Hallucinations in LLMs do not stem from a single cause, but rather from a group of factors, including training data limitations and prompt misinformation. By splitting these factors up into their own categories, researchers and developers can design multiple solutions towards reducing hallucinations, instead of only relying on one approach.[1] A deeper dive into these specific factors will provide a better understanding of their contributions towards hallucinations and will also provide a roadmap for developing reliable LLMs that only deliver factual and trustworthy outputs.[35]

■ Synthesis and Recommendations

This review demonstrates that neither prompt engineering nor context engineering alone is sufficient to consistently minimize hallucinations in LLMs. Evidence across recent studies suggests that prompt engineering, especially techniques such as linguistic tuning, DecoPrompt, and Chain-of-Thought, effectively reduces hallucinations caused by ambiguous or misleading inputs. However, prompt engineering is limited by the LMM's base knowledge and may not address gaps or inaccuracies within the model's training data. Context engineering complements prompt-engineering strategies by providing relevant, up-to-date external information through RAG and graph-based data. This enables LLMs to ground their responses in factual data, addressing issues of data bias and knowledge obsolescence. A hybrid technique leveraging the strengths of both approaches is recommended. The most robust framework combines well-crafted prompts with context retrieval mechanisms that supply the LLM with accurate data.

■ Conclusion

No single approach eliminates hallucinations in Large Language Models. However, the combination of prompt engineering and context engineering provides an effective and reliable strategy in mitigating them. This paper has demon-

strated how prompt engineering – focusing on the phrasing, structure, and word choice of input – guides the LLM more effectively. Specifically, Section 2 examined prompt engineering strategies such as linguistic tuning, DecoPrompt, and Chain-of-Thought reasoning, which reduce ambiguity, rewrite problematic prompts, and enable step-by-step logical processing to enhance output reliability. Complementing this, Section 3 delved into context engineering techniques, including Retrieval Augmented Generation (RAG) and graph-based inputs. These methods address knowledge gaps and provide up-to-date, structured information, thereby grounding the LLM's responses in factual data. Section 4 provided a detailed analysis of the multifaceted causes of hallucinations, attributing them primarily to training data limitations and prompt misinterpretation. While a singular solution for mitigating hallucinations remains elusive, the comprehensive review presented here underscores the necessity of a hybrid approach tailored to specific fields and tasks. Moving forward, critical questions for future research include the real-time self-detection of hallucinations by models and the development of a classification framework to distinguish between safe and dangerous forms of hallucination.

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■ References

1. Tonmoy, S. M. T. I.; Zaman, S. M. M.; Jain, V.; Rani, A.; Rawte, V.; Chadha, A.; Das, A. A Comprehensive Survey of Hallucination Mitigation Techniques in Large Language Models. arXiv January 3, 2024. https://doi.org/10.48550/arXiv.2401.01313.
2. Barkley, L.; Merwe, B. van der. Investigating the Role of Prompting and External Tools in Hallucination Rates of Large Language Models. arXiv October 25, 2024. https://doi.org/10.48550/arXiv.2410.19385.
3. Xu, N.; Ma, X. DecoPrompt : Decoding Prompts Reduces Hallucinations When Large Language Models Meet False Premises. arXiv November 12, 2024. https://doi.org/10.48550/arXiv.2411.07457.
4. Mei, L.; Yao, J.; Ge, Y.; Wang, Y.; Bi, B.; Cai, Y.; Liu, J.; Li, M.; Li, Z.-Z.; Zhang, D.; Zhou, C.; Mao, J.; Xia, T.; Guo, J.; Liu, S. A Survey of Context Engineering for Large Language Models. arXiv July 21, 2025. https://doi.org/10.48550/arXiv.2507.13334.
5. Chen, Q.; Wang, B. Valuable Hallucinations: Realizable Non-Realistic Propositions. arXiv February 18, 2025. https://doi.org/10.48550/arXiv.2502.11113.
6. White, J.; Fu, Q.; Hays, S.; Sandborn, M.; Olea, C.; Gilbert, H.; Elnashar, A.; Spencer-Smith, J.; Schmidt, D. C. A Prompt Pattern Catalog to Enhance Prompt Engineering with ChatGPT. arXiv February 21, 2023. https://doi.org/10.48550/arXiv.2302.11382.
7. Rathod, J. D. Systematic Study of Prompt Engineering. *Int. J. Res. Appl. Sci. Eng. Technol.* 2024, *12* (6), 597–613. https://doi.org/10.22214/ijraset.2024.63182.
8. Muktadir, G. M. A Brief History of Prompt: Leveraging Language Models. (Through Advanced Prompting). arXiv November 28, 2023. https://doi.org/10.48550/arXiv.2310.04438.
9. Pajo, P. *(PDF) Context Engineering: Enhancing Large Language Model Performance Through Comprehensive Contextual Management*. https://www.researchgate.net/publication/393511218_Context_Engineering_Enhancing_Large_Language_Model_Performance_Through_Comprehensive_Contextual_Management (accessed 2025-08-07).
10. Geroimenko, V. Generative AI Hallucinations in Healthcare: A Challenge for Prompt Engineering and Creativity. In *Human-Computer Creativity: Generative AI in Education, Art, and Healthcare*; Geroimenko, V., Ed.; Springer Nature Switzerland: Cham, 2025; pp 321–335. https://doi.org/10.1007/978-3-031-86551-0_17.
11. Sato, K.; Kaneko, H.; Fujimura, M. Reducing Cultural Hallucination in Non-English Languages Via Prompt Engineering for Large Language Models. OSF May 6, 2024. https://doi.org/10.31219/osf.io/4hzya.
12. Joseph, T.; Keneth, M. H. Exploring the Synergy of Grammar-Aware Prompt Engineering and Formal Methods for Mitigating Hallucinations in LLMs. *East Afr. J. Inf. Technol.* **2024**, *7* (1), 188–201. https://doi.org/10.37284/eajit.7.1.2111.
13. Velásquez-Henao, J. D.; Franco-Cardona, C. J.; Cadavid-Higuita, L. Prompt Engineering: A Methodology for Optimizing Interactions with AI-Language Models in the Field of Engineering. *DYNA* **2023**, *90* (230), 9–17.
14. Jha, S.; Jha, S. K.; Lincoln, P.; Bastian, N. D.; Velasquez, A.; Neema, S. Dehallucinating Large Language Models Using Formal Methods Guided Iterative Prompting.
15. Longpre, S.; Perisetla, K.; Chen, A.; Ramesh, N.; DuBois, C.; Singh, S. Entity-Based Knowledge Conflicts in Question Answering. arXiv January 12, 2022. https://doi.org/10.48550/arXiv.2109.05052.
16. Feldman, P.; Foulds, J. R.; Pan, S. Trapping LLM Hallucinations Using Tagged Context Prompts. arXiv June 9, 2023. https://doi.org/10.48550/arXiv.2306.06085.
17. Sarkar, R.; Sarrafzadeh, B.; Chandrasekaran, N.; Rangan, N.; Resnik, P.; Yang, L.; Jauhar, S. K. Conversational User-AI Intervention: A Study on Prompt Rewriting for Improved LLM Response Generation. arXiv June 25, 2025. https://doi.org/10.48550/arXiv.2503.16789.
18. Rawte, V.; Priya, P.; Tonmoy, S. M. T. I.; Zaman, S. M. M.; Sheth, A.; Das, A. Exploring the Relationship between LLM Hallucinations and Prompt Linguistic Nuances: Readability, Formality, and Concreteness. arXiv September 20, 2023. https://doi.org/10.48550/arXiv.2309.11064.
19. Sahoo, P.; Singh, A. K.; Saha, S.; Jain, V.; Mondal, S.; Chadha, A. A Systematic Survey of Prompt Engineering in Large Language Models: Techniques and Applications. arXiv March 16, 2025. https://doi.org/10.48550/arXiv.2402.07927.
20. Cleti, M.; Jano, P. Hallucinations in LLMs: Types, Causes, and Approaches for Enhanced Reliability. Open Science Framework, October 21, 2024. https://doi.org/10.31219/osf.io/tj93u.
21. Zhang, H.; Deng, H.; Ou, J.; Feng, C. Mitigating Spatial Hallucination in Large Language Models for Path Planning via Prompt Engineering. *Sci. Rep.* **2025**, *15* (1), 8881. https://doi.org/10.1038/s41598-025-93601-5.
22. Sun, Y.; Liu, Z.; Liu, C.; Pu, B.; Zhang, Z.; Xie, H. Hallucination Mitigation Prompts Long-Term Video Understanding. arXiv June 17, 2024. https://doi.org/10.48550/arXiv.2406.11333.
23. Abootorabi, M. M.; Zobeiri, A.; Dehghani, M.; Mohammadkhani, M.; Mohammadi, B.; Ghahroodi, O.; Baghshah, M. S.; Asgari, E. Ask in Any Modality: A Comprehensive Survey on Multimodal Retrieval-Augmented Generation. arXiv June 2, 2025. https://doi.org/10.48550/arXiv.2502.08826.
24. Yan, S.-Q.; Gu, J.-C.; Zhu, Y.; Ling, Z.-H. Corrective Retrieval Augmented Generation. arXiv October 7, 2024. https://doi.org/10.48550/arXiv.2401.15884.

DOI: 10.36838/IJHSR811.16

25. Chen, K.; Chen, Q.; Zhou, J.; Tao, X.; Ding, B.; Xie, J.; Xie, M.; Li, P.; Zheng, F.; He, L. Enhancing Uncertainty Modeling with Semantic Graph for Hallucination Detection. arXiv April 5, 2025. https://doi.org/10.48550/arXiv.2501.02020.
26. Zhou, J.; Ghaddar, A.; Zhang, G.; Ma, L.; Hu, Y.; Pal, S.; Coates, M.; Wang, B.; Zhang, Y.; Hao, J. Enhancing Logical Reasoning in Large Language Models through Graph-Based Synthetic Data. arXiv December 16, 2024. https://doi.org/10.48550/arXiv.2409.12437.
27. Guan, X.; Liu, Y.; Lin, H.; Lu, Y.; He, B.; Han, X.; Sun, L. Mitigating Large Language Model Hallucinations via Autonomous Knowledge Graph-Based Retrofitting. *Proc. AAAI Conf. Artif. Intell.* **2024**, *38* (16), 18126–18134. https://doi.org/10.1609/aaai.v38i16.29770.
28. Nonkes, N.; Agaronian, S.; Kanoulas, E.; Petcu, R. Leveraging Graph Structures to Detect Hallucinations in Large Language Models. arXiv July 5, 2024. https://doi.org/10.48550/arXiv.2407.04485.
29. Liu, X. A Survey of Hallucination Problems Based on Large Language Models. *Appl. Comput. Eng.* **2024**, *97* (1), 24–30. https://doi.org/10.54254/2755-2721/2024.17851.
30. Reddy, G. P.; Pavan Kumar, Y. V.; Prakash, K. P. Hallucinations in Large Language Models (LLMs).
31. Dziri, N.; Milton, S.; Yu, M.; Zaiane, O.; Reddy, S. On the Origin of Hallucinations in Conversational Models: Is It the Datasets or the Models? arXiv April 17, 2022. https://doi.org/10.48550/arXiv.2204.07931.
32. Ang, T. L.; Choolani, M.; See, K. C.; Poh, K. K. The Rise of Artificial Intelligence: Addressing the Impact of Large Language Models Such as ChatGPT on Scientific Publications. *Singapore Med. J.* **2023**, *64* (4), 219. https://doi.org/10.4103/singaporemedj.SMJ-2023-055.
33. Bruno, A.; Mazzeo, P. L.; Chetouani, A.; Tliba, M.; Kerkouri, M. A. Insights into Classifying and Mitigating LLMs' Hallucinations. arXiv November 14, 2023. https://doi.org/10.48550/arXiv.2311.08117.
34. Aftab, W.; Apostolou, Z.; Bouazoune, K.; Straub, T. Optimizing Biomedical Information Retrieval with a Keyword Frequency-Driven Prompt Enhancement Strategy. bioRxiv April 28, 2024, p 2024.04.23.590746. https://doi.org/10.1101/2024.04.23.590746.
35. Ye, H.; Liu, T.; Zhang, A.; Hua, W.; Jia, W. Cognitive Mirage: A Review of Hallucinations in Large Language Models. arXiv September 13, 2023. https://doi.org/10.48550/arXiv.2309.06794.

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RESEARCH ARTICLE

Balancing Tradition and Transformation: An Ethnographic Study of Sattriya Culture of Assam, India

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ABSTRACT: The Sattriya culture of Assam, India, is centered in the monastic institutions known as Satras and has been a centerpiece of Assamese regional identity since the 15th century. This culture is now facing the tension between preserving its ancient traditions and adapting to the strong forces of globalization. This paper argues that the Sangeet Natak Akademi's (National Academy of Music, Dance, and Drama) recognition of Sattriya dance as a classical form in 2000 accelerated Sattriya culture's global exposure and rapidly transformed its economic, technological, and pedagogical domains. Drawing on ethnographic fieldwork in Majuli island (2025), including interviews with *bhakats* (monks) from multiple generations, this study analyzes how the integration of formal education, adoption of modern communication technologies, and efforts to mitigate the new economic pressures (such as the burgeoning interest in tourism) are reshaping the mindsets and practices of devotees, particularly those from the younger generation. This paper also explores the evolving socio-political role of the *Satra*, which necessitates ongoing negotiation between Sankardeva's founding egalitarian principles and current, sometimes contradictory viewpoints concerning caste and gender. This research studies the complex strategies employed by traditional culture to maintain continuity while navigating modernization, highlighting the crucial role of individuals within the *Satras* in shaping the future spiritual, social, and economic trajectories of these institutions.

KEYWORDS: Social Anthropology, Ethnomusicology, Cultural Globalization, Sattriya Culture, Heritage Preservation.

Introduction

The *Satras* of Assam, India, are monastic institutions that serve as epicenters for Sattriya culture - a tradition rooted in the 15th-century Neo-Vaishnavite movement started by Srimanta Sankardeva. This movement established *Ekasarana Dharma*, a devotional practice centered on Lord Vishnu, and is expressed through unique artistic forms such as *Borgeet* (devotional songs), *Naam Kirtan* (congregational chanting), and specific dance forms.[1] For over five centuries, these Satras, mainly concentrated on Majuli island in the Brahmaputra River, functioned as relatively insulated repositories of spiritual and cultural knowledge and played a crucial role in shaping Assamese identity.[2]

The late 20th century saw numerous political forces, such as the problem of large-scale illegal immigration from Bangladesh and a prolonged insurgency, at play.[3] The efforts to preserve the cultural identity of Assam gained momentum in the local population, and a pivotal moment in this process was the recognition of Sattriya dance as one of India's eight classical dance forms by the Sangeet Natak Akademi (SNA) in 2000.[3,4] This validation at a national level significantly amplified the tradition's visibility. At the same time, it accelerated the pressures and opportunities associated with modernization, tourism, and global cultural exposure.

This paper examines how the Sattriya culture, particularly within the Satras of Majuli, is managing this delicate balance. It argues that while globalization's influence predates 2000, the SNA recognition served as a powerful catalyst, intensifying tensions and adaptations across multiple domains. Specifically, this study explores how increased outreach to a wider audience and exposure are reshaping economic structures and technology adoption within the Satras. It also analyzes the impact of integrating formal education alongside traditional pedagogical methods (*Guru-Sishwa parampara*) and the changes it has brought upon the motivations and experiences of younger bhakats (devotees/monks). Finally, it investigates if the socio-political role of the *Satras* has evolved while exploring the ongoing negotiation between Sankardeva's foundational egalitarian principles and current practices related to caste and gender hierarchies. The paper begins with an outline of the methodology of the study, which includes ethnographic fieldwork, followed by a historical overview of the *Satras*, the Neo-Vaishnavite movement, and the evolution of Sattriya culture. Following this, the paper discusses the results of the ethnographic fieldwork on the key areas of change (increased outreach to a wider audience, reshaping of economic structures, technology adoption, integration of formal education, and the evolution of socio-political life). Finally, it concludes by summarizing the findings and suggesting avenues for future inquiry.

Methodology

Research for this paper was conducted using both primary and secondary sources, including intensive ethnographic field research in Majuli Island in Assam. Fieldwork was conducted in January 2025 in Auniati and Uttarkamalabari *Satra*. The *Satras*, belonging to *Brahmasamhati* and *Nikasamhati*, were chosen to obtain an additional range of opinions from orthodox and liberal sects, respectively.

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Methods used for primary data collection included participant observation during rituals like Naam Prasanga and performances, as well as semi-structured interviews with individuals from four key areas of engagement – heads of *Bohas*, senior *bhakats*, younger *bhakats*, and former *bhakats*/cultural advocates.

Data recording techniques included detailed field notes, audio recordings of interviews, and photographic documentation.

The research sought to uphold the highest standards of ethical consideration by obtaining verbal informed consent, ensuring anonymity where requested, and respecting cultural sensitivities and hierarchies within the *Satras*.

Qualitative field research techniques were used, like thematic analysis of interview transcripts and field notes, identifying patterns of continuity and change, comparing perspectives across generations and different *Satras/Samhatis*, and triangulation of interview data with observations and secondary sources.

This paper furthermore relies upon secondary sources drawn from scholarly papers, journals, and articles to help reinforce observations from the visit, view the tradition in its historical context, and gain perspectives related to the culture.

My position as a researcher was that of an 'insider-outsider'. I was able to establish a connection due to my Assamese family heritage and semi-fluency in the language. However, because I was born and raised in Gurgaon, outside of Assam, I lacked the same cultural context as many of my interviewees. To ensure accuracy, I sought help from a native Assamese speaker (my mother) who accompanied me in interviews and clarified complex sentences. The findings are limited by the brief fieldwork period and small sample size.

■ Historical Overview

Srimanta Sankardeva (c. 1449–1568) initiated the Neo-Vaishnavite movement, or *Ekasarana Dharma*, which emerged during a period of socio-religious tumult, broadly known as the Bhakti movement, across India. Like other Bhakti traditions, *Ekasarana Dharma* emphasized devotion (*bhakti*) to a single, supreme deity (primarily *Krishna/Vishnu*) and sought to make religion accessible to all social strata, challenging orthodox Brahminical rituals and rigid caste hierarchies.[5] As Dr. Karuna Bora, a former *bhakat* and cultural advocate, stated to me in an interview, Sankardeva aimed to *unite the Assamese people as a whole, bring the different communities together... irrespective of caste and creed*.[6] This reformist effort was central to the movement's initial spread and enduring influence on Assamese identity for over five centuries.[7]

The *Satras* became the epicenter of the movement. Structurally, a typical *Satra* includes a *Namghar* (prayer hall), *Manikuta* (shrine), and residential quarters (*Bohas*) for the *bhakats*.[8] Their leader is the *Satradhikar*, while *bhakats*, often celibate monks (*kevaliya bhakats*), are recruited in youth. They dedicate their lives to spiritual practice and the preservation of Sattriya tradition. Other disciples (*shishyas*) form the broader community base.[1]

Following Sankardeva and his primary disciple Madhavdeva, the movement evolved with differing interpretations. This led to the formation of four main sub-sects or *Samhatis: Brahmasamhati, Purushsamhati, Nikasamhati,* and *Kalasamhati*.[9] The *Brahmasamhati*, which was patronized by the Ahom kingdom, reintroduced certain Brahminical elements and caste considerations. This diverged from Sankardeva's founding egalitarianism.[10] These historical divergences continue to influence the practices and social structures within different *Satras* today.

Central to Sattriya practice are its unique artistic forms. Sankardeva and Madhavdeva composed Borgeets ('celestial songs') in Brajavali, using specific *ragas* (melodic modes) and often accompanied by the *khol* (drum) and *taal* (cymbals).[11,12] *Naam Kirtan* (congregational chanting) remains a core devotional activity. Sankardeva also created *Ankiya Naat* (one-act plays), performed as *Bhaona*, utilizing dance, music, elaborate costumes, and sometimes masks (*Mukha Bhaona*), which are also used to disseminate Vaishnavite philosophy.[13] These integrated art forms were designed not merely for aesthetic pleasure but also served as powerful tools for spiritual devotion and community building.

For centuries, these traditions remained largely confined to the *Satras* and the Assamese region. The post-independence era saw efforts by Assamese scholars, notably Maheswar Neog, to gain national recognition for Sattriya dance as a classical form, presenting it at platforms like the 1958 Sangeet Natak Akademi seminar.[3] This decades-long campaign culminated in the SNA's formal recognition in 2000. This decision significantly elevated Sattriya's national profile and acted as a major catalyst for its increased engagement with the world outside.[4]

■ Results and Discussion: Navigating Globalization Post-2000

The SNA recognition acted as a catalyst, accelerating the interaction between the historically insular Sattriya culture and the forces of globalization. The increased outreach directly supported the cultural economy of the *Satras* through an increase in tourism, performance fees, and government grants.[14]

Historically, the *Satras* have been supported by land grants (especially *Brahmasamhati Satras*) or community patronage. Many *Satras* now rely on a broader mix of revenue, which includes government funding, performance fees, tourism revenue, and individual enterprise.[15] Government grants facilitate crucial renovations, help in improving living conditions for the *bhakats*, and make the *Satras* more presentable to external visitors. National recognition, such as the award of Padma Shri, brings prestige and also inspires younger generations (as noted in the case of Mask-maker Kosha Kanta Deva Goswami).[16] Despite these expanded revenue channels, the realities of economic hardships persist. During our interview, the 102-year-old Padma Shri awardee Gopiram Borgayan Burabhakat lamented the rising cost of living and how it is a challenge to meet even the daily needs within the *Satra*.[17] This situation manifests across various dimensions, creating a need for adaptation, resistance, opportunity, and concern.

Performance vs. Ritual: Following the 2000 SNA recognition, Sattriya performance found a newer space beyond the ritual context of the *Namghar*. With access to a conventional stage, both national and international,[4] came a shift that was driven by a desire to share the culture, gain recognition, and secure economic support. Upen Borgayan, head of a *Boha* at Uttarkamalabari Satra, confirmed this trend, stating that *bhakats* now teach and "*perform in different places, even abroad, like London, France, America to spread the culture*," viewing this as a "*good development*."[18] This increased visibility has tangible outcomes, increasing tourism to places like Majuli—a significant source of income—and funding infrastructure improvements within the *Satras*.[14,19]

This shift towards performance for external audiences, including international tourists, has required adaptations. Dr. Karuna Bora described the recent creation of an outdoor performance area at Uttarkamalabari *Satra* specifically for tourists who might be unfamiliar with *Namghar* decorum or unable to sit on the floor for extended periods.[6] The field visit included witnessing one such performance for a group of French tourists on the outdoor stage.

Authenticity vs. Commercialization: The changes have also given rise to a debate between authenticity and commercialization. This tension is evident in reactions to modern renditions, such as Anurag Saikia's 'Project Borgeet,' which blends *Borgeet* melodies with Western orchestral arrangements.[20]

In the song "Are Kompito"[21] by Madhavdeva, Anurag Saikia predominantly uses Western instruments like the violin, cello, double bass, etc. The music video begins by showing visuals of the orchestra in Skopje, Macedonia, showing the sole singer Mizee and several instruments being played by members of the orchestra, with the piano being played by Anurag Saikia himself. A little over two minutes into the video, the visuals switch to rural Assam. Shots of a *Satra* and some dancers can be seen. Meanwhile, the music is dominated by the flute as the singing pauses. After about a minute, the visuals switch back to the orchestra and the singing resumes. We are also able to see the Shillong choir, although they are barely heard. This video reached a diverse audience, appealing to the younger generation. One YouTube comment captured the essence – "*I am a 13 y/o teenager, and I think my generation should listen to more songs like these and strengthen our roots to our motherland...This is the only way we can preserve this beautiful culture and heritage of Assam...*"

Other Assamese artists have also begun composing and performing music based on Sattriya culture. For example, Papon, an Assamese playback singer who currently has 1.44 million YouTube subscribers and is famous on a national level, has collaborated with Satras to publish Borgeet.[22] The video garnered over 1 million views with 20,000 positive affirmations.

Despite aiming to promote the "universality" of the music and culture, Upen Borgayan expressed reservations, suggesting such projects, while perhaps acceptable, require community consent: the artist "must seek permission first."[18] This indicates a desire within the community to maintain control over how their sacred traditions are represented and adapted for global consumption. The emphasis reveals a shift from devotional practice to cultural product, potentially altering the meaning for both practitioners and audiences. Dr. Bora summarized this, worrying that while performances spread awareness, "through media, one cannot convey the spiritual essence."[6]

Digital Outreach and Resistance: Technology serves as a tool for adaptation as well as a source of concern with the Sattriya culture. The power of digital platforms enabled unprecedented reach to a wider audience base. Upen Borgayan actively uses YouTube ("Upen Borgayan official")[23] to share *Borgeet* performances. While his channel has 14 videos, he acknowledges the double-edged nature of technology in that it increases awareness but potentially supports a superficial engagement with shorter attention spans. "*Online knowledge can be superficial," he cautioned, worrying that users might "take it easy and [not] want to devote enough time and energy*".[18] His perspective in the interview has an experimental tone: "*It comes with both pros and cons... trying to determine whether it will be a net positive in the Long run*." On the other hand, the elderly Gopiram Borgayan Burabhakat shared a stark warning that unchecked technology "*may destroy the essence of Satra life*."[17]

Within the *Satras*, the new is integrated pragmatically: harmoniums are used in teaching (though not in prayer rituals), modern instruments like violins and flutes feature in some performances, and sound systems help amplify *Bhaonas*.[6] These adaptations reflect a conscious effort to remain relevant even as the core dilemma persists on how to leverage modern tools without compromising the tradition's "*original essence*".[18] Dr. Bora shared this concern, noting that commercial motivations can lead individuals to "*imparting half-baked knowledge...*" diluting the art form.[6]

Evolving Transmission: The traditional method of transmitting Sattriya knowledge is the *Guru-Sishwa parampara* (teacher-disciple lineage), which relied on immersive apprenticeship within the *Boha* residential system.[8] This model has been indelibly changed with the increasing emphasis on formal education. Dr. Karuna Bora described the resistance he faced as one of the first *bhakats* from his *Satra* to pursue higher education in the mid-to-late 20th century: "*Back then, school education was not encouraged... I had to face a lot of hardship and resistance*."[6]

Today, the situation has reversed; formal schooling is now an acceptable standard, and many young bhakats pursue higher education alongside their monastic duties. Jumon Gayan, a 19-year-old *bhakat*, studying Political Science, exemplifies this new reality. He manages a demanding schedule of *Satra* duties (cleaning, cooking, rituals, fieldwork) alongside his college studies by relying on determination and support from friends: "*If he has to go for a function and has to miss school, his friends give him notes*."[24] His views on formal education are positive, and he believes it will help "*preserve Sattriya culture by adapting it to modern times*."[24]

However, this integration of formal education has influenced motivation and recruitment. Some interviewees noted that fewer boys join the *Satras*, partly due to increased education-

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al and career opportunities outside.[25] There is also a concern that some recruits might be attracted more by the "*glamour of becoming a performer*" on the international stage, rather than deep spiritual devotion.[25] Upen Borgayan linked this to the role of technology in reducing our ability to focus: "*Use of mobile phones has reduced people's attention span... These days, the usage of phones and technology leaves no time for introspection.*"[18] This raises a critical question on whether the depth of spiritual training and embodied knowledge central to the *Guru-Sishwa* tradition can co-exist alongside modern educational pathways and digital distractions.

Socio-political role and contested hierarchies:

Caste: Sankardeva's *Ekasarana Dharma* explicitly aimed to create a unified spiritual community, void of any caste structures.[7] Historically, *Satras* achieved this by facilitating the integration of various communities, including lower castes.[8] However, one can see the existence of a paradox where some *Satras*, particularly within the more orthodox *Brahmasamhati*, maintain caste-based hierarchies. Reserving key leadership positions such as *Satradhikar* for individuals from only Brahmin or high-caste backgrounds confirms this paradox. When questioned about this practice, the reasoning offered was adherence to a long-standing "*tradition that has prevailed for fourteen generations and cannot be broken*."[18] This acceptance of an evolved institutional custom over Sankardeva's founding egalitarian principles illustrates the complex interplay between founding ideology and entrenched interpretations.

Gender: Gender roles have sparked both tension and transformation within the Sattriya mindset. While vital to the socio-economic support of the *Satras*, women were traditionally excluded from core ritual spaces and leadership roles.[26] The SNA recognition facilitated the emergence of several women as prominent performers of Sattriya dance on public stages.[4] The pursuit of the Sattriya dance form took new dimensions - in the way it was learnt, the incorporation of newer costumes, and the entry of trained professional dancers into this art form. While there was a wave of change in training and performance of this dance, the inclusion of women within the ritual life of the *Satras* is still contested. In 2010, a landmark intervention occurred when the then-Governor J.B. Patnaik facilitated women's entry into the Patbausi *Satra Namghar*, invoking Sankardeva's inclusive vision. Yet, it did not lead to universal change; conservative institutions like Barpeta Satra continue to restrict women's access. Furthermore, acceptance of female performers is not uniform even among relatively liberal *bhakats*. Upen Borgayan expressed a nuanced view on female Sattriya dancers: "*He believes that excellence in the practice is characterized by strength and grace. He says that girls are able to exude grace but not strength, which is required in certain movements of the dance. In a way, the dance loses its original character.* "[18] This perspective highlights the ongoing debate surrounding authenticity, aesthetic standards, and gender as the tradition evolves beyond its historically male-dominated monastic origins.

■ Conclusion

The Sattriya culture of Assam, particularly as currently practiced within the *Satras* of Majuli, offers a compelling case study of how traditional cultures navigate the multi-dimensional forces of globalization as well as their survival. The entire ecosystem experienced a pivotal catalyst when its dance was formally recognized as a classical dance form of India. This single decision ushered in a new period of globalization, accelerating Sattriya music and dance's popularization and forcing the community to adapt quickly. This paper has demonstrated that managing this vital balance is not a uniform strategy handed down from the top. Rather, it is a constant, often conflicted negotiation happening among the individual monks, with every generation trying to figure out how much of the new world to embrace while still honoring the old.

The findings clearly reveal a spectrum of individual responses from the stakeholders. On one end, we have the determined guardians like Gopiram Borgayan Burabhakat. He represents the elders who fiercely guard authenticity and warn against any form of dilution. In the center, there are pragmatic leaders such as Upen Borgayan, who strategically experiment - adopt technology and adapt performance practices - to ensure the tradition's economic viability. On the other end is the young generation, exemplified by Jumon Gayan. They embody a more resolved synthesis: acceptance of formal education and modern life along with monastic duties, fueled by personal drive and a deep sense of cultural duty. Additionally, it has revealed how individuals outside of the *Satras* also engaged in the commercialization process, thereby impacting the broader Assamese community.

We see the impacts of globalization in clear, tangible ways: economic dependencies on tourism and government grants, the infiltration of digital media, acceptance of formal education, and evolving social hierarchies. These forces clash dramatically. The spiritual devotion of the past negotiates the commercial demands of performance, the immersive traditional transmission confronts the easy accessibility of digital platforms, and the egalitarian promises of the founder question the hierarchies and interpretations that came later.

However, these tensions are not just threats, but a focal point where the Sattriya identity is being shaped. The *bhakats* are the real agents of change with their daily choices - how they use their phones, how they explain caste practices, what they prioritize in their teaching. While this initial study was geographically constrained to Majuli and relies on a small sample of interviews, the consistency in commitment from the bhakats to the purpose of *Satra* life is clear, and they are the ones actively deciding the future trajectory of this tradition.

This ethnographic study offers a foundation for some significant future avenues for expansion. Future research can quantitatively investigate the true economic costs and benefits of tourism across various *Satras* as well as track changes in recruitment patterns and motivations for bhakats post 2000. Additionally, it could engage with the often-overlooked experiences of women practitioners - both inside and outside the *Satra*. Finally, this research encourages further discourse on whether the traditional power structures will finally yield to

Sankardeva's liberal founding ideals, or if those structures are simply too dominant to be overturned.

Ultimately, the Sattriya culture's evolution tells us that tradition is never static. Its survival hinges on its ability to adapt, a process linked with the personal experiences and deliberate choices of the custodians who guard it. The real challenge is to navigate change in a way that protects the essence while ensuring that the echoes of Borgeet still hold meaning for the generations to come.

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References

1. Sarma, S. N. The Neo Vaisnavite Movement and The Satra Institution of Assam. PhD Thesis, Department of Publication, Gauhati University, 1966. https://ia601402.us.archive.org/12/items/in.ernet.dli.2015.461471/2015.461471.The-Neo-vaisnavite.pdf.
2. Saikia, B. An Introduction to the Sattra Culture of Assam: Belief, Change in Tradition and Current Entanglement. *Journal of Ethnology and Folkloristics* 2019, No. 12(2):21-47, 47. https://doi.org/10.2478/jef-2018-0009.
3. Sethi, A. An Overlay of the Political: The Recognition of Sattriya. *India Seminar* 2015.
4. Rajkumari, M. The Journey of Sattriya Dance through Time and Space. *CONTEMPORARY SOCIAL SCIENCES* 2023, *32* (No 2 (April-June)), 114–136.
5. Neog, M. *Early History of the Vaisnava Faith and Movement in Assam*, Second.; Motilal Banarsidass: New Delhi, 1980.
6. Bora, Dr Karuna (K. Bora). Personal Interview, Jan 2025, Majuli, Assam.
7. Kutum, D. Srimanta Sankardeva and Neo-Vaishnavism Movement in Assam. *International Journal of Scientific Research and Engineering Development* 2025, *8* (4), 885–889.
8. Kashyap, U. K. The Evolution and Modern Challenges of Monastic Sattras in Assam. *International Journal of Creative Research Thoughts (IJCRT)* 2024, *12* (7), 856–860.
9. Bhuyan, D. P. Sectarian Divisions of Sankardeva's Neo- Vaishnavism in Assam. *IJSDR2205056* 2022, *7* (5), 335–341.
10. Saharia, D. The Interplay of State and Religion in the Brahmaputra Valley from 16th to the 18th Centuries. *Journal of North East India Studies* 2021, *11*(2) (Jul-Dec), 1–16.
11. Mahanta, B. *Borgeet*, 2nd ed.; Stores: Students, 2008.
12. Barua, B. K. Sankaradeva: His Poetical Works. In *Aspects of Early Assamese Literature*; Kakati, B., Ed.; Gauhati University: Guwahati, 1953; pp 64–125.
13. Malakar, K.; Borchetia, A. An Ethnographic Exploration of the Change and Continuity of the "Bhaona" Tradition of Assam. *ShodhKosh: Journal of Visual and Performing Arts* 2024, *5* (6), 875–893.
14. Mody, D. P.; Borah, A. Economic Impacts of Tourism in Majuli District of Assam: An Analysis of Public Perceptions. ResearchGate. *Shodh Sanchar Bulletin* 2020, *10* (40), 33–39. https://doi.org/10.13140/RG.2.2.14815.12967.
15. Pope, G. E. Mobilising Assamese Vaishnavite Performance Practices: Cultural Value on the Move. PhD Thesis, King's College London, 2019. https://kclpure.kcl.ac.uk/ws/portalfiles/portal/130914747/2020_Pope_Georgina_1443561_ethesis.pdf.
16. K_K_Deva_Goswami. Akademi Award: Mask-making Bhaona (Assam), 2003. https://sangeetnatak.gov.in/public/uploads/awardees/docs/K_K_Deva_Goswami.pdf.
17. Borgayan, Gopiram Burabhakat (G. Borgayan). Personal Interview, Jan 2025, Majuli, Assam.
18. Borgayan, Upen (U. Borgayan). Personal Interview, Jan 2025, Majuli, Assam.
19. Bezborah, C. J.; Gogoi, D.; Sen, S. Sattras of Assam: Balancing Tradition and Modernity for Sustainable Community Development. *Library Progress International* 2024, *44* (3), 21365–21373.
20. *PROJECT BORGEET - CHAPTER 1. YouTube*; 2019. https://www.youtube.com/watch?v=QwYScG2CyP0.
21. *Are Kompito | Sri Sri Madhavdeva | Anurag Saikia | Mizee | Borgeet | Devotional Song; YouTube*; 2020. https://www.youtube.com/watch?v=W4nYbrPvUYQ.
22. *Börgeet Ghôxaa - Borgeet Vol 1|| Pāpön || Audio JukeBox; YouTube*; 2019. https://www.youtube.com/watch?v=6BHYTGxwMvw.
23. *Jadaba Jadu Nandan/Ghuxa Chandra/Upen Bor Gayan; YouTube*; 2024. https://www.youtube.com/watch?v=QoShOmhhdvw.
24. Gayan, Jumon (J. Gayan). Personal Interview, Jan 2025, Majuli, Assam.
25. Saikia, Dr Baburam (B. Saikia). Personal Interview, May 2025, Guwahati, Assam.
26. Das, M. Understanding the Caste & Gender Dynamics within Sattras in Assam, 2024. https://theambedkarianchronicle.in/caste-in-temple/understanding-the-caste-gender-dynamics-within-sattras-in-assam/.

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RESEARCH ARTICLE

Evaluating the Financial and Environmental Impact of Prompt Engineering and Quantization on LLMs for Code Generation

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ABSTRACT: Prompt engineering is a technique that helps extend a Large Language Model's (LLMs) capability without altering the core model. However, these prompting techniques can often be inefficient as they require multiple LLM inferences and large context windows. LLMs have gotten exceptionally big and are being used billions of times every day. This implies that inefficient prompt engineering techniques can have huge impacts when scaled up, especially financial and environmental impacts. As resources are used inefficiently, due to prompt engineering, they often lead to higher costs in electrical usage, which can make LLMs more expensive to use and run. Additionally, this higher electricity use can raise carbon emissions, increasing the cost to the environment. Most cloud providers don't use renewable sources of energy. This underscores why a deeper analysis of the environmental impacts of LLMs is necessary. Any inefficiencies can often scale up, leading to huge costs, negatively impact the environment, and make LLMs cost-intensive. This study aims to evaluate the trade-offs between accuracy and the environmental and financial costs of various prompting techniques, enabling practitioners to make informed decisions about the cost efficiency and sustainability of their LLM pipelines.

KEYWORDS: Computer Science, Artificial Intelligence, Large Language Model (LLM), Quantization Prompt.

Introduction

Large language models are Natural language processing models designed to predict word sequences based on the transformer architecture.[1] They are trained on vast amounts of text data to understand and generate human-like language, and are capable of performing tasks such as translation, summarization, question answering, and code generation.[2] Though very capable models, they often can't match human-level reasoning and intelligence in logical contexts. Hendrycks *et al.*[3] mention that LLMs, even the big ones, are far behind Humans in complex math tasks, and Patel *et al.*[4] mention that LLMs often struggle with simple grade school math regardless of size.

To extend their performance in complex logical contexts, LLMs use prompting techniques. This is done by engineering and tuning the prompts sent to the model. Prompt engineering is especially powerful because it allows the model to function better than its standard capacity and also improves the model's ability in unseen or untrained contexts, while not requiring any tuning or training.[2]

Recent advances in prompt engineering have brought the models close to human-level reasoning.[5] Regardless, prompt engineering is often inefficient. Most prompting techniques often utilize a large portion of the context or require multiple inferences.[2]

This paper compares different techniques used to improve LLMs, examining whether the additional accuracy of some techniques justifies the cost. As LLMs are getting bigger and more widespread, this question becomes more and more important as inefficiencies in the model scale up. These issues are especially impactful in two segments: Financial and environmental.

Most APIs often charge for the token count. This makes the large context windows for many techniques costly. Additionally, the electrical input and computational power required lead to huge carbon emissions, which create an environmental cost. This makes LLMs unsustainable for the environment. This is why this study measures electrical and token output throughout different prompting techniques to compare and identify how prompting techniques fare on common reasoning datasets.

The data collected will include prompt tokens, completion tokens, and the electrical output, and will evaluate the different prompting techniques on factors such as accuracy and relative environmental emissions. The tests will be run on a Mistral-7B-Instruct-v0.1 quantized at 4bit and 8bit precision levels to gain a more diverse perspective on how size and quantization might have impacts. Additionally, the evaluation will also consider the differences between self-hosting and the API for the model.

Background Theory

The goal of an LLM is to create an intelligent natural language model that is capable of using its token-predicting capabilities to synthesize and generate text automatically. LLMs are first trained on huge corpora of text data, such as the common crawl, Wikipedia, online books, GitHub, Arxiv, and open source.[6] This data is for pretraining used to train the model into creating a token prediction model that can predict patterns and generate a distribution of next possible token combinations.

LLMs learn to understand the logic between different tokens, but this isn't just restricted to human languages. Trained on millions of examples, LLMs can go beyond basic conver-

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sation and generate code. LLMs are becoming exceptionally common for software development due to their ability in coding tasks, especially those that are tedious, with exceptional speed.[6] Therefore, code generation is an important factor to measure the LLMs' performance in the real world, because code generation is one of the most common uses for LLMs.[6]

There are many ways to improve the ability of LLMs, but the simplest and most efficient way is to use prompt engineering.

One of the simplest prompting techniques is a few-shot. It involves giving the model a set of examples in the prompt. These examples are designed to provide the LLM with additional context to help with the problem. The number of examples chosen can range from 2 to 100, as many as possible in the context window, and they showcase impressive increases in accuracy. Though they perform worse than state of the art fine tuned models.[1] Regardless, they allow the model to significantly improve accuracy without an abundance of data samples or any retraining.

Chain of Thought (Chain of Thought) is a promoting technique that prompts an LLM to think and process complex processes similar to a human. When humans approach a multi-step or complex problem, they often approach it step by step. Similarly, COT encourages the model to think about the task in multiple steps rather than answering the question directly. It is highlighted to have multiple benefits for reasoning performance. It significantly improves LLM performance on reasoning tasks, especially big models like PaLM 540B: boosting accuracy on GSM8K from 17.9% to 58.1%.[7] For this study, we will compare 0-shot COT.

Sample reasoning

```markdown
To solve the task, we need to follow these steps:
1. Convert the input string to a list of numbers using the `split()` function.
2. Sort the list of numbers using the `sorted()` function.
3. Convert the sorted list of numbers back to a string using the `join()` function.
```

Scratchpad is a form of reasoning technique that allows the model to generate an arbitrary sequence of intermediary tokens before producing the answer. Unlike COT, which is designed to think before an answer, the scratchpad is meant to use its reasoning tokens as a notebook and pen to solve the problem. When Zero Shot COT generates steps for complex problems, it can often make errors in reasoning or skip steps, leading to the LLM making errors while executing. Scratchpad performs steps in the planning, which improves accuracy as the answer is less likely to be impacted by faulty reasoning. Scratchpad improved performance by approximately 50% on the MultiArith benchmark and by almost 40% on the Python code execution benchmark.[8]

Sample reasoning

```
* **Step 1:** Take the input string of numbers, e.g., `"3 1 2"`.
* **Step 2:** Split the string into a list using `split()`.
* Input: `"3 1 2"` → `["3", "1", "2"].`
* **Step 3:** Sort the list using `sort()` (or `sorted()`).
* Sorted list: `["1", "2", "3"].`
* **Step 4:** Join the sorted list back into a string using `' '.join()`.
* Result: `"1 2 3"`
```

Structured Chain of Thought (SCOT) is another prompting technique that builds on COT. COT, designed to improve the reasoning ability of LLMs, doesn't do as well on Code generation tasks. SCOT is a version of COT that specializes in code through precise instructions, such as loops and branches.[9] Instead of writing in natural language like COT, it generates reasoning in pseudocode. These pseudocode instructions are often more precise and specific, which allows for easier conversion, leading to better accuracy than their counterparts. SCOT reveals better performance than COT by 13.79% on Human Eval benchmark.[10]

Sample reasoning

```
// Sequence: Parse input and prepare data
INPUT ← READ_INPUT_STRING()
LIST ← SPLIT(INPUT, delimiter=" ")
// (Optional branch: ensure elements are numeric)
IF ANY_ELEMENT_NOT_NUMERIC(LIST) THEN
ERROR ← "Invalid input: non-numeric detected."
RETURN ERROR
END IF
// Sequence: Sort operation
SORTED_LIST ← SORT(LIST)
// Sequence (could be seen as a loop underpinning join)
OUTPUT ← ""
FOR EACH ELEMENT in SORTED_LIST DO
OUTPUT ← CONCATENATE_WITH_SPACE(OUTPUT, ELEMENT)
END FOR
RETURN TRIM_LEADING_SPACE(OUTPUT)
```

Quantization is a process that can help with both financial and environmental aspects of running an LLM. Quantization is the process of shrinking the precision of numbers used in LLMs by reducing the number of bits used to represent them. This process rounds values, thereby reducing the number of calculations done by the computer during inference. However, the process of rounding can reduce the accuracy and performance of LLM. Regardless, according to Giagnorio *et al.*,[11] A 4-bit quantization to Deepseek Coder 33B led to 70% reduction in memory footprint without significant loss in performance, highlighting its usefulness in running LLMs with limited hardware.

Methods

Datasets:

Human Eval is a dataset by OpenAI. It contains many samples of coding problems meant to test LLM's ability in code generation. It asks the user to write code based on an input and then tests the code using an evaluator to provide a quantitative measurement of the model's ability through its 164

samples. Exactly 100 samples will be used in this study for each prompting technique.

Example HumanEvel/01[12]

Question

```python
from typing import List
def has_close_elements(numbers: List[float], threshold: float) -> bool:
Check if in the given list of numbers, there are any two numbers closer to each other than
given threshold.
>>> has_close_elements([1.0, 2.0, 3.0], 0.5)
False
>>> has_close_elements([1.0, 2.8, 3.0, 4.0, 5.0, 2.0], 0.3)
True
"""
```

Test

```
METADATA = {
'author': 'jt',
'dataset': 'test'
}
def check(candidate):
assert candidate([1.0, 2.0, 3.9, 4.0, 5.0, 2.2], 0.3) == True
assert candidate([1.0, 2.0, 3.9, 4.0, 5.0, 2.2], 0.05) == False
assert candidate([1.0, 2.0, 5.9, 4.0, 5.0], 0.95) == True
assert candidate([1.0, 2.0, 5.9, 4.0, 5.0], 0.8) == False
assert candidate([1.0, 2.0, 3.0, 4.0, 5.0, 2.0], 0.1) == True
assert candidate([1.1, 2.2, 3.1, 4.1, 5.1], 1.0) == True
assert candidate([1.1, 2.2, 3.1, 4.1, 5.1], 0.5) == False
```

Metrics collected:

Tokens refer to the sub-word level encoding that LLMs use to work with information. In this experiment, they are split into prompt tokens, tokens that are generated by the user and imputed into the model, and completion tokens, tokens generated by the model. Separating provides more accurate estimations of the cost, because prompt tokens tend to take less energy than completion tokens, so that prompt-heavy response sparse techniques aren't at a disadvantage.

Electrical input is the energy required to run the model. Beyond hardware costs, which are usually constant for all techniques, electrical input helps measure the true environmental impact and financial cost for self-hosting. Both GPU and total electrical input will be measured. This is because the total electrical input allows trends and provides accurate values for total consumption, but can be noisy and easily impacted by other factors. Whereas, GPU energy is directly linked with LLM inference, and isn't affected significantly by background processes. Code Carbon will be used to measure the electrical input. Code Carbon is a Python library used to estimate the electric consumption and the carbon footprint of executed code.[13,14] It calculates electric power consumption using system hardware.

The financial cost of using a model with an API can be calculated by multiplying the token count by the rate. Usually, prompt tokens cost less than completion tokens, but for the Mistral API, our standard of measure, the cost of input and output tokens is $0.25 per million input tokens,[15] or $0.00000025 per token.

Self-hosting financial cost will be the financial cost of operating the model. This involves setting a standard rate for electricity and cost, and then multiplying it by $0.13 per kilowatt-hour (kWh).[16] Though not identical in all locations, it is comparable between prompting techniques. Iowa was chosen as the location, as the data collection was done on a server in Iowa.

Self-hosting CO_2 emissions are based on multiplying the electrical input by the carbon intensity of electricity. The carbon intensity comes from the same location as the electricity rate, and the carbon intensity for Iowa is 252 g CO_2 / kWh. [17]

Model:

Mistral 7B was chosen because it is an open-source and light model, with 7 billion parameters, while still being comparable to much bigger models in reasoning performance. This allows easy and comprehensive evaluation. Additionally, the data will be collected with 4-bit quantization and 8-bit quantization.

Sampling Strategies/ Inference Settings:

input_ids=inputs,
attention_mask=attention_mask,
max_new_tokens=1000,
do_sample=True,
temperature=0.7,
top_p=0.95

Tools Used:

Nvidia T4x2
Kaggle Notebook

Results and Discussion

Table 1: 4-bit quantization: Prompting techniques performed worse than 0-shot in accuracy.

	Zero Shot	COT	Scratchpad	Few Shot	SCOT
Accuracy at Human Eval(%)	86	86	82	76	81
Prompt tokens	15855	22755	37155	78755	33555
Completion Tokens	33123	38548	26139	30568	32318
Total Tokens	48978	61303	63294	109323	65873
GPU Electrical input (kWh)	0.07771985162	0.09367008827	0.05964057355	0.0744172125 9	0.07820676784
Total Energy Input (kWh)	0.1295784956	0.186484157	0.1041235153	0.1271711545	0.1340371129
Duration (Seconds)	2989.058672	4307.521816	2563.834739	3040.547511	3217.871555
API Financial cost ($)	0.0122445	0.01532575	0.0158235	0.02733075	0.01646825
Self-Hosting Financial Cost	0.01010358071	0.01217711148	0.00775327456 1	0.0096742376 37	0.01016687982
Self Hosting CO2 released (g CO_2)	19.58540261	23.60486224	15.02942453	18.75313757	19.7081055

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Table 2: 8-bit quantization: Improvements in ability for few-shot and reasoning methods, but 0-shot still performs better than prompting techniques.

	Zero Shot	COT	Scratchpad	Few Shot	SCOT
Accuracy at Human Eval(%)	87	81	81	80	81
Prompt tokens	15855	22755	37155	78755	33555
Completion Tokens	28034	41842	28071	30420	30341
Total Tokens	43889	64597	65226	109175	63896
GPU Electrical input (kWh)	0.1291323489	0.2092452868	0.1234488821	0.1539121323	0.1412329944
Total Energy Input (kWh)	0.2411115047	0.3681580369	0.2302056308	0.2737391468	0.255693612
Duration (Seconds)	6454.04618	9158.96719	6152.92477	6906.287735	6596.967327
API Financial cost ($)	0.01097225	0.01614925	0.0163065	0.02729375	0.015974
Self-Hosting Financial Cost	0.01678720535	0.02720188729	0.01604835467	0.0200085772	0.01836028927
Self Hosting CO2 released (g CO_2)	32.54135191	52.72981228	31.10911829	38.78585734	35.59071458

The Impact of Quantization on Prompting Efficacy:

The results from Table 1 and Table 2 reveal that for 4-bit quantization, the zero-shot tends to perform as well as zero-shot COT, and better than scratchpad and other techniques; furthermore, higher prompt tokens were negatively linked to accuracy. This means that adding more details to your prompt context can lead to a loss of accuracy. However, most papers, such as Brown *et al.*,[1] Zhou *et al.*,[18], and Wei *et al.*[7], highlight that adding more context, examples, and reasoning steps tends to improve the model. The main reason for the reduction in accuracy is quantization. Quantization can reduce the precision of the bits, which doesn't affect accuracy too much, but reasoning is often sensitive and can be affected by quantization. Research reveals that quantization, especially at 4 bits, reduces the performance of the model.[19] Furthermore, quantization can have a huge impact on the logical reasoning ability of LLMs.[20] These highlight that quantization, especially with a small model like Mistral 7b, can make reasoning techniques ineffective.

Additionally, the 4-bit model had greater issues with hallucination. Instead of writing the code, the model would be stuck in a loop, repeating similar lines till it reached the token limit. However, when quantization was reduced, the model was much more consistent in its replies and didn't hallucinate in such a way. Additionally, both 4-bit and 8-bit underscored similar performance. This implies that even though they have similar accuracy, reducing quantization might be good for better structure and formatting tasks.

Table 3: Few shot Vs 0 Shot with 8-bit SCOT.

	SCOT	Few Shot SCOT
Accuracy at Human Eval(%)	81	86
Prompt tokens	33555	114155
Completion Tokens	30341	33766
Total Tokens	63896	147921
GPU Electrical input (kWh)	0.1412329944	0.1706562693
Total Energy Input (kWh)	0.255693612	0.3056164071
Duration (Seconds)	6596.967327	7778.500091

Moreover, in 4-bit quantization, adding a few shots highlighted a reduction in performance, but in 8-bit quantization, a few-shot approach performed better than 0-shot versions. For example, in the exploratory sample above in Table 3, where SCOT was run with a few shots, it performed 5% better. While the same trials in 4 bits revealed that the model actually performed worse. This implies that heavy quantization could reduce the few-shot performance of LLMs.[21]

Overall, quantization was found to be very useful in reducing the GPU energy usage by 46% and the time by 51%. This highlights that reducing the bit precision by half can reduce the processing required by approximately half, without a significant decrease in quality. This underscores the ability of quantization to make LLMs more accessible and easier to run.

Methods of improving efficiency:

Furthermore, while analyzing the outputs across all prompting techniques, one common waste of electricity and token count was post-reasoning. Post-reasoning is when a model reasons and thinks after writing the code. This can help explain code to the user in an interactive chatbot environment, but in the context of code generation, it is usually ineffective. When forced to think before writing the code, the reasoning capability of models increases, but thinking after writing the code can't improve the code; therefore, tokens are often wasted. To reduce post-reasoning, the model can be prompted to avoid reasoning after code, or can be terminated after detecting patterns, such as three back ticks (``"), that signify that the code is complete.

Another way to improve the performance would also be to merge the techniques. Though the paper works with and discusses discrete prompting techniques, many of these techniques can be merged to create more efficient or capable techniques. For example, Scratchpad could be combined with a few-shot approach to improve model performance with complex tasks.

Comparative Efficiency of Prompting Techniques:

Overall, the best performance is showcased by the 0-shot approach, even though it's the most basic technique. This is because quantization reduces the ability of the model to handle large context windows, which benefits 0-shot learning because it doesn't fill context with examples and thinking.[21]

COT can compete with 0 shot accuracy, but due to reasoning tokens, it takes much longer. This leads to 120% the energy usage when compared to 0 shots. Scratchpad, on the other hand, falls by 4% on accuracy, but is the most efficient prompting technique. Using 20% less electricity when compared to 0 shot and only 35% less than COT. This means it is recommended for efficient workloads that require reasoning.

Few-Shot is usually an efficient technique, but examples for code generation can take a huge portion of the context window, and quantization isn't able to handle huge context windows as well. In 8-bit quantization, we see a huge jump for few-shot, while other techniques maintain their accuracy. This means that for higher bit precision, few should be an effective technique.

However, few-shot is much worse in an API context because APIs value prompt tokens almost as much as completion tokens, which leads to higher API costs even though energy usage for prompt tokens is much lower. Overall, few-shot works better for less quantized models, and usually isn't efficient when examples are large, or the API is used.

SCOT is a version of COT, but in these experiments, it performs 4% worse. Though it highlights 20% less energy usage when compared to COT. This implies that pseudocode-like reasoning is much more efficient, but can come at the price of accuracy.

External threats to validity:

Models tend to perform significantly better as the parameter size increases.[5] This means that for bigger models with greater reasoning abilities, small improvements that may seem negligible may start to become more apparent, especially due to the non-linear nature of reasoning and LLM parameter size. This highlights another point of study into how bigger parameter size differences affect the gap in the accuracy between two similar models. Additionally, different LLMs process information differently, which makes generalization across all models difficult. For example, different LLMs require different quantities of energy for the same task.[22] Hence, using the same prompting techniques across different LLMs can give different results.

Furthermore, in our tests, we used 4-bit and 8-bit quantization. However, different levels of quantization could show different results. Quantization's impact on accuracy isn't linear,[23] and this paper does not test across a lot of quantization levels, such as 2-bit and 16-bit. Thereby, quantization could add more complexity and potentially hinder some prompting techniques more than others.

Moreover, some different LLMs have different value prompt tokens and completion tokens. This means that prompt-heavy techniques may have an advantage while using the API, but not be helpful while using another. This can be seen with COT and few-shot in Table 1, where even though few-shot has a much higher API cost, it is cheaper to run, because the API gives prompt tokens and Completion tokens equal value, in spite of prompt tokens taking less energy.

In addition, sampling strategies like top_P or temperature affect the token probability distribution used to predict the next word. For programming and code generation, a low temperature and top_P is recommended,[24] but different values could alter the result.

Internal threats to validity:

Though the experiment took precautions to prevent inaccuracies in data collection, specific issues could act as a threat to the validity of the study. To start, we used a popular code generation dataset, but not every sample from the dataset was used. For example, the first 100 samples for Human Eval. Additionally, Code Carbon measures the energy usage of the hardware components, but it can encounter noise from background tasks, though CPU and RAM usage were removed to reduce noise.

Future Work:

This study opens several avenues for future research. While this study focuses on the Mistral 7B instruct model with 4-bit and 8-bit quantization, future research could explore how the results change when some controlled factors are changed.

For example, evaluating the performance across other models could help substantiate the generalizability of the findings, and examining models with bigger parameter sizes could also highlight how reasoning ability and quantization affect the model.

Moreover, we did not explore methods that involve fine-tuning. Investigating techniques that leverage fine-tuning could reveal approaches that improve performance while reducing environmental and computational costs,[25] providing a broader view of sustainable model optimization.

Furthermore, methods that require the use of multi-inference pipelines, such as Least to Most prompting,[18] Automatic COT,9 and Plan & Solve,[26] are not included in the study. A similar study could be done for these types of techniques.

Conclusion

Overall, this study examined the effect of quantization and prompting techniques on the performance and efficiency of an LLM for code generation. The results indicate that while quantization provides a substantial reduction in energy usage and computational cost, it tends to reduce the model's reasoning ability, making planned reasoning and few-shot generalization through prompting techniques ineffective. It also reveals that quantization can lead to hallucination and also reduces the structural and formatting ability of the LLM. In addition, the study further compares that for heavily quantized models, 0-shot tends to work best for performance, whereas scratchpad tends to work best for cost and environmental efficiency, but also highlights that quantized models struggle with few-shot learning.

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References

1. Vaswani A; Shazeer N; Parmar N; Uszkoreit J. Attention is all you need. Adv. Neural Inf. Process. Syst. 2017, 30.
2. Brown, T; Mann B; Ryder N; Subbiah, M. Language models are few-shot learners. Adv. Neural Inf. Process. Syst. 2020, 33, 1877–1901.
3. Hendrycks, D.; Burns, C.; Kadavath, S.; Arora, A Measuring mathematical problem solving with the MATH dataset. arXiv 2021, arXiv:2103.03874.
4. Patel, A.; Bhattamishra, S.; Goyal, N.; Patel, A. Are NLP models really able to solve simple math word problems? arXiv 2021, arXiv:2103.07191.
5. Huang, J.; Chang, K.; Huang, J.; Chang, K. Towards reasoning in large language models: A survey. arXiv 2022, arXiv:2212.10403.
6. Huynh, N.; Lin, B.; Huynh, N.; Lin, B. Large language models for code generation: A comprehensive survey of challenges, techniques, evaluation, and applications. arXiv 2025, arXiv:2503.01245.
7. Wei, J.; Wang, X.; Schuurmans, D.; Bosma, M. Chain-of-thought prompting elicits reasoning in large language models. Adv. Neural Inf. Process. Syst. 2022, 35, 24824–24837.
8. Nye, M.; Andreassen, A.; Gur-Ari, G.; Michalewski, H. Show your work: Scratchpads for intermediate computation with language models. arXiv 2021, arXiv:2104.03464. 9. Shubham, V, Dubey, H. Survey of Prompt Engineering Techniques and Challenges, 2024.
10. Li, J.; Li, G.; Li, Y.; Jin, Z. Structured chain-of-thought prompting for code generation. ACM Trans. Softw. Eng. Methodol. 2025, 34 (2), 1–23.

DOI: 10.36838/IJHSR811.27

11. Giagnorio, A.; Mastropaolo, A.; Afrin, S.; Di Penta, M. Quantizing large language models for code generation: A differentiated replication. arXiv 2025, arXiv:2503.07103.
12. OpenAI. openai\humaneval. Hugging Face, 2021. Available online: [https://huggingface.co/datasets/openai/openai\humaneval](https://huggingface.co/datasets/openai/openaihumaneval).
13. Rubei R.; Moussaid A.; di Sipio C.; di Ruscio D. Prompt engineering and its implications on the energy consumption of large language models. arXiv 2025, arXiv:2501.05899.
14. Impact, M. C. Codecarbon: A tool to estimate the carbon emissions of machine learning models, 2024; accessed 2024-03-05. Available online: https://mlco2.github.io/codecarbon/.
15. Mistral AI. API Pricing. Mistral AI. Available at: https://mistral.ai/pricing#api-pricing. Accessed September 1, 2025.
16. EnergySage. How Much Does Electricity Cost in 2025? Available at: https://www.energysage.com/local-data/electricity-cost/. Accessed September 1, 2025.
17. LowCarbonPower.org. Iowa Electricity Generation Mix 2024/2025
18. Zhou, D.; Schärli, N.; Hou, L.; Wei, J. Least-to-most prompting enables complex reasoning in large language models. arXiv 2022, arXiv:2205.10625.
19. Liu, R.; Sun, Y.; Zhang, M.; Bai, H. Quantization hurts reasoning? An empirical study on quantized reasoning models. arXiv 2025, arXiv:2504.04823.
20. Li, Z.; Su, Y.; Yang, R.; Xie, C. Quantization meets reasoning: Exploring LLM low-bit quantization degradation for mathematical reasoning. arXiv 2025, arXiv:2501.03035.
21. Liu, Y.; Meng, Y.; Wu, F.; Peng, S.; Yao, H.; Guan, C.; Tang, C.; Ma, X.; Wang, Z.; Zhu, W. Evaluating the Generalization Ability of Quantized LLMs: Benchmark, Analysis, and Toolbox. arXiv 2024, 2406.12928 (preprint, posted June 15, 2024).
22. Jegham, N.; Abdelatti, M.; Elmoubarki, L.; Hendawi, A. How hungry is AI? Benchmarking the energy, water, and carbon footprint of LLM inference. arXiv 2025, arXiv:2505.09598.
23. Gong, Z.; Liu, J.; Wang, J.; Cai, X. What Makes Quantization for Large Language Model Hard? An Empirical Study from the Lens of Perturbation. Proc. AAAI Conf. Artif. Intell. 2024, 38 (16).
24. Arora, C.; Sayeed, A. I.; Licorish, S.; Wang, F. Optimizing large language model hyperparameters for code generation. arXiv 2024, arXiv:2408.10577.
25. Wei, J.; Wang, X.; Schuurmans, D.; Bosma, M. Distilling step-by-step! Outperforming larger language models with less training data and smaller model sizes. arXiv 2022, arXiv:2305.02301. (please confirm identifier)
26. Wang, L.; Xu, W.; Lan, Y.; Hu, Z. Plan-and-solve prompting: Improving zero-shot chain-of-thought reasoning by large language models. arXiv 2023, arXiv:2305.04091.

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RESEARCH ARTICLE

The Economic Fallout of Aviation Accidents on Airlines, Manufacturers, and Insurers

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ABSTRACT: Major aviation disasters, such as the Pan Am Flight 103 bombing (1988), the Boeing 737 MAX crashes (2018–2019), and the September 11 attacks (2001), have disrupted not only air travel but also the financial stability of airlines, manufacturers, and insurers. These events provide compelling case studies for examining how aviation accidents provoke multifaceted economic shocks that extend beyond the immediate tragedy. This study investigates: What are the economic consequences of major aviation accidents on airlines, aircraft manufacturers, and insurance markets—and how do differences in crisis response shape those outcomes? Scholars in aviation safety and transportation economics have extensively analyzed technical failures and consumer risk perceptions, yet few focus on the long-term economic and market impacts of aviation disasters. Building on recent work in crisis economics and reputational risk, this research uses a comparative case study approach integrating financial data, stock market analysis, and policy reviews to reveal patterns in post-disaster economic trajectories. This paper argues that major aviation accidents cause significant financial shocks whose severity and duration are heavily influenced by the effectiveness of institutional responses and public communication strategies. Understanding these dynamics offers new insights into risk management and economic resilience in high-stakes industries, highlighting the critical role of crisis response in corporate and market survival.

KEYWORDS: Economics, Behavioral Economics, Aviation Accidents, Economic Impact, Crisis Response, Financial Markets, Reputation Management.

Introduction

On October 29, 2018, Lion Air Flight 610 plunged into the Java Sea shortly after takeoff, marking the start of a global aviation crisis that escalated with Ethiopian Airlines Flight 302 five months later. Both crashes involved Boeing's 737 MAX aircraft, grounding over 300 planes worldwide and inflicting over $20 billion in damages. These incidents shook public trust in Boeing and highlighted how aviation disasters inflict complex economic and reputational damage beyond the tragic loss of life.

While the causes of aviation disasters—engineering failures and regulatory lapses—are well documented, the broader economic and financial repercussions and their underlying mechanisms remain underexplored. This paper investigates: What are the economic consequences of major aviation accidents on airlines, manufacturers, and insurance markets, and how do varying crisis responses influence these outcomes? Through three case studies—the Pan Am Flight 103 bombing, the Boeing 737 MAX crashes, and the September 11 attacks—this research argues that aviation accidents produce acute, multidimensional financial shocks whose severity and duration are shaped by institutional responses and public communication strategies.

Previous research often focuses on technical or psychological aftermaths, such as pilot errors or risk perception.[1,2] However, economic analyses reveal significant stock market impacts and shifts in safety investments linked to financial conditions.[3,4] This paper draws on financial filings, market data, insurance settlements, and policy reports, applying an economic lens to illustrate aviation accidents as major financial inflection points. This interdisciplinary approach builds on crisis economics and reputational risk theory, expanding the field's focus to long-term economic adaptation and survival, rather than immediate technical failure.

Understanding the economic consequences of aviation disasters illuminates how corporate resilience and public trust hinge on effective crisis management. This analysis demonstrates that disaster response—not disaster alone—determines whether firms navigate recovery or face severe decline. In doing so, it contributes to emerging research on how information asymmetry, regulatory intervention, and reputational damage translate into market volatility and financial restructuring.

The paper proceeds in three sections: Section I analyzes the Pan Am Flight 103 bombing's role in the airline's collapse; Section II evaluates Boeing's 737 MAX crisis, focusing on market repercussions and regulatory changes; Section III assesses the financial consequences of 9/11 for the airline industry's systemic vulnerabilities. Together, these cases show how the nature of a crisis and the quality of institutional response mediate economic fallout and shape the trajectory of industry-wide risk.

Data, Case Selection, and Methodology

2.1. Case Selection Rationale:

This research examines three high-profile aviation disasters: the 1988 bombing of Pan Am Flight 103 over Lockerbie, Scotland; the 2018–2019 Boeing 737 MAX crashes involving Lion Air Flight 610 and Ethiopian Airlines Flight 302; and

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the September 11, 2001, terrorist attacks in the United States. These cases were selected for three reasons.

First, each event triggered substantial economic disruption within the aviation industry, offering clear examples of financial shock at the corporate, sectoral, and systemic levels. Second, they represent different types of crises — sabotage, product failure, and geopolitical terrorism — which allows for comparison across varying causal mechanisms and crisis-response contexts. Third, each incident has been extensively documented in academic studies, financial reports, news media, and government investigations, ensuring sufficient data availability for a rigorous comparative analysis.

By selecting cases that differ in event type, actors, and institutional constraints, the study is able to examine how distinct crisis mechanisms interact with market structures and regulatory environments to shape economic outcomes. This diversity improves the analytical leverage of the comparison and supports broader inferences about crisis dynamics in the aviation sector.

2.2. Data Sources:

The study draws from a combination of primary and secondary sources.

Primary sources include corporate financial statements (e.g., SEC 10-K filings for Boeing and major U.S. airlines), stock price and trading volume data retrieved from market archives, and legal or insurance settlement records where available. These provide quantitative measures of immediate and long-term financial impact.

Secondary sources include peer-reviewed scholarship on aviation safety, crisis economics, and corporate reputation management, along with historical accounts of each incident. News archives — such as The New York Times, The Washington Post, The Guardian, and Reuters — are used to track real-time reporting, public sentiment, and shifts in media framing. Policy documents from agencies such as the National Transportation Safety Board (NTSB), the Federal Aviation Administration (FAA), and the International Civil Aviation Organization (ICAO) contribute to understanding regulatory responses.

By integrating these diverse data types, the study balances quantitative analysis with qualitative insights into public perception and institutional behavior.

2.3. Analytical Framework:

This research employs a comparative case study approach, combining financial metrics with qualitative indicators of reputational and operational damage. The framework is guided by the concept of crisis economics, which views catastrophic events not only as safety failures but as market shocks that can reshape competitive landscapes.

For each case, the analysis focuses on three core dimensions: Immediate Financial Impact — measured through stock price changes, revenue losses, insurance payouts, and direct costs of grounded fleets or halted operations. Reputational Consequences — assessed via media sentiment, consumer behavior, and brand perception metrics. Institutional Response — including corporate crisis communication strategies, regulatory interventions, and legal proceedings.

Comparative analysis identifies patterns and divergences in how these dimensions unfold, highlighting the role of crisis type, regulatory environment, and speed of response in shaping outcomes. This framework enables evaluation not only of financial shock, but of the mechanisms through which organizational and institutional behavior mediates economic recovery or decline.

2.4. Limitations & Scope:

This study focuses on the economic and market-facing consequences of aviation disasters rather than technical accident causation. While engineering failures, security lapses, and political factors underpin each case, the emphasis here is on their economic aftermath.

Several limitations apply. Financial data from historical cases, such as Pan Am Flight 103, may be incomplete or inconsistently reported across sources. Stock price analysis is limited to publicly traded companies, excluding some airlines and manufacturers from direct comparison. Additionally, isolating the financial effects of an aviation disaster from broader market conditions — for instance, economic recessions or concurrent geopolitical events — presents methodological challenges.

Despite these constraints, the triangulation of multiple data sources, the comparative design, and the focus on both financial and institutional dynamics strengthen the validity of the findings and provide a robust basis for drawing conclusions about the economic impact of major aviation disasters.

■ Findings

3.1. Case Study 1: Pan Am Flight 103:

The 1988 bombing of Pan Am Flight 103 over Lockerbie demonstrated how a single aviation accident, compounded by liability exposure and weak corporate fundamentals, can accelerate an airline's financial collapse.

On December 21, 1988, Pan Am Flight 103 was destroyed by a terrorist bomb, killing 270 people. While stock price data initially showed a paradoxical increase—shares rose nearly 18% in the two weeks after the crash—5 this short-term market behavior concealed deep structural weaknesses. As Bosch and colleagues argue, market participants may have initially perceived the event as "firm-specific" and manageable, rather than systemic (p. 512).

The financial liabilities proved far more devastating. Pan Am ultimately paid an estimated $500 million in settlements and legal costs tied to Flight 103.[1] Insurance premiums for the airline rose dramatically, reflecting what Chance and Ferris (1987) describe as a "re-pricing of catastrophic risk" that often follows aviation disasters. By 1989, aviation insurance rates across the U.S. industry had risen 40%, squeezing already fragile carriers.1 These rising costs were particularly damaging because Pan Am entered the disaster with high debt, aging fleet infrastructure, and declining competitive advantage, leaving little margin for absorbing adverse shocks.

Consumer behavior compounded the problem. Passenger bookings on Pan Am's transatlantic routes fell by nearly 20%

in the year following Lockerbie, as media coverage framed the airline as unsafe.[5] Scholars emphasize that reputational damage magnifies direct financial costs; in this case, Pan Am lacked the liquidity to absorb either. A negative feedback loop emerged: declining revenues reduced cash flow, which increased borrowing costs, which further limited the airline's ability to reassure stakeholders or invest in safety improvements.

Institutional response also contributed to the collapse. Pan Am's crisis communication strategy was widely criticized for being defensive and opaque, which reinforced perceptions of negligence rather than competence. Crisis economics predicts that credibility shocks increase firm vulnerability, especially when firms are financially weak before the crisis. This dynamic was visible in 1991, when the airline declared bankruptcy, marking one of the most prominent airline failures in modern history.

Pan Am 103 illustrates how catastrophic accidents can trigger cascading liabilities, insurance repricing, and reputational collapse. Importantly, the case shows that market resilience is conditional—firms with weak financial structures may not survive even if initial stock reactions appear muted. This disaster did not create the airline's weaknesses; it exposed and accelerated them.

3.2. Case Study 2: Boeing 737 MAX Crisis:

The 2018–2019 Boeing 737 MAX crashes highlight how manufacturer-linked accidents generate long-tail economic costs, including lost market capitalization, halted production, regulatory overhaul, and global reputational decline. It also illustrated how institutional dominance can delay accountability, increasing eventual economic consequences.

The crisis began with two nearly identical crashes: Lion Air Flight 610 (October 2018) and Ethiopian Airlines Flight 302 (March 2019), which together killed 346 people. Market reaction was immediate: Boeing's stock lost $60 billion in market capitalization between March and December 2019, representing a 25% decline.[6] While this decline reflects classic market repricing after a catastrophic event, it also signaled investor skepticism about Boeing's ability to resolve technical failures and restore global confidence in the MAX platform.

Direct financial costs were immense. Boeing set aside more than $20 billion to compensate airlines, reflecting both grounded aircraft and lost revenue opportunities.[7] When the company halted 737 MAX production in January 2020, revenue fell $18.6 billion in that year alone.[8] These figures reveal the dual economic burden of catastrophic failure: firms lose money not only from legal liability, but from disrupted supply chains, lost economies of scale, and delay-sensitive capital investments. The broader industry also suffered: U.S. airlines operating large MAX fleets—Southwest, American, United—recorded an estimated $5 billion in combined losses.[9] This indicates that manufacturer-linked crises impose sector-wide costs, creating negative externalities.

The crisis also reshaped regulatory trust. As international regulators grounded the 737 MAX ahead of the U.S. Federal Aviation Administration, Boeing's perceived dominance in certification processes came under scrutiny. As one study noted, "the erosion of FAA authority revealed the systemic risks of regulatory capture."[10] Loss of legitimacy imposed transaction costs long after the physical problems were corrected: certification timelines increased, engineering oversight became more intrusive, and Boeing's monopoly status began to lose political protection.

Unlike Pan Am, Boeing's financial reserves and strategic monopoly status allowed it to survive. But the scale of its losses demonstrates how reputational damage and regulatory breakdown can impose costs as high as direct accident-related payouts. The crisis also underscores the economic risk of delayed or evasive communication strategies: firms may slow immediate stock declines, but deepen long-term distrust.

3.3. Case Study 3: 9/11 Airline Industry Impact:

Unlike Pan Am 103 or the Boeing crisis, the September 11 attacks inflicted systemic costs on the entire airline sector, combining massive immediate losses with permanent increases in security-related operating expenses. The event generated a shock not only to individual firms, but to the market architecture underpinning commercial aviation.

The hijackings of four aircraft on September 11, 2001, killed nearly 3,000 people and represented an unprecedented shock to global aviation. Within days, U.S. airline stock values fell by 40%, and passenger traffic dropped nearly 30%.[11] Industry losses totaled $7.7 billion in 2001 alone, according to the U.S. Bureau of Transportation Statistics. These losses were magnified by high fixed costs: airlines could not quickly scale down labor or fleet capacity, leading to liquidity crises.

The insurance sector absorbed record payouts—more than $40 billion in claims, the largest single-event insurance loss in history at that time.[12] With insurers hesitant to cover terrorism risk, governments were forced to step in, providing backstop coverage to prevent a collapse in aviation operations. This state intervention transformed the industry's risk structure, shifting catastrophic risk from firms to taxpayers.

Bankruptcies followed quickly. United Airlines filed for Chapter 11 in 2002, while US Airways also entered bankruptcy, highlighting the uneven resilience across carriers. Scholars note that "firms with weaker cash reserves or heavy reliance on hub airports were disproportionately vulnerable."[1] Economic structure—more than business strategy—determined who survived.

The long-term costs were structural. The creation of the Transportation Security Administration (TSA) and Department of Homeland Security embedded billions of dollars in annual compliance costs. Airlines were forced to invest in reinforced cockpit doors, enhanced passenger screening, and expanded liability coverage—all of which permanently reshaped industry cost structures. Unlike previous disasters, which produced acute financial shocks, 9/11 generated a permanent regulatory tax on aviation.

The 9/11 case demonstrates that aviation accidents tied to geopolitical events can shift entire regulatory regimes, creating lasting industry-wide cost burdens far beyond immediate financial losses. The crisis changed not just firm behavior, but the institutional environment in which the industry operates.

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3.4. Cross-Case Patterns:

Comparing the three cases reveals consistent short-term market shocks, but divergent long-term trajectories depending on financial strength, regulatory intervention, and communication strategies.

First, all cases triggered sharp, short-term market declines—10–40% stock losses within weeks—but recovery paths varied. Pan Am collapsed due to preexisting weaknesses, Boeing survived due to its monopoly position, and airlines post-9/11 experienced uneven survival outcomes. These trajectories indicate that crisis outcomes reflect organizational resilience more than event severity.

Second, regulatory responses consistently increased costs but also restored confidence. Strong interventions—such as the FAA's eventual overhaul of certification after the MAX or TSA reforms post-9/11—were expensive but ultimately necessary for recovery. Regulation acted as a stabilizing force, but one that redistributed costs across firms.

Third, the communication strategy shaped resilience. Pan Am's denial and defensiveness accelerated distrust. Boeing's blame-shifting worsened reputational damage, slowing stock recovery. Airlines after 9/11, constrained by government-led communication, saw mixed reputational outcomes. Academic studies confirm that firms adopting transparent, accountable messaging recover 2–3 times faster in stock market terms.[5] Communication is therefore not cosmetic—it is economically consequential.

Finally, insurance and liability markets reset after each event, raising premiums across the industry. These shocks increased barriers to entry, disproportionately affecting weaker or newer firms. Catastrophic events, therefore, reshape competitive landscapes by accelerating market consolidation.

Together, these patterns suggest that the economic consequences of aviation accidents are not determined by the accidents alone but by a triad of resilience factors: financial strength, regulatory response, and communication effectiveness. Catastrophic events, therefore, reshape competitive landscapes by accelerating market consolidation.

■ Discussion

4.1. The Role of Crisis Communication:

Crisis communication is consistently shown to mediate the economic consequences of aviation accidents. Firms that respond with speed, transparency, and empathy tend to mitigate reputational damage and investor backlash. Boeing's handling of the 737 MAX crisis is frequently cited as a failure of communication. The company initially framed the crashes as isolated incidents linked to pilot error rather than systemic design flaws, delaying acknowledgment of the MCAS software issue.[13] This signaling problem created uncertainty around Boeing's technical competence, increasing perceived risk among investors and prompting more sustained market volatility.

This denial strategy eroded trust among regulators, airlines, and the public, exacerbating financial losses. Indeed, studies in crisis management note that "shifting blame" typically deepens reputational harm and extends stock underperformance.[14] Boeing's case illustrates that communication failure is not merely reputational—it can materially alter cost structures through prolonged litigation, regulatory intervention, and halted production, magnifying the direct financial shock of an accident.

By contrast, Alaska Airlines' response to Flight 261 (2000) illustrates the opposite dynamic. The carrier quickly grounded its MD-83 fleet for inspection and communicated openly with both regulators and passengers. Although it suffered a temporary financial strain, investor confidence rebounded within a year.[15] Here, proactive disclosure created short-run operational costs but reduced uncertainty, allowing markets to price the crisis as finite and controllable. This suggests that clear communication, while costly in the short run, supports long-run reputational resilience.

Crisis communication is also intertwined with insurance and liability outcomes. Transparent responses can reduce litigation severity, while opacity may encourage legal escalation. For example, Boeing's initial reluctance to disclose internal MCAS communications heightened scrutiny in subsequent lawsuits, leading to a $2.5 billion settlement with the U.S. Department of Justice in 2021.[16] This demonstrates how communication choices directly influence the scope and duration of legal risk, contributing to the long-tail financial impact of an accident.

Taken together, these patterns highlight that crisis communication functions as an economic variable: it shapes investor expectations, alters the trajectory of litigation costs, and determines whether financial losses remain acute or become chronic.

4.2. Regulatory Response and Market Confidence:

Regulatory behavior plays a dual role: stabilizing markets by enforcing safety, yet also intensifying short-term financial shocks through operational restrictions. The FAA's grounding of the 737 MAX in March 2019, followed by a global grounding, created one of the costliest regulatory interventions in aviation history. The rapid, synchronized grounding transformed a product-specific incident into a global operational crisis, eliminating near-term revenue streams for both Boeing and its airline customers. Airlines operating the MAX faced billions in capacity losses; Southwest Airlines alone estimated a $830 million hit in 2019.[7]

The speed and coordination of regulatory action also influence investor confidence. When multiple jurisdictions act in unison, markets tend to interpret this as a sign of systemic severity. For instance, the staggered global groundings of the MAX (starting in China and cascading across Europe and the U.S.) highlighted Boeing's declining international credibility, amplifying downward stock pressure.[17] This loss of regulatory legitimacy reduced Boeing's bargaining position in post-crisis negotiations, extending the firm's recovery timeline.

However, swift regulatory intervention can also reassure investors that risks are contained. After the Concorde crash in 2000, European regulators mandated modifications including Kevlar-lined fuel tanks and tire reinforcements. These decisive measures allowed Concorde to return to service, albeit temporarily, and maintained residual confidence in Airbus and Air France despite the program's eventual retirement.[18] This illus-

trates that regulatory penalties can function as a mechanism for restoring market confidence, especially when paired with credible reform.

Thus, regulatory action operates both as a cost and as an investment in future safety: while it generates immediate disruption, it also lays the foundation for renewed demand by reducing perceived systemic risk.

4.3. Media Coverage and Public Perception:

Media narratives shape not only consumer demand but also long-term brand equity. Aviation accidents tend to dominate front-page coverage because of their rarity and symbolic gravity. The volume and framing of reporting amplify financial consequences, a phenomenon captured by agenda-setting theory.[19] Media therefore acts as a transmission channel, converting safety failures into reputational crises that influence consumer behavior and investor sentiment.

Boeing's case illustrates how negative framing compounds economic damage. Major outlets repeatedly emphasized internal emails that described the MAX as "designed by clowns".[20] Such coverage reframed the crisis from a technical failure into a story of corporate negligence, reinforcing investor skepticism and prolonging the company's market underperformance. In economic terms, this reframing increased the perceived probability of future failures, which investors priced into long-term valuations.

In contrast, when US Airways Flight 1549 ("Miracle on the Hudson") successfully ditched in the Hudson River in 2009, media coverage emphasized heroism rather than failure. Although the airline faced immediate logistical disruptions, the overwhelmingly positive narrative boosted brand goodwill and limited financial fallout.[21] Here, narrative framing acted as reputational insurance, converting a high-risk event into a positive brand asset.

Social media further accelerates this reputational volatility. Research indicates that online outrage can magnify crises disproportionately, even when technical risks remain low.[22] In Boeing's case, hashtags like #BoycottBoeing and viral graphics of grounded planes amplified reputational damage beyond what traditional media alone would have generated. The speed and scale of digital amplification lowered the thresholds for brand contagion, enabling faster spillover to airline customers and supply chains.

Overall, the media does not simply reflect aviation crises; it co-produces their economic consequences by shaping public interpretation, emotional salience, and expectations of corporate competence.

4.4. Comparative Resilience Factors:

The comparative resilience of firms and industries to aviation accidents hinges on several structural and strategic factors:

1. Financial Cushioning: Airlines with stronger liquidity and diversified fleets recover faster. Southwest Airlines, despite MAX losses, leveraged its robust balance sheet and loyalty network to preserve market share.[23] By contrast, Lion Air in Indonesia—already financially fragile—struggled to maintain operations after the 2018 crash. This explains why otherwise similar shocks generate asymmetric financial outcomes.

2. Geographic and Market Diversification: Global firms like Airbus absorbed the reputational spillover from Concorde relatively well, as the supersonic jet was a niche product compared to its broader commercial lineup. Narrower firms, such as Alaska Airlines after Flight 261, face disproportionate shocks when crises strike core fleets. Diversification, therefore, functions as a structural hedge against accident-induced revenue shocks.

3. Reputation Capital: Firms with stronger pre-crisis reputations can absorb greater shocks. Research in corporate reputation shows that established goodwill operates as a buffer, reducing abnormal stock losses in crisis events.[24] This explains why Delta and American Airlines, though impacted by MAX groundings, did not face the same reputational collapse as Boeing itself. Reputation thus acts as a form of intangible insurance, lowering expected future liability.

4. Regulatory Environment: Companies operating in jurisdictions with clear, transparent, and trusted regulators experience faster confidence recovery. ICAO's involvement in clarifying post-MAX reforms reinforced systemic safety standards, signaling to markets that long-run risks were being addressed.[10] Weak regulatory credibility, by contrast, increases uncertainty and prolongs market disruption.

Taken together, these resilience factors highlight the heterogeneity in financial and reputational recovery following aviation accidents. Market punishment is not uniform but contingent on pre-existing resources, communication strategies, and regulatory environments. Crucially, these elements are not independent: weak communication can undermine regulatory legitimacy, which amplifies financial loss; strong reputation can offset temporary market shocks.

This interdependence reinforces the paper's central claim: accidents trigger economic shocks, but institutional response determines whether damage becomes existential or temporary.

■ Concluding Remarks

5.1. Summary of Key Insights:

This study has examined the economic consequences of major aviation accidents, with a focus on how stock markets, insurers, and manufacturers respond in the aftermath of such crises. Several key findings emerge:

- Airline stock prices consistently suffer immediate short-term declines following accidents, often between 5–15% within the first week, depending on accident severity and the airline's preexisting financial health.[5,25]
- Manufacturers experience a slower-moving but more persistent effect, as seen in Boeing's multi-quarter stock volatility after the 737 MAX crashes, which wiped out over $25 billion in market capitalization during 2019.[8] Insurance markets, while initially exposed to large payouts, demonstrate systemic resilience, with premiums rising temporarily but stabilizing within one to two quarters.[26]
- Broader macroeconomic effects remain limited; aviation accidents do not destabilize global markets, but

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they can reshape industry competition and public trust in the medium term.[27]

In sum, aviation accidents represent a localized financial shock, disproportionately affecting airlines and manufacturers tied to the specific incident, while the broader industry demonstrates significant resilience.

5.2. Broader Implications for Policy and Industry:

The findings have several implications for both policymakers and industry stakeholders:

1. Crisis Preparedness and Communication
   - Airlines with established crisis communication protocols (e.g., Singapore Airlines after Flight SQ006 in 2000) recover faster in both financial and reputational terms. Regulators may therefore encourage or mandate communication frameworks that emphasize speed, transparency, and accountability.[14]
2. Regulatory Oversight and Market Stability
   - Regulatory agencies such as the FAA and EASA play a critical role in restoring market confidence after high-profile accidents. Swift action—such as the global grounding of the 737 MAX—provides reassurance to the public but can also impose massive economic costs. A balance must therefore be struck between safety enforcement and economic continuity.
3. Insurance and Risk Management
   - The demonstrated resilience of insurance markets suggests that the aviation sector has developed robust mechanisms of financial risk transfer. However, catastrophic accidents or clustering events (e.g., multiple crashes within a short period) could test this stability. Policymakers should continue to monitor the adequacy of liability caps, reinsurance structures, and solvency frameworks.
4. Industry Strategy
   - For airlines and manufacturers, the key lesson is that reputation is an economic asset. Investments in safety culture, maintenance, and transparent governance not only reduce accident likelihood but also mitigate post-crisis economic fallout.

5.3. Future Research Directions:

While this study has drawn on existing empirical literature and selected case studies, several gaps remain that future research could address:

- Cross-industry comparisons: Aviation is often contrasted with other high-risk sectors such as nuclear power or shipping. Comparative research could illuminate whether aviation's resilience mechanisms are unique or part of a broader pattern in transportation economics.
- Behavioral finance dimensions: Market overreaction to aviation accidents may reflect investor psychology rather than fundamentals. Future work could employ event-study methodologies with sentiment analysis to better isolate these effects.
- Global vs. regional variation: The majority of current literature focuses on the U.S. and European carriers. More data on emerging market airlines (e.g., Asia, Africa, Latin America) could test whether institutional differences alter the financial trajectory of post-crisis recovery.
- Long-term consumer demand effects: While short-term demand impacts are well-documented, less is known about whether repeated accidents permanently shift consumer preferences toward specific airlines or aircraft types.

By addressing these avenues, future scholarship can deepen our understanding of how aviation accidents intersect with economics, policy, and public trust, offering insights not only for academics but also for practitioners in an increasingly globalized and interconnected aviation industry.

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■ References

1. Phillips, R. A., & Talley, W. K. (1992). Airline safety investments and operating conditions: Determinants of aircraft damage severity. Southern Economic Journal, 59(2), 157–164. https://doi.org/10.2307/1060522
2. Sobieralski, J. B. (2013). The cost of general aviation accidents in the United States. Transportation Research Part A: Policy and Practice, 47, 19–27. https://doi.org/10.1016/j.tra.2012.10.018
3. Chance, D. M., & Ferris, S. P. (1987). The effect of aviation disasters on the air transport industry: A financial market perspective. Journal of Transport Economics and Policy, 21(2), 151–165. http://www.jstor.org/stable/20052813
4. Wang, Z., Hofer, C., & Dresner, M. E. (2013). Financial condition, safety investment, and accident propensity in the US airline industry: A structural analysis. Transportation Research Part E: Logistics and Transportation Review, 49(1), 24–32. https://doi.org/10.1016/j.tre.2012.07.001
5. Bosch, J.-C., Eckard, D. D., Morrison, W. F., & Smith, J. W. (1998). The competitive impact of air crashes: Stock market evidence. Journal of Law and Economics, 41(2), 503–519. https://doi.org/10.1086/467399
6. Strohm, C. (2008, April 9). FAA's oversight of Southwest is criticized. Bloomberg News. https://www.bloomberg.com/news/articles/2008-04-09
7. The 737 MAX grounding cost Southwest $828 million in 2019. (2020, January 23). CNN Business. https://www.cnn.com/cnn/2020/01/23/business/southwest-american-airlines-earnings/index.html
8. Boeing posts its first annual loss since 1997. (2020, January 29). Axios. https://www.axios.com/2020/01/29/boeing-worst-financial-results-two-decades
9. Pasztor, A. (2019). More Whistleblower complaints emerge in Boeing 737 MAX Safety Inquiries. The Wall Street Journal, April 27, https://www.wsj.com/articles/more-whistleblower-complaints-emerge-in-boeing-737-max-safety-inquiries-11556418721
10. House Committee on Transportation and Infrastructure. (2020). Investigation into the Boeing 737 MAX certification and FAA oversight. U.S. House of Representatives.

11. International Air Transport Association (IATA). (2002). Economic impact of September 11 on the airline industry. IATA Annual Report.
12. Swiss Re. (2002). Insurance claims from 9/11 surpass $40 billion. Swiss Re Industry Trauma Report.
13. Kitroeff, N., & Gelles, D. (2019). Legislators call on F.A.A. to say why it overruled its experts on 737 MAX. The New York Times, November 7 (updated December 11), https://www.nytimes.com/2019/11/07/business/boeing-737-max-faa.html
14. Coombs, W. T. (2007). Protecting organization reputations during a crisis: The development and application of Situational Crisis Communication Theory. Corporate Reputation Review, 10(3), 163–176. https://doi.org/10.1057/palgrave.crr.1550049
15. National Transportation Safety Board (NTSB). (2002). Aviation accident docket: Alaska Airlines Flight 261. NTSB Docket.
16. U.S. Department of Justice. (2021). Boeing settles with DOJ for $2.5 billion over 737 MAX scandal. DOJ Press Release. https://www.justice.gov
17. Campbell, D. (2019). The many human errors that brought down the Boeing 737 MAX. The Verge, May 2, https://www.theverge.com/2019/5/2/18518176/boeing-737-max-crash-problems-human-error-mcas-faa
18. Bureau d'Enquêtes et d'Analyses (BEA). (2002). Concorde accident technical modifications and return to service. BEA Safety Bulletin.
19. McCombs, M. E., & Shaw, D. L. (1972). The agenda-setting function of mass media. Public Opinion Quarterly, 36(2), 176–187. https://doi.org/10.1086/267990
20. Gelles, D., Kitroeff, N., Nicas, J., & Ruiz, R. R. (2019). Boeing was 'Go, Go, Go' to beat Airbus with the 737 MAX. The New York Times, March 23, https://www.nytimes.com/2019/03/23/business/boeing-737-max-crash.html
21. Jenkins, B. M. (2012). Aviation security: After four decades, it's time for a fundamental review. RAND Corporation, 1–10. http://www.jstor.org/stable/10.7249/j.ctt1q60kx.2
22. Etter, M., Gerca, I., & Angriawan, A. (2019). How digital platforms amplify crisis narratives: Social media and aviation accidents. Journal of Communication Management, 23(2), 85–100. https://doi.org/10.1108/JCOM-09-2018-0090
23. CAPA – Center for Aviation. (2020). Southwest Airlines resilience post-737 MAX grounding. CAPA Report.
24. Rhee, M., & Valdez, M. E. (2009). Contextual factors surrounding reputation and earnings surprises. Journal of Business Ethics, 88(2), 251–263. https://doi.org/10.1007/s10551-009-0102-6
25. Chen, Z., Rose, A. Z., Prager, F., & Chatterjee, S. (2017). Economic consequences of aviation system disruptions: A reduced-form computable general equilibrium analysis. Transportation Research Part A: Policy and Practice, 95, 207–226. https://doi.org/10.1016/j.tra.2016.09.027
26. Fitzgerald, R. (2005). Aviation insurance resilience and systemic risk. Journal of Risk Management in Transport and Logistics, 1(1), 31–45.
27. Kaplanski, G., & Levy, H. (2010). Explosions and stock price: The impact of terrorism on aviation markets. Journal of Financial Studies, 15(3), 55–75.

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REVIEW ARTICLE

Leveraging Machine Learning in Bank Risk Management

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ABSTRACT: As markets evolve, so too must bank practice. The increase in complexity of financial markets, the volume of transactional data, and the demand for great transparency regarding bank operations all place pressure on bank risk management practices. Traditional methods of financial risk management, credit and liquidity risk more specifically, that rely on historical data and linear models, sometimes fail to capture the nonlinear and interconnected nature of risk. This paper displays that artificial intelligence (AI), namely supervised machine learning (ML) and neural networks, will become imperative in improving the methods banks employ to mitigate financial risk. This paper also addresses commonly expressed concerns within AI and ML research and bank risk management literature, such as explainability and implementation, and proposes a unique framework for regulatory compliance of banks with regulatory institutions. By reviewing documented AI applications in banking and other data-intensive fields, this review underscores successful use cases that can be extended into credit and liquidity risk management and identifies best practices when doing so. This work contributes to the literature mainly by proposing structured pathways to internal integration and regulatory compliance.

KEYWORDS: Robotics and Intelligent Machines, Machine Learning, Risk Management, Credit Risk, Liquidity Risk.

Introduction

Artificial intelligence (AI) is the wide-ranging field of science that describes computer algorithms that give non-human entities the ability to reason, solve, and compute with human-like or superior proficiency. Currently, we are witnessing the proliferation of AI and its subsectors, such as machine learning (ML), into many popular and relevant fields. In the past decade, AI has made exponential leaps in progress, from the founding of DeepMind, an AI research lab that was later acquired by Google, in 2010, to the recent release of OpenAI's GPT-5, available to their more than 700 million weekly users.

AI is actively playing a large role in banking, yet its role stands to become much larger. Data taken from major commercial banks show that AI is already being used to detect fraud in online banking and for digital chatbots that interact with clients and employees to provide information and feedback (Oyeniyi *et al.*, 2024).[1] Morgan Stanley, a large commercial bank, has implemented OpenAI's GPT-4 model into their workflows, which OpenAI says has "enhanced how financial advisors access the firm's knowledge base and respond to client needs."[2] Much of the integration by these firms is successful, with many banks exhibiting higher efficiency after implementing AI into internal operations.[3] Yet, banks still look for further opportunities to optimize their workflows and tasks with artificial intelligence, especially as financial markets expand.

Financial markets are expanding at extremely rapid paces, both in scale and complexity. In the early 2000s, technological change made it easier than ever for consumers to access many financial services and cheaper for providers to deliver them.[4] Lowering the threshold needed for someone to make a deposit or take out a loan, for example, allowed there to be a market response to meet lower-income consumers' demands and create exciting opportunities for new demographics. Emerging markets have also experienced substantial growth, increasing the level of integration and interconnectedness in our global market.[5] Markets in Asia, Latin America, and Africa experienced heightened foreign investment, robust economic development, and rising middle classes. However, these benefits brought along challenges, including increased market volatility and systemic risks. Increased interconnectedness and the emergence of larger consumer bases are in themselves both a benefit and a risk, as they give opportunities to new consumers but introduce higher chances of default, liquidity mismatches, and other contagion effects across institutions. The traditional methods to handle risk simply cannot keep up.

This paper offers artificial intelligence as the solution to mitigate bank risk more efficiently, as the successful use cases of AI decision making and fraud prevention suggest that it can be extended into credit and liquidity risk mitigation. This study also offers best practices when implementing AI practically into daily workflows and internal structures, and seeks to address commonly expressed concerns with AI in the financial industry.

The literature review covers traditional financial risk methodology and AI's current place in the risk management field. It covers fields such as stress-testing, early warning sign prediction, and credit risk evaluation. This is key for understanding why traditional financial risk methods cannot continue to withstand increasingly complex financial markets and how AI is currently being leveraged.

The discussion of AI methods and future pathways posits that AI is the future of bank risk management. This section not only explains the most applicable AI and ML algorithms, but works to address explainability and interpretability concerns, regulatory compliance concerns, and issues regarding real-world accuracy. Currently, AI is most leveraged in sensor

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networks, wireless networks, and even accounting to process and analyze large amounts of data.[6-9] AI undoubtedly has the capacity to better serve us than traditional methods in bank risk management, and its adoption should be made immediately.

The last section concludes.

This paper aims to contribute to the literature by addressing the most expressed concerns when discussing the feasibility of AI being applied to banking. It prescribes future steps to ensure that banks can integrate these AI models smoothly into their existing internal operations, maintain constant oversight of their models, interact with their regulatory counterparts, and address all explainability and interpretability roadblocks.

■ Literature Review

The following literature review can be considered as both reviewing how AI is being used in the banking industry more broadly and establishing the urgency for AI to expand further into risk management, where traditional methods will not suffice as markets expand. It also sets the groundwork for the subsequent discussion of AI and ML models that is more in-depth.

AI in Banking:

Prediction, the fundamental premise of risk management, is becoming a strong suit of AI in banking. ML can make increasingly accurate predictions in areas such as asset risk premiums,[10] financial credit risk,[11,12] and liquidity risk via stress testing and advanced decision networks and modeling.[13,14] Supervised machine learning methods allow for more efficient adaptation and accuracy in prediction, as it uses data sets with pre-marked data. This makes it one of the most common forms of ML.[15] Ensemble learning, which compiles a group of individual algorithms, and hybrid models, which compile different ML models, have been explored in predicting default.[16,17]

AI is also being experimented with in bank stress-testing. Stress-testing is a primary tool used by commercial banks to understand the level of capital resources to undergo certain levels of risk, should they take it on. A support vector machine (SVM) modeled to forecast risk in a sample of 1443 U.S. banks, including 481 that failed from 2007-2013, was 99.22% overall accurate in predicting insolvency in banks.[18] Other supervised ML models have also been highly successful in interpreting risk in bank stress-testing.[19,20]

Explainability, however, is a common challenge that has been acknowledged within the financial industry and elsewhere. The application of neural networks and DL is the next step after implementing ML algorithms, as they can drastically improve beyond the capabilities of general ML.[15,21] However, DL networks and algorithms have encountered issues with being "black box" and incomprehensible in their decision-making.[22,23] The "black box" problem needs to be solved for banks and large financial institutions to rely on their decisions for risk mitigation. Banks, ultimately, must understand the rationale behind decisions before they act, especially in domains such as risk management.

Traditional Financial Risk Management Methods:

Traditional financial risk management methods involve large amounts of historical data, simplified statistical models, and regulatory frameworks that aim to protect banks from liquidity and credit risk.

In credit, classic approaches to mitigating risk rely on linear statistical techniques such as logistic regression to analyze financial ratios and large data sets. Doko *et al.* verified that across numerous types of credit risk assessment, including credit scoring and loan approvals, logistic regression and linear regression models were among the most common.[24] These models are reliable when it comes to transparency and consistency with linear assumptions in data sets and are suitable for regulatory and supervisory purposes. Yet, these models' dependence on linear assumptions limits their ability to capture nonlinear relationships, a crucial element in improving validity measures.[25]

Liquidity risk management traditionally subsists on liquidity regulations and quantitative buffers. Metrics introduced by the Basel Committee on Banking Supervision, such as the Liquidity Coverage Ratio (LCR), help banks withstand short- and medium-term disruptions.[26] The LCR maintains that banks with more than $50 billion in total assets (LCR banks) must hold a portfolio of high-quality liquid assets large enough to sustain a 30-day stress period of high cash outflows. Macchiavelli and Pettit find that regulations regarding metrics such as the LCR can slow efficiency, as liquidity holdings and maturities are increased.[27] These measures improve stability by preparing financial institutions for worst-case scenarios, yet they can constrain credit supply.

Another vein of literature underscores the role of transparency in risk management. Ratnovski argues that transparency plays a central role in covering large shocks to liquidity, and that liquidity requirements should be complemented by measures that increase bank incentives to adopt transparency.28 Risk management is not solely a matter of analyzing historical data trends and maintaining buffers, but of information disclosure and appropriate governance quality. However, transparency and governance will not be able to fully mitigate spikes in financial risk.

These studies highlight the strengths and weaknesses of traditional methods. They provide standardized frameworks that fit well with regulatory needs, but they struggle when forced to grapple with nonlinear and complex data sets and the adaptive nature of modern financial markets. These shortcomings motivate interest in AI and ML practices, which this paper discusses as more flexible and accurate tools for credit and liquidity risk management.

■ Discussion of AI Methods and Future Pathways

Simply put, the future of bank risk management — in general, but, for this paper, in credit and liquidity risk — is AI. ML algorithms, and DL trees and networks that can consume and learn from more data than is currently possible, will allow banks to not only keep up with the bank risk management crisis but advance past it. This section will cover solutions to

credit and liquidity risk that are currently explored, as well as make suggestions for implementing new methods in the future and avoiding challenges that banks will encounter.

AI in Credit and Liquidity Risk Management:

Risk management for credit risk and liquidity risk is not so dissimilar. Mitigating credit and liquidity risk requires ensuring borrowers are capable of and willing to repay and securing reliable funding sources to meet short-term and unforeseen obligations, even in turbulent macroeconomic conditions. In the case that many borrowers withdraw from a bank, banks need to be liquid enough to meet these demands. Bank credit and liquidity risk are intertwined, and it is for these reasons that the methods to mitigate both risks will be quite similar.

In the domain of credit risk, Generative AI and ML algorithms have been utilized to increase accuracy in default predictions through more accurate risk modeling and scenario analysis. A systematic review of default prediction models in 250 published research papers conducted by Alvi *et al.* discovered highly successful predictive models.[29] From neural networks, with prediction accuracy as high as 96.15%, to combinations of hybrid models (AI techniques — ML and DL) and traditional methods (e.g., logistic regression) that report superior accuracy to traditional methods alone, AI and ML outperform benchmark models consistently.[29] Random forest models, formally introduced by Breiman, use an ensemble learning method that compiles multiple decision trees.[30] They, too, outperform baseline models such as autoregressive ones in areas such as predicting market conditions in the money market and FX (foreign exchange) markets.[31] This ability to accurately predict market conditions allows banks to make better-informed decisions when it comes to risk management.

As for liquidity risk, multiple models are used for discovering hidden patterns and outlining relationships in liquidity behavior. While supervised learning methods use pre-labeled data in training, unsupervised learning uses unmarked data. ML clustering methods, a form of unsupervised learning, are particularly useful in identifying hidden patterns and have been widely utilized in financial risk analysis.[32] Kou *et al.* utilized a multiple criteria decision making (MCDM) approach to evaluating clustering methods in financial risk and found the method to be effective.[33] Since liquidity risk is inherently relationship-driven, Graph Neural Networks (GNNs) are also useful in anticipating its dynamics. GNNs do not only observe individual pieces of data, but the relationships between them (like a function on a graph) and have thus become a leading approach for building predictive models.[34] An experiment conducted by Xu *et al.* modeled the entire financial market in a graph and used a GNN to predict market volatility.[35] The results showed that the GNN was superior in the field of financial volatility prediction. While the model in the experiment predicted market volatility, the broader implications are that GNNs have a superior ability to make accurate predictions despite complex relationships in data sets. GNNs that predict market volatility could, too, be influential in mitigating liquidity risk, given the traditionally inverse relationship between volatility and liquidity,[36] and the inverse relationship between market liquidity and liquidity risk.[37]

Recommended AI Methods for Risk Mitigation:

There is an extensive list of AI models that could be used in bank risk management. This section will cover a smaller selection of the models that may be more appropriate for risk management in the financial industry, divided into two categories. The first category consists of more classical supervised ML algorithms, namely GBMs (Gradient Boosting Machines) and RFs (Random Forests). The second category consists of deep learning (DL) neural network systems, namely LSTM (Long Short-Term Memory) and CNNs (Convolutional Neural Networks).

Classical Supervised ML Algorithms:

Supervised learning requires human-labeled input and output data sets to learn.[38] Classical supervised learning algorithms are more traditional methods of pattern recognition, such as decision trees, GBMs, RFs, and logistic regression, and they contrast with newer neural network models that analyze more complex relationships.

GBMs should be widely adopted in credit and liquidity risk management, given their ability to iteratively minimize prediction error. Gradient boosting is an ensemble learning method that compiles multiple decision trees. The idea of this algorithmic approach to predictive modeling was introduced by Jerome H. Friedman, and the method has since proven to excel at predictive modeling tasks.[39] The individual decision trees are not highly accurate on their own, and are prone to making mistakes, yet when combined in a method called "boosting," the sum of these less accurate decision trees is one large tree that has learned from the previous trees' mistakes and is thus far more accurate.[40,41]

The most popular GBMs are eXtreme Gradient Boosting (XGBoost) and Light Gradient Boosting Machine (LightGBM). XGBoost expands its decision trees level by level (Figure 1), keeping them stable, whereas LightGBM expands its decision trees using leaf-wise tree growth (Figure 2), developing leaves in the tree that will result in the greatest error reduction.[42,43] Level-wise tree growth keeps trees balanced but is slower than leaf-wise tree growth. However, it increases stability and reduces the chance of overfitting, which is a risk that increases as trees grow deeper due to leaf-wise expansion.[44]

As for applications of both XGBoost and LightGBM to financial risk management, a credit risk assessment in digital lending platforms conducted by Ying *et al.* found that a hybrid ML model centered around LightGBM was highly effective in predicting borrower default risk and filtering key borrower attributes.[45] XGBoost and LightGBM were also cited as being highly trustworthy and accurate in predicting loan defaults, illustrating their promising nature in the realm of mitigating credit risk.[29] Banks should implement multiple types of GBMs to leverage the full adaptability and prediction accuracy of these models. It is also important to keep in mind that diversity of models is crucial as well, as the tree growth

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methods employed by specific GBMs can result in overfitting, while others can result in a slower adjustment to new data.

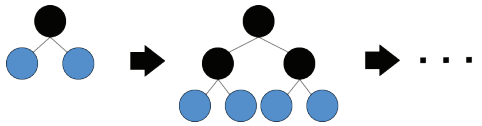

Figure 1: Level-wise tree growth in GBMs. This figure depicts how the decision trees are improved layer by layer, in tandem with each other. The primary benefit of this tree growth method is that it keeps the rate of evolution stable.

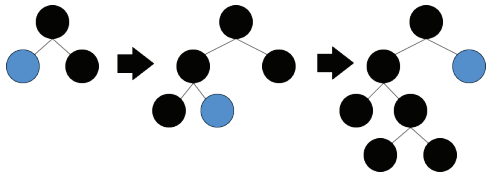

Figure 2: Leaf-wise tree growth in GBMs. This figure illustrates a model with more pointed development of decision trees. This targeted approach helps eliminate errors at a quicker rate than the level-wise growth method.

Another classical supervised ML method that would be highly effective is RFs, as their ensemble learning and voting system offers high adaptability and can reduce variance and overfitting. RFs, unlike GBMs, utilize, loosely put, a voting committee. The decision trees that compose each RF are trained with samples from a training set with replacement, called a bootstrap sample.[46] Then, bagging – a process in which more data with replacement is injected – reduces correlation between the individual trees. Finally, RFs have two methods when making decisions. If they are presented with a classification task, the individual trees will take a vote, and the majority vote will yield the predicted class, whereas for a regression task, the votes from individual decision trees will be averaged.[46] This allows RFs to majorly reduce the issue of overfitting, becoming too familiar with the training data and performing poorly when given new data. GBMs will make one ensemble of decision trees to perform tasks, so if that model becomes too comfortable with its training data, the entire algorithm has succumbed to overfitting. The RF, because of its voting system, surpasses other methods, including GBMs, in its ability to handle model overfitting, as one decision tree does not hold all the deciding power.[47]

As for applications of RFs in bank risk management, a study of early liquidity risk warnings done by Drudi and Nobili found that random forests, especially when combined with XGBoost and the logistic LASSO, are highly effective in preventing overfitting and achieve low percentages of false negatives and false positives.[48] In terms of readability, a significant attribute of RFs is their voting system and non-correlated decision trees, making their outputs easily interpretable.[49] In areas of financial risk where transparency is a primary concern for AI models, RFs will be a good fit. In liquidity risk specifically, RFs can be trained on institutional net flows, loan demand, market funding conditions, and more to help banks predict early warning signs of liquidity risk.

Supervised DL Models:

Supervised deep learning models are a subset of supervised machine learning methods that use artificial neural networks to process and analyze information,[50] often complex and non-linear relationships. Some common types of DL models include feedforward neural networks, LSTMs, CNNs, and Generative Adversarial Networks (GANs), though this section will focus solely on LSTMs and CNNs.

Two supervised DL models that can be adopted by banks to combat credit and liquidity risk are LSTMs and CNNs. Both are neural networks able to identify dependencies and relationships within data, though they have their differences. LSTMs have memory cells and use a three-gate system (input/forget/output) that determines what information should impact the input, whether the internal state should be reset to 0 or forgotten, and what should be allowed to impact the cell's output.[51] The three-gate system and usage of memory cells allow for the LSTM model to adapt to dependencies over long periods of time.

CNNs are not too dissimilar. They consist of three main layers: input, hidden, and output.[52] There are also other classifications of the layers into what are convolutional layers and pooling layers,[15] yet the essence of the model remains the same. An input, such as an image or signal, will be broken down in a process called convolution, where each part of the input will be reassigned a mathematical value, combined with other values called weights, and ultimately yield a two-dimensional array called a filter (Figure 3). These filters search for different things within the input (for an image, maybe one filter searches for curved lines, another for straight, another for color, etc.), pool the information together in the pooling layers, and then output a classification or identify a motif within the input information (Figure 4). A CNN's framework can allow it to identify local patterns within data sets using its learnable filters and down-sample with its pooling layers.

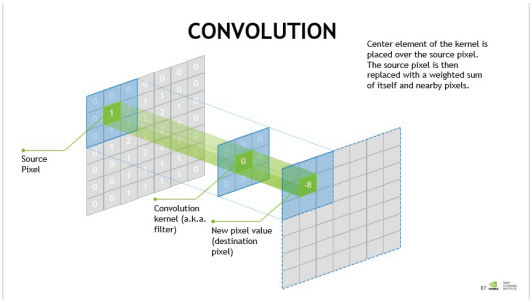

Figure 3: The process of convolution. A kernel, or filter, is placed over a source pixel or subsection of data and performs a weighted sum at the position, resulting in a new value for the pixel or subsection. This process helps reduce the number of trainable parameters significantly when performing hierarchical feature extraction, increasing efficiency.

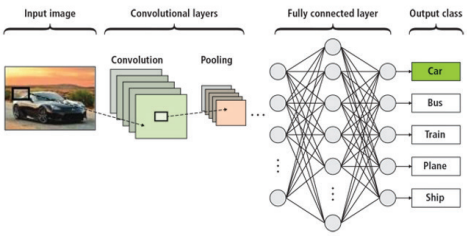

Figure 4: Layers and architecture of a convolutional neural network. After the CNN is given an input, multiple layers begin the process of convolution (Figure 3), piece together information in the pooling layers, and work to classify some pattern or identity of the input. This architecture underpins the model's ability to learn discriminative features.

LSTMs and CNNs can be used for time series forecasting, and outperform many other models, with LSTMs obtaining the most accurate forecasts (Lara-Benítez *et al.*, 2021).[53] Zhang *et al.* predicted price movements from limit order book data of cash equities in the London Stock Exchange, using convolutional layers to capture the spatial structure of the limit order books as well as LSTM modules to capture longer time dependencies.[54] The model delivered remarkably stable results and outperformed many other algorithms on the benchmark data set. LSTMs and CNNs can be paired in financial risk management to identify shifts in intraday flows, wholesale funding spreads, and even the news (using convolutional filters). Market microstructures can be monitored, and asset prices can be tracked following the same LSTM-CNN stack structure that Zhang *et al.* employed. Teams in banks will be able to identify early warning signs in both liquidity and credit risk with a combination of both LSTM and CNN models.

Best Practices and Possible Challenges:

Many challenges will arise when attempting to effectively implement AI into banks' internal structures. As it stands, AI is still a relatively new technology, and it is advancing at an extremely rapid pace. If we fail to take certain precautions when introducing AI and ML into workspaces within large financial institutions, or an institution for that matter, we may end up being unable to control what the outcomes are.[55]

One pressing challenge that must be dealt with is the "black box" problem. Explainability and transparency are crucial not just for regulatory compliance but for sound decision-making within the financial industry. Many researchers have expressed their concerns about the need for explainability in bank risk AI.[29,56,57] A feasible solution to this issue is the implementation of explainability frameworks such as SHAP (SHapley Additive exPlanations) by Lundberg and Lee in post-hoc justifications of model predictions.[58] The traditional Shapley value by Lloyd Shapley was popular in game theory (1952).[59] It used a mathematical formula to find the average contribution by multiple players to the outcome of the game. However, it wasn't well-suited for ML predictions, so SHAP restructured the traditional value to arrive at weighted averages for multiple features in a model that drove its prediction. What researchers have found is that SHAP is highly accurate and effective when it comes to model interpretability.[29] Best practice for the sake of full transparency is for SHAP's discoveries to be presented alongside visual output plots and with simple language.[60] Utilizing SHAP and eventually future explainability frameworks in post-hoc justification of model prediction will slowly remove the concern of a lack of transparency and explainability in leveraging AI in risk management.

Another frequently expressed concern is that of regulatory compliance.[56,61,62] The financial industry is characterized by strict compliance with both federal and international regulations. AI will need to fit into this web of regulations as well (Figure 5). A recommendation that many have is forming an "AI strategy."[63] This section will build on the idea of an AI strategy and highlight core elements of what the standard AI strategy for bank risk management should look like. One element of the banks' AI strategy is to have a human team that provides constant oversight of models to ensure effectiveness, explainability, and prevent the model from deviating from its intended purpose (this could look like bias or some form of misinformation). Another large element would be for banks and agencies to collaborate on developing proper regulations for AI models. The current Federal Reserve Supervision and Regulation Letter, SR 11-7, of Guidance on Model Risk Management was last updated on April 4, 2011.[64] There is no mention of AI within the document, though it should be noted that the letter itself is quite broad and could be argued as applying to any method, AI or not. Not only should there be a development of regulatory frameworks for AI models, but there should be a framework for the official auditing of said models. Auditing is crucial in the financial industry and will be useful in monitoring AI and keeping it on track with its intended purposes. Agencies need to create branches designated to perform AI audits, similar to how the International Atomic Energy Agency audits and inspects virtually every country's nuclear program. The same agencies that perform audits should also meticulously record each bank's model within a registry for ease of access and to ensure transparency and consistency in compliance assessments. Finally, proper documentation and public reporting of how AI models are being used and advanced is necessary for public transparency.

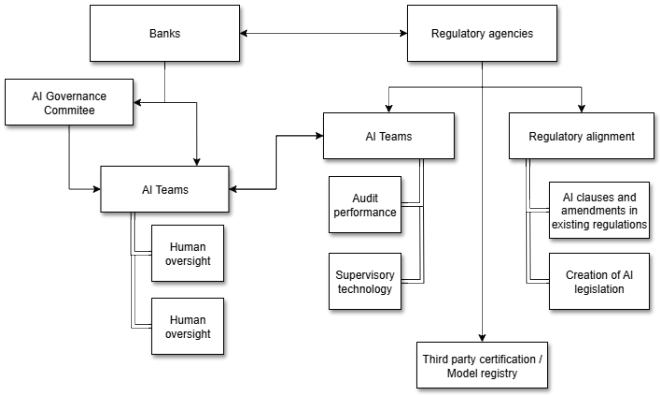

Figure 5: Proposed AI regulatory compliance framework for banks and regulatory agencies. This figure depicts the relationship that banks and regulatory agencies will have on multiple levels. This proposed structure synthesizes regulatory, technical, and human governance mechanisms into a unified model.

Banks also need to ensure that their models are effective in real-world situations, not just in simulations. This issue goes hand in hand with ensuring there is adequate availability of high-quality data to train these models. AI Teams need to be integrated seamlessly with the rest of a bank's existing segments and must be able to freely and easily draw upon information in the firm's databases. The best way for banks to increase the certainty of successful performance of AI models in real-world scenarios is by feeding them and training them on as much available, diverse, realistic information as possible.[56] The best way for this to occur is if the AI Teams that provide human oversight to and train these AI models can be integrated smoothly into the established operational structure of the bank.

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Finally, banks will need to ensure that AI is implemented practically and smoothly into existing operational frameworks. AI Teams need to roll out models in tandem with introducing the best practices for usage. Banks can also create "AI sandboxes,"[65] where AI tools can be experimented with in safe environments with practice data, giving humans who will work side-by-side with these models an opportunity to grow comfortable with how these models work. Dashboards need to be developed to not only ensure proper interpretability and readability, but also quick and easy access to AI risk management tools. The AI Team in the above framework should be able to address any concerns that arise. In essence, banks must ensure that they introduce AI risk management tools in an appropriate fashion and utilize the best practices when doing so.

Conclusion

The results of this paper suggest that banks need to implement AI into their internal structures to improve risk mitigation. AI and ML models, namely GBMs, RFs, LSTMs, and CNNS, can be leveraged in credit and liquidity risk management. These methods present highly advanced ways of consuming and interpreting high quantities of complex, non-linear data, which is abundant in finance. Models such as GBMs and CNNs can identify complex and hidden relationships in large data sets, allowing banks to identify trends in borrower behavior and funding source stability. There are also upsides to having a diversity of AI models, as each has its own downsides that can be compensated for by another's strengths. However, it is key for banks to understand that there is a plethora of challenges that will arise in adopting AI strategies in risk management. Commonly expressed issues, such as explainability, data availability, public transparency, and regulatory compliance, will need to be addressed and handled accordingly. However, there are many feasible solutions to each of these problems, such as interpretability methods like SHAP and readability frameworks that can be implemented to ensure there is no confusion. Banks must also take the necessary precautions in implementing AI risk tools into the existing operational taxonomy and allow AI Teams the full bandwidth of correcting complications that arise. With time, the financial industry will be able to employ AI strategies in internal risk management structures to combat the impending global risk management crisis.

There are, inevitably, issues that will arise that were not addressed in this paper. For one, ethical concerns were not discussed. There are possibilities yet to be seen for data breaches when it comes to risk management models and the data sets that they work on. Banks must also work to ensure there is sufficient accountability should their models develop biases or deviate from their intended purpose, and future research can address how this developing method of risk management will affect the job market and future workforce in banks. Many of these issues have yet to become pressing, though they will be poignant as time passes, and will be better served in future research.

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References

1. Oyeniyi, L. D.; Ugochukwu, C. E.; Mhlongo, N. Z.; Oyeniyi, L. D.; Ugochukwu, C. E.; Mhlongo, N. Z. Implementing AI in Banking Customer Service: A Review of Current Trends and Future Applications. *International Journal of Science and Research Archive* **2024**, *11* (2), 1492–1509. https://doi.org/10.30574/ijsra.2024.11.2.0639.
2. *Morgan Stanley uses AI evals to shape the future of financial services.* https://openai.com/index/morgan-stanley/ (accessed 2025-08-11).
3. Agustiawan, D. A. Digital Banking Transformation AI Enhances Efficiency And Customer Experience Seminar Perspective Industry. *WACANA: Jurnal Ilmiah Ilmu Komunikasi* **2024**, *23* (1), 191–200. https://doi.org/10.32509/wacana.v23i1.4130.
4. Weissbourd, R.; Ventures, R. BANKING ON TECHNOLOGY: EXPANDING FINANCIAL MARKETS AND ECONOMIC OPPORTUNITY.
5. Bakhtiyorovich, A. F. Growth In Financial Markets Around The World. *International Conference of Economics, Finance and Accounting Studies* **2024**, *7*, 5–9.
6. Rahmani, A. M.; Azhir, E.; Ali, S.; Mohammadi, M.; Ahmed, O. H.; Ghafour, M. Y.; Ahmed, S. H.; Hosseinzadeh, M. Artificial Intelligence Approaches and Mechanisms for Big Data Analytics: A Systematic Study. *PeerJ Comput. Sci.* **2021**, *7*, e488. https://doi.org/10.7717/peerj-cs.488.
7. Kibria, M. G.; Nguyen, K.; Villardi, G. P.; Zhao, O.; Ishizu, K.; Kojima, F. Big Data Analytics, Machine Learning, and Artificial Intelligence in Next-Generation Wireless Networks. *IEEE Access* **2018**, *6*, 32328–32338. https://doi.org/10.1109/ACCESS.2018.2837692.
8. Bose, S.; Dey, S. K.; Bhattacharjee, S. Chapter 3: Big Data, Data Analytics and Artificial Intelligence in Accounting: An Overview; **2023**.
9. Gandomi, A. H.; Chen, F.; Abualigah, L. Big Data Analytics Using Artificial Intelligence. *Electronics* **2023**, *12* (4), 957. https://doi.org/10.3390/electronics12040957.
10. Gu, S.; Kelly, B.; Xiu, D. Empirical Asset Pricing via Machine Learning. *Rev Financ Stud* **2020**, *33* (5), 2223–2273. https://doi.org/10.1093/rfs/hhaa009.
11. Ma, X.; Lv, S. Financial Credit Risk Prediction in Internet Finance Driven by Machine Learning. *Neural Comput & Applic* **2019**, *31* (12), 8359–8367. https://doi.org/10.1007/s00521-018-3963-6.
12. Mashrur, A.; Luo, W.; Zaidi, N. A.; Robles-Kelly, A. Machine Learning for Financial Risk Management: A Survey. *IEEE Access* **2020**, *8*, 203203–203223. https://doi.org/10.1109/ACCESS.2020.3036322.
13. Guerra, P.; Castelli, M.; Côrte-Real, N. Machine Learning for Liquidity Risk Modelling: A Supervisory Perspective. *Economic Analysis and Policy* **2022**, *74*, 175–187. https://doi.org/10.1016/j.eap.2022.02.001.
14. Barongo, R. I.; Mbelwa, J. T. Using Machine Learning for Detecting Liquidity Risk in Banks. *Machine Learning with Applications* **2024**, *15*, 100511. https://doi.org/10.1016/j.mlwa.2023.100511.

15. LeCun, Y.; Bengio, Y.; Hinton, G. Deep Learning. *Nature* **2015**, *521* (7553), 436–444. https://doi.org/10.1038/nature14539.
16. Wang, G.; Ma, J.; Huang, L.; Xu, K. Two Credit Scoring Models Based on Dual Strategy Ensemble Trees. *Knowledge-Based Systems* **2012**, *26*, 61–68. https://doi.org/10.1016/j.knosys.2011.06.020.
17. Barboza, F.; Kimura, H.; Altman, E. Machine Learning Models and Bankruptcy Prediction. *Expert Systems with Applications* **2017**, *83*, 405–417. https://doi.org/10.1016/j.eswa.2017.04.006.
18. Gogas, P.; Papadimitriou, T.; Agrapetidou, A. Forecasting Bank Failures and Stress Testing: A Machine Learning Approach. *International Journal of Forecasting* **2018**, *34* (3), 440–455. https://doi.org/10.1016/j.ijforecast.2018.01.009.
19. Khunger, A.; Anand, K.; Jagdale, A. D.; Shukla, C.; Chinnakannan, A.; Dbritto, C. DEEP LEARNING FOR FINANCIAL STRESS TESTING: A DATA-DRIVEN APPROACH TO RISK MANAGEMENT. Social Science Research Network: Rochester, NY, March 22, 2022. https://doi.org/10.2139/ssrn.5146509.
20. Metha, S.; Lakhamraju, M. V.; Miriyala, N. S.; Macha, K. Stress Testing Financial Systems– Simulating Economic Disruption Using AI-Driven Risk Models. *International Journal of Computational and Experimental Science and Engineering* **2025**, *11* (2). https://doi.org/10.22399/ijcesen.2132.
21. Hussain, J. *Deep Learning Black Box Problem*; 2019.
22. Şahin, E.; Arslan, N. N.; Özdemir, D. Unlocking the Black Box: An in-Depth Review on Interpretability, Explainability, and Reliability in Deep Learning. *Neural Comput & Applic* **2025**, *37* (2), 859–965. https://doi.org/10.1007/s00521-024-10437-2.
23. Lei, D.; Chen, X.; Zhao, J. Opening the Black Box of Deep Learning. arXiv May 22, 2018. https://doi.org/10.48550/arXiv.1805.08355.
24. Doko, F.; Kalajdziski, S.; Mishkovski, I. Credit Risk Model Based on Central Bank Credit Registry Data. *Journal of Risk and Financial Management* **2021**, *14* (3), 138. https://doi.org/10.3390/jrfm14030138.
25. Lohmann, C.; Möllenhoff, S.; Ohliger, T. Nonlinear Relationships in Bankruptcy Prediction and Their Effect on the Profitability of Bankruptcy Prediction Models. *J Bus Econ* **2023**, *93* (9), 1661–1690. https://doi.org/10.1007/s11573-022-01130-8.
26. Sundaresan, S.; Xiao, K. Liquidity Regulation and Banks: Theory and Evidence. *Journal of Financial Economics* **2024**, *151*, 103747. https://doi.org/10.1016/j.jfineco.2023.103747.
27. Macchiavelli, M.; Pettit, L. Liquidity Regulation and Financial Intermediaries. **2018**.
28. Ratnovski, L. Liquidity and Transparency in Bank Risk Management. *Journal of Financial Intermediation* **2013**, *22* (3), 422–439. https://doi.org/10.1016/j.jfi.2013.01.002.
29. Alvi, J.; Arif, I.; Nizam, K. Advancing Financial Resilience: A Systematic Review of Default Prediction Models and Future Directions in Credit Risk Management. *Heliyon* **2024**, *10* (21). https://doi.org/10.1016/j.heliyon.2024.e39770.
30. Breiman, L. Random Forests. *Machine Learning* **2001**, *45* (1), 5–32. https://doi.org/10.1023/A:1010933404324.
31. Aldasoro, I.; Hördahl, P.; Schrimpf, A.; Zhu, X. S. Predicting Financial Market Stress with Machine Learning.
32. Phua, C.; Lee, V.; Smith, K.; Gayler, R. A Comprehensive Survey of Data Mining-Based Fraud Detection Research. *Computers in Human Behavior* **2012**, *28* (3), 1002–1013. https://doi.org/10.1016/j.chb.2012.01.002.
33. Kou, G.; Peng, Y.; Wang, G. Evaluation of Clustering Algorithms for Financial Risk Analysis Using MCDM Methods. *Information Sciences* **2014**, *275*, 1–12. https://doi.org/10.1016/j.ins.2014.02.137.
34. Corso, G.; Stark, H.; Jegelka, S.; Jaakkola, T.; Barzilay, R. Graph Neural Networks. *Nat Rev Methods Primers* **2024**, *4* (1), 17. https://doi.org/10.1038/s43586-024-00294-7.
35. Xu, K.; Wu, Y.; Xia, H.; Sang, N.; Wang, B. Graph Neural Networks in Financial Markets: Modeling Volatility and Assessing Value-at-Risk. *Journal of Computer Technology and Software* **2022**, *1* (2).
36. *Examining the relationship between equity volatility and liquidity – A longer-term perspective - CME Group*. https://www.cmegroup.com/articles/2022/volatility-spikes-vs-liquidity-a-longer-term-perspective.html (accessed 2025-08-17).
37. Drehmann, M.; Nikolaou, K. Funding Liquidity Risk: Definition and Measurement.
38. Belcic, I.; Stryker, C. *What Is Supervised Learning? | IBM*. https://www.ibm.com/think/topics/supervised-learning (accessed 2025-08-18).
39. Friedman, J. Greedy Function Approximation: A Gradient Boosting Machine. The Annals of Statistics 2001, 29 (5), 1189–1232.
40. *What Is Boosting? | IBM*. https://www.ibm.com/think/topics/boosting (accessed 2025-08-18).
41. *What is Gradient Boosting? | IBM*. https://www.ibm.com/think/topics/gradient-boosting (accessed 2025-08-18).
42. Chen, T.; Guestrin, C. XGBoost: A Scalable Tree Boosting System. In *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*; 2016; pp 785–794. https://doi.org/10.1145/2939672.2939785.
43. Ke, G.; Meng, Q.; Finley, T.; Wang, T.; Chen, W.; Ma, W.; Ye, Q.; Liu, T.-Y. LightGBM: A Highly Efficient Gradient Boosting Decision Tree. In *Advances in Neural Information Processing Systems*; Curran Associates, Inc., 2017; Vol. 30.
44. Saha, S. *XGBoost vs LightGBM: How Are They Different*. neptune.ai. https://neptune.ai/blog/xgboost-vs-lightgbm (accessed 2025-08-18).
45. Ying, C.; Shi, A.; Li, X. Hybrid Boosted Attention-Based LightGBM Framework for Enhanced Credit Risk Assessment in Digital Finance. *Humanit Soc Sci Commun* **2025**, *12* (1), 1036. https://doi.org/10.1057/s41599-025-05230-y.
46. *What Is Random Forest? | IBM*. https://www.ibm.com/think/topics/random-forest (accessed 2025-08-19).
47. Matsuki, K.; Kuperman, V.; Van Dyke, J. A. The Random Forests Statistical Technique: An Examination of Its Value for the Study of Reading. *Sci Stud Read* **2016**, *20* (1), 20–33. https://doi.org/10.1080/10888438.2015.1107073.
48. Nobili, S.; Drudi, M. L. A Liquidity Risk Early Warning Indicator for Italian Banks: A Machine Learning Approach. *SSRN Journal* **2021**. https://doi.org/10.2139/ssrn.3891566.
49. Abbasov, R. Revolutionizing Risk Management in Banking: Implementation of AI/ML-Based Gradient Boosting Machines (GBM) and Random Forests for Credit Risk Management. *Int. J. Finance Manage.* **2023**, *6* (1), 441–444. https://doi.org/10.33545/26175754.2023.v6.i1d.324.
50. *Deep learning vs machine learning vs AI*. Google Cloud. https://cloud.google.com/discover/deep-learning-vs-machine-learning (accessed 2025-08-18).
51. *10.1. Long Short-Term Memory (LSTM) — Dive into Deep Learning 1.0.3 documentation*. https://d2l.ai/chapter_recurrent-modern/lstm.html (accessed 2025-08-19).
52. *What is a Convolutional Neural Network?*. NVIDIA Data Science Glossary. https://www.nvidia.com/en-us/glossary/convolutional-neural-network/ (accessed 2025-08-19).
53. Lara-Benítez, P.; Carranza-García, M.; Riquelme, J. C. An Experimental Review on Deep Learning Architectures for Time Series

DOI: 10.36838/IJHSR811.40

Forecasting. *Int. J. Neur. Syst.* **2021**, *31* (03), 2130001. https://doi.org/10.1142/S0129065721300011.
54. Zhang, Z.; Zohren, S.; Roberts, S. DeepLOB: Deep Convolutional Neural Networks for Limit Order Books. *IEEE Trans. Signal Process.* **2019**, *67* (11), 3001–3012. https://doi.org/10.1109/TSP.2019.2907260.
55. Suleyman, M.; Bhaskar, M. *The Coming Wave: Technology, Power, and the Twenty-First Century's Greatest Dilemma*; Crown Publishing Group: New York, NY, 2023.
56. Moolchandani, S. The Integration of Generative AI in Credit Risk Management. *IJMIE* **2024**, *14* (2), 137–145.
57. Misheva, B. H.; Osterrieder, J.; Hirsa, A.; Kulkarni, O.; Lin, S. F. Explainable AI in Credit Risk Management. arXiv March 1, 2021. https://doi.org/10.48550/arXiv.2103.00949.
58. Lundberg, S.; Lee, S.-I. A Unified Approach to Interpreting Model Predictions. arXiv November 25, 2017. https://doi.org/10.48550/arXiv.1705.07874.
59. Shapley, L. A Value for N-Person Games, 1952.
60. Salih, A. M.; Raisi-Estabragh, Z.; Galazzo, I. B.; Radeva, P.; Petersen, S. E.; Lekadir, K.; Menegaz, G. A Perspective on Explainable Artificial Intelligence Methods: SHAP and LIME. *Advanced Intelligent Systems* **2025**, *7* (1), 2400304. https://doi.org/10.1002/aisy.202400304.
61. Calderón, A. Regulatory Compliance & Supervision in AI Regime: Banks and FinTech. **2020**.
62. Deshpande, A. Regulatory Compliance and AI: Navigating the Legal and Regulatory Challenges of AI in Finance. In *2024 International Conference on Knowledge Engineering and Communication Systems (ICKECS)*, 2024; Vol. 1, pp 1–5. https://doi.org/10.1109/ICKECS61492.2024.10616752.
63. *Navigating compliance in the age of AI: Insights from risk experts*. https://www.wolterskluwer.com/en/expert-insights/navigating-compliance-in-the-age-of-ai-insights-from-risk-experts (accessed 2025-08-16).
64. *The Fed - Supervisory Letter SR 11-7 on guidance on Model Risk Management -- April 4, 2011*. https://www.federalreserve.gov/supervisionreg/srletters/sr1107.htm (accessed 2025-08-16).
65. *Google, Oliver Wyman, Corridor launch gen AI sandbox for banks*. American Banker. https://www.americanbanker.com/news/google-oliver-wyman-corridor-launch-gen-ai-sandbox-for-banks (accessed 2025-08-19).

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RESEARCH ARTICLE

Optimizing Blade Geometry for Vertical Axis Wind Turbines for Usage in Low-Speed Urban Environments

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ABSTRACT: In urban environments, such as Berlin, Germany, where wind is slow, turbulent, and multidirectional, conventional wind turbine designs often fail to operate effectively, especially during startup (Mertens). The challenge of effectively harnessing wind power in cities remains largely unsolved, despite multiple benefits: electrical infrastructure, undisturbed habitats, and proximity to where the electricity is most used (Stathopoulos *et al.*). Even though horizontal-axis wind turbines are more efficient than their vertical counterparts, especially at higher wind speeds, they are often deemed unsuitable for urban areas. However, vertical-axis wind turbines (VAWT) are more adaptive to changing wind directions because they don't require yaw and pitch adjustments (Al-Rawajfeh & Gomaa). This makes them more convenient for multidirectional gusts of wind, as is typically the case in urban areas. This study employs Computational Fluid Dynamics (CFD) to simulate the startup behavior of vertical-axis wind turbines at low air speeds. Since drag-based approaches have a faster startup response than lift-based vertical axis wind turbines (Darrieus blades), the geometry of the Savonius blade will be optimized to achieve the highest power output within a set time period.

KEYWORDS: Engineering, Aerodynamics, Vertical Axis Wind Turbine, Urban Environment, Efficiency, Computational Fluid Dynamics.

Introduction

In the face of accelerating urbanization and the ever-growing energy demand, the shift toward sustainable, decentralized energy sources has evolved into both a practical necessity and a strategic priority.[1] As cities expand and populations concentrate in metropolitan areas, the strain on centralized energy grids intensifies, increasing the urgency to reduce dependency on large-scale, fossil-fuel-based power plants.[2] Within this context, renewable energy technologies, particularly those capable of being deployed directly within cities, are positioned to serve a crucial function in enabling a resilient, low-carbon energy future.

Wind energy stands out as one of the most mature, reliable, and environmentally friendly forms of renewable energy available today. Traditionally, however, the majority of wind energy systems have been installed in rural landscapes or offshore locations, where the benefits of high and steady wind speeds, minimal obstructions, and reduced land-use conflicts can be fully leveraged.[3] While this deployment pattern has been instrumental in scaling global wind capacity, it has also left a big gap: the integration of wind turbines into densely populated urban environments remains limited.[4]

This underutilization is notable because urban wind energy offers considerable strategic advantages. By generating electricity close to the point of consumption, urban wind turbines can help reduce energy losses during transmission, lower peak demand on national grids, and increase resilience against large-scale outages or supply disruptions due to the possibility of multiple independent local grids. Furthermore, localized generation can support broader sustainability goals by complementing rooftop solar installations and contributing to a diversified, multi-source urban microgrid.[5]

Cities like Berlin, Germany, provide a particularly fertile ground for exploring small-scale wind energy harvesting. Their dense infrastructure, spanning rooftops, building facades, bridges, and transportation corridors, offers ample, underused surfaces and structural supports for turbine installation, eliminating the necessity for additional land use.[6] Moreover, the unique aerodynamics of urban landscapes can be turned from a challenge into an asset: air can be accelerated around corners, channeled between high-rise buildings, or induced by vehicular movement on busy streets.[7]

However, harnessing wind energy in urban areas is not without significant technical hurdles. Low average wind speeds, elevated turbulence intensity, and rapid fluctuations in wind direction make it difficult for wind turbines to operate efficiently.[4] These conditions demand systems capable of starting and generating power at low wind speeds (below 5 ms^{-1}), responding quickly to directional changes, and tolerating unsteady aerodynamic loads. Vertical-axis wind turbines (VAWTs), specifically Savonius-type configurations, offer inherent advantages in meeting these requirements. HAWTs require yaw adjustments to operate in areas with fast-changing wind directions, while VAWTs require no additional mechanisms to adapt. VAWTs also tend to operate more quietly, a crucial factor in maintaining community acceptance in noise-sensitive urban neighbourhoods.[8]

This study focuses on the city of Berlin, so the average annual wind speed of approximately 4.1 ms^{-1} was chosen to test the wind turbines.[9, 10] In an urban environment like Berlin, the wind direction changes on an hourly basis. This calls for

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two conditions: an omnidirectional design and a rapid startup, which are both possible with a VAWT. Therefore, the central aim is to improve start-up characteristics and operational responsiveness, and not the maximum possible angular velocity by optimizing the blade geometry of a VAWT. Short startup time is important, as changing wind directions mean short gusts of wind. Therefore, a higher power output after a certain amount of time was the most crucial factor for this study. A simple Savonius-type blade was taken and then iteratively designed to increase the peak moment, angular velocity, and hence power output within 150 seconds. 150 s was chosen as it provides an equal balance between short gusts of wind that typically last up to 30 seconds and slower, more constant wind that keeps blowing continuously. The changing wind directions were not considered within each simulation, as the VAWT is omnidirectional, but the VAWT performance was tested when the wind came from a different direction.

Principles of a Vertical-Axis Wind Turbine

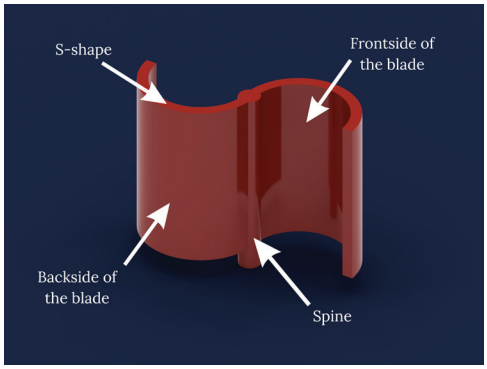

Figure 1: Synthetic Parts of a Savonius wind turbine, highlighting the core components involved in this study.

The Savonius wind turbine typically comprises two blades arranged around a central vertical shaft or spine. The blades form an S-shape from above, causing the front side of each blade to be concave and the back side to be convex, as shown in Figure 1.

When wind strikes the concave side of one of the blades, the curved surface traps more air, leading to a buildup of pressure, as illustrated in Figure 2. This pressure generates drag, which in turn exerts a force on the blade. Since the vertical spine of the turbine serves as the pivot point, this force produces a moment about the axis, initiating rotation. At the same time, the convex side of the opposing blade is also exposed to the wind. Although this side experiences airflow, its shape causes the air to pass over more smoothly, resulting in significantly lower pressure buildup. As a result, the force, and thus the opposing moment, or negative torque, is significantly weaker compared to the driving side. This imbalance between the stronger driving torque and the weaker resisting torque allows the turbine to rotate consistently in a single direction. Every time the blades sweep through the airflow, this process is repeated, sustaining the continuous motion of the Savonius wind turbine.

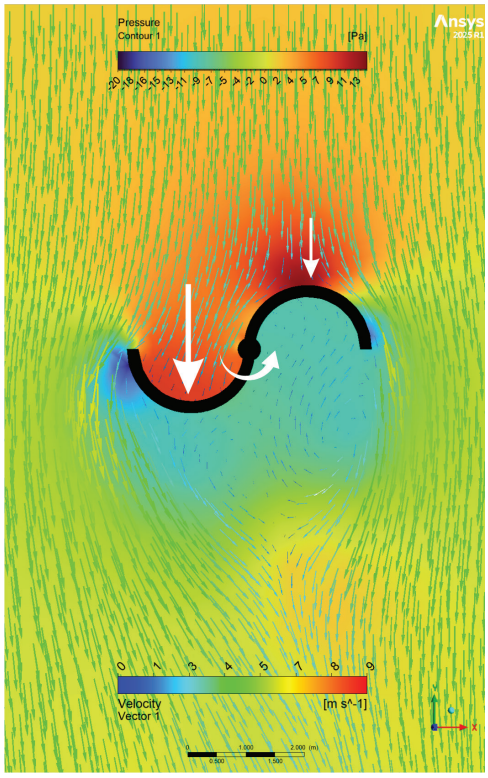

Figure 2: Forces acting on a Savonius VAWT. The imbalance between drag on the concave and convex sides produces a net torque that drives rotation.

There are various ways to increase the torque and angular velocity of the turbine: increasing the drag difference; increasing the distance between the forces and pivot point, to increase moment; reducing the moment of inertia of the wind turbine; and producing torque more consistently. Moment of inertia refers to the distribution of mass in relation to the rotational axis. A smaller moment of inertia means the object is less resistant to changes in its angular velocity. Mass further away from the rotational axis induces a higher resistance to changes in angular velocity, thus implying a slower start-up time. Thus, the efficiency of a Savonius wind turbine ultimately depends on maximizing the asymmetry between the driving and resisting forces while minimizing rotational resistance, thus allowing for a faster angular acceleration.

Methods

3.1. Experimental Setup and Tools:

For this study, the Ansys Fluent application was used for the CFD testing and Autodesk Fusion for the CAD modeling and other model-related calculations (moment of inertia, etc.).[11, 12]

These specific programs were chosen as they provide high compatibility and accuracy for engineering simulations, with Fusion enabling precise geometrical control and Fluent offering advanced turbulence and fluid interaction modeling.

In Autodesk Fusion, all models were created with two main parts: the blades and the central spine that would act as the turning axis. The same measurements for all models were applied:

- 4.2 m diameter of the entire wind turbine at its largest point

- 3 m high excluding spine (3.4 m with spine)
- central spine with 0.4 m diameter

These dimensions were selected to represent a small-scale turbine that would produce realistic aerodynamic behavior while keeping the computational load manageable. The proportions also ensured stability and minimized excessive tip effects during airflow analysis.

All models were assigned steel properties and then hollowed. The assumption that a 10mm thick wall would be sufficient to sustain all structures was not tested, as it was not included in the scope of this study. A moment of inertia for every design interaction for the turbine was calculated around the central rotational axis.

In Ansys Fluent, the watertight workflow was implemented to ensure accurate meshing and precise control over the simulation.

To create the meshes, a surrounding body was constructed. This body had the following dimensions: 5 times the diameter of the turbine downstream, double the diameter of the turbine upstream, and any of the other boundaries.

These boundary distances were chosen to eliminate external flow interference and ensure that wake development could occur naturally within the domain, avoiding reflections or artificial constraints on the airflow.

Growth rate, size of the mesh, and curvature normal angle were fixed to 1,1, 0.02, and 8 degrees, respectively, to ensure a high-quality mesh, even in the wake section.

3.1.1. Transient Simulations:

The viscous model used for all transient simulations was the realizable k-epsilon model with enhanced wall treatment. It is a two-equation turbulence model widely used in CFD simulations because it balances accuracy and computational efficiency.[13] Since this simulation involved rotating parts and keeping y+ in exactly the ideal range (y+ < 3) everywhere is difficult to achieve, the enhanced wall treatment was applied. This allowed the simulation to handle both fine meshes and coarser meshes without switching models for accurate near-wall effects, even with a coarser mesh.

The inlet speed was set at 4.1 ms^{-1}, which reflects the yearly average wind speed in Berlin over the entire year. As urban environments are categorized as turbulent environments, a turbulent intensity of 30%, and a viscosity ratio of 10 were chosen. To enable the wind turbines to spin freely, the 6DOF solver within Ansys Fluent was applied. This allowed the air particles to interact with the wind turbine and turn it around its specified axis. Given the correct moment of inertia from Autodesk Fusion, the startup behavior could now be simulated. The output parameters could be graphed against time and were set as follows:

- ω - angular velocity (rad s^{-1})
- T - torque (Nm)

Using this data, the power output could be calculated using the formula:

$P = T$

These parameters allow a fair evolution of each VAWT. All of these variables were tracked throughout the full 150 seconds of simulation time (unless otherwise specified). All transient simulations consisted of over 3000 timesteps, each 0.05 seconds long. Every simulation ran at least 20 iterations for every timestep, resulting in over 60,000 iterations for all transient simulations.

3.1.2. Steady Simulations:

For some modifications, only the drag of the concave and convex sides was tested. These simulations required far less computational time because they were steady rather than transient, which also made it possible to employ the more advanced transition SST viscous model, based on four governing equations. Each run was carried out for 200 iterations to ensure high reliability of results. The drag force of the convex and concave sides of the blade was tested individually, and then a difference was calculated. However, the difference in drag between the two sides was not sufficient to determine suitability, as the moment of inertia also significantly affects the turbine's angular velocity. For this reason, a ratio between the drag difference and the moment of inertia was calculated in every case, allowing the optimal balance between aerodynamic performance and rotational efficiency to be identified.

3.2. Variables:

To optimize the performance of the Savonius wind turbine, several design modifications were systematically tested to evaluate their effect on torque generation, rotational speed, and power.

Firstly, we investigated the number of blades, comparing the Savonius turbine designs with 2, 3, 4, and 5 blades. More blades should increase the smoothness of power output, but the increased number of blades will increase the moment of inertia significantly.

Secondly, the peak of the blades was offset outwards, as shown in Figure 3. This would shift the focus of the drag force experienced by the concave side further away from the pivot, thus increasing the torque. The peak was offset in 20 cm increments up to 60 cm.

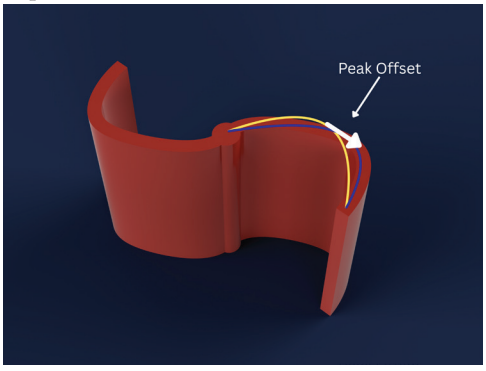

Figure 3: Offset outwards of the blade peak.

Thirdly, the geometry of the blade was manipulated in multiple ways to increase the difference in drag between the convex and concave sides of the blade. The first modification involved changing the peak radius of the blade illustrated in Figure 4. The radius was gradually increased in 10 cm increments, up to a maximum of 40 cm. Increasing the radius makes the

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concave side "deeper," allowing it to trap and redirect a larger volume of airflow, which results in higher pressure buildup and therefore higher drag. In contrast, the convex side becomes smoother with a larger radius, which encourages airflow to remain attached and slip past with relatively less resistance. This asymmetry enhances the difference in aerodynamic forces acting on the two sides of the blade, which is the driving principle of a drag-based turbine. By systematically increasing the peak radius (the depth of the blade), the balance between the drag difference of the concave and convex sides and the moment of inertia can be found.

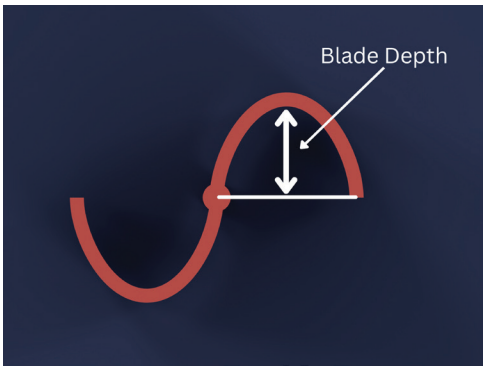

Figure 4: Variating the peak radius of the blade.

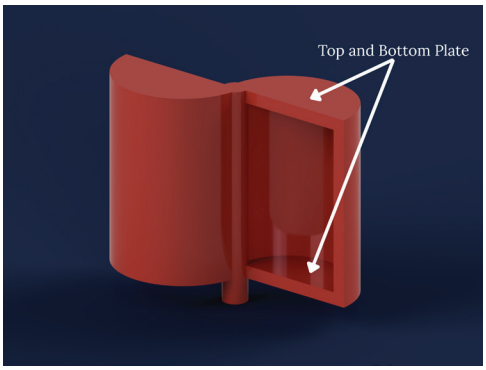

Figure 5: Adding top and bottom plates to the blades.

The fourth modification focused on attaching plates to the top and bottom edges of each blade, which is shown in Figure 5. These plates were designed to act as barriers that block air from escaping around the blade edges, forcing more of the airflow to interact with the concave surface. As a result, the concave side experienced even higher drag, while the convex side remained relatively unaffected. The design was refined through three iterations, each improving the positioning and geometry of the plates to maximize the drag difference while minimizing additional rotational momentum. By confining the airflow in this way, the plates served a similar function to endplates in aerodynamics, which are often used in wings and diffusers to reduce unwanted losses.

Finally, the best performing modifications based on the previous tests in this study were combined and tested for 150 seconds using the realizable k-epsilon model with enhanced wall treatment.

Results

4.1. The controlled case:

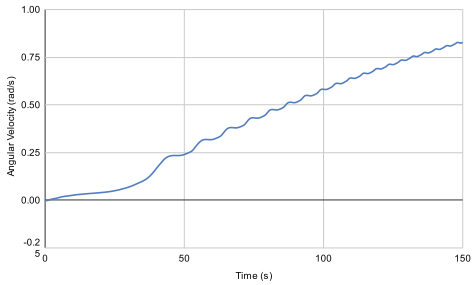

Figure 6: Angular velocity of the baseline Savonius turbine over time. The turbine accelerates gradually with strong oscillations within 150 s.

Firstly, the standard Savonius turbine was tested without any changes. Figure 6 shows the angular velocity over 150 seconds. The turbine ended up achieving an angular speed of 0.814 rad s^{-1}.

However, the angular velocity did not always increase. Instead, it changed in waves, with little peaks forming. This is due to the structure of this type of VAWT, due to the torque always changing and never staying constant, as shown in Figure 7. As time continues, these peaks become less prominent and more frequent because the turbine starts spinning faster. The faster spinning blades lower the peaks and troughs on the torque plot due to the relative speed between the blades and the surrounding air changing. The concave side creating most of the turning moment, starts moving with the wind, which decreases the relative speed of the air hitting the blade. This decreases the drag force on the blade, meaning less torque. On the other side, the convex side moves against the air flow. Hence, the relative speed between the blade and the air increases, increasing the drag force on the blade, meaning more torque working against the rotation. Therefore, the acceleration of the turbine slows until the forces acting on the concave and convex sides are in equilibrium.

Therefore, the power output of the VAWT fluctuates a lot, as shown in Figure 8. However, generator types like Double Fed Induction mean this is not an issue, due to their ability to easily being able to adjust to changing energy outputs.

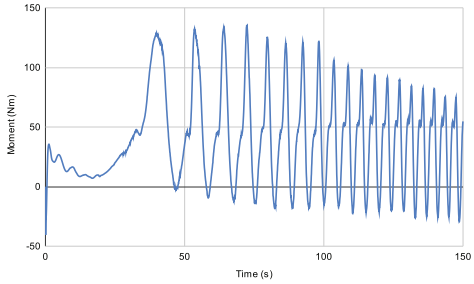

Figure 7: Torque of the Savonius turbine over time. The oscillatory torque profile explains the fluctuations observed in angular velocity and highlights the unsteady nature of drag-based VAWT operation.

4.2. Number of Blades:

The standard Savonius wind turbine design was tested with configurations of three, four, and five blades in order to evaluate how blade number influences startup behavior, angular velocity,

and energy output, and compared with the control. Across all cases, none of the turbines reached a steady-state speed within the 150 seconds of simulated runtime. Instead, each configuration was still in its startup phase, gradually accelerating under the influence of the wind. Nevertheless, the results still provided valuable insights into the comparative performance of different blade numbers, as each setup achieved significant angular velocities and torque outputs despite not reaching equilibrium.

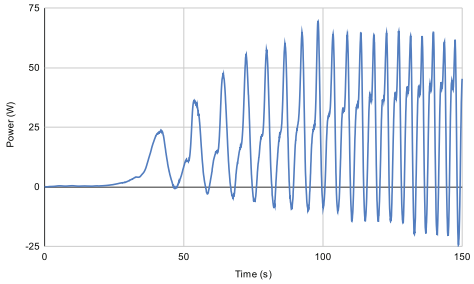

Figure 8: Power output of the Savonius turbine over time with strong fluctuations due to the unsteady torque and gradual increase in angular momentum.

The quantitative results of the blade number investigation are summarised in Table 1. The turbine with five blades performed the worst, producing the lowest maximum angular speed (0.533 rad s^{-1}), torque (102.3 Nm), and final energy output (26.1 W). The primary reason for this is its relatively large moment of inertia: with five blades distributed around the rotor, the turbine had more mass positioned farther from its axis of rotation, which substantially increased resistance to angular acceleration. Furthermore, with so many blades occupying the flow path, interference effects became prominent. As one blade attempted to capture airflow, adjacent blades obstructed or redirected part of that flow, leading to aerodynamic inefficiencies. Despite these drawbacks, the five-blade turbine displayed one noteworthy advantage: it was the first configuration to achieve noticeable angular speed, and its torque curve was the most stable and consistent. The overlapping operation of multiple blades smoothed out fluctuations and outputted power more consistently than the two-blade setup, which can be seen in Figure 8. This suggests that while the five-blade design is less efficient at maximizing power, it could be advantageous in applications where torque consistency is prioritized over peak performance.

In stark contrast, the two-bladed Savonius turbine delivered the best performance. It achieved the highest angular speed, the greatest peak torque, and the largest energy output. With only two blades, its moment of inertia was significantly lower than in the multi-blade cases, allowing it to accelerate more rapidly under the same wind conditions. Additionally, the reduced number of blades minimized aerodynamic interference, ensuring that each blade was exposed to a greater share of unobstructed airflow. However, one important factor influencing this result was the turbine's initial orientation. In the simulation, the blades were positioned perpendicular to the incoming wind, maximizing the drag difference between the convex and concave surfaces from the very start. Theoretically, if the turbine had instead started with its blades parallel to the wind direction, its initial torque would have been much lower. With less surface area directly exposed to the wind, the turbine would likely have taken longer to accelerate to meaningful angular speeds.

For turbines with three, four, or five blades, this orientation issue is irrelevant. Their symmetrical arrangements ensure that, regardless of the starting position, at least one blade will always face the airflow in a drag-producing orientation. To test the effect of orientation more rigorously, one additional simulation was performed on the two-bladed turbine. This time, the rotor was rotated 90 degrees so that the blades were parallel to the incoming wind, minimizing the exposed drag area at startup. Based on initial reasoning, this configuration was expected to perform worse, since it presented less effective surface area to the flow and should therefore have generated less torque in the early phase.

Table 1: Results of the blade number investigation. The two-bladed configuration achieves the highest angular velocity and power output due to its lower moment of inertia.

Number of Blades					
Number of Blades	Moment of Inertia (kg m^2)	Angular speed (rad s^{-1})	Peak moment (Nm)	Final moment (Nm)	Final power (W)
2.0	6,699	0.814	131.8	72.3	58.9
3.0	10,040	0.661	93.6	51.9	34.3
4.0	13,380	0.560	95.4	57.6	32.2
5.0	16,730	0.533	102.3	49.0	26.1
Starting position turned by 90 degrees					
2.0	6,699	0.925	128.5	74.5	68.9

Surprisingly, the results revealed the opposite: the two-bladed turbine actually performed better in this setup. Its angular velocity increased more rapidly, reaching 0.925 rad s^{-1}, and it achieved its first peak in rotational speed more than 70% earlier than in the perpendicular orientation. A likely explanation lies in the phenomenon of flow attachment. When the front-facing blade was aligned with the airflow, the air did not simply slip past it; instead, a portion of the flow adhered to the blade's curved surface, following its contour due to the Coanda effect. The attached flow redirected a significant portion of air into the concave surface of the trailing blade, as shown in Figure 9. Effectively, the leading blade acted as a guide vane, channeling airflow into the optimal region of the downstream blade and generating torque. This aerodynamic interaction gave the turbine a substantial head start, allowing it to spin up more quickly than in the perpendicular case.

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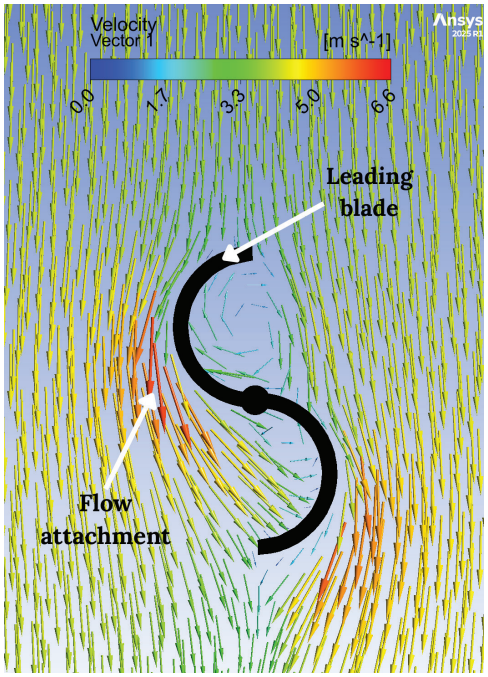

Figure SEQ Figure * ARABIC 9: Flow attachment on leading blade of VAWT, enhancing startup torque.

These findings suggest that parallel alignment can, in fact, yield superior acceleration due to flow redirection effects. Therefore, the orientation has little effect on the performance of the two-bladed VAWT, making it overall superior to its multi-bladed counterparts.

4.3. Peak Offset:

To investigate ways of increasing the torque generated by the turbine, the geometry of the blade was modified by offsetting the peak of its curve outward from the central axis. In a standard Savonius turbine, the blades are typically formed from semicylindrical shapes, where the peak of the curve lies directly on the diameter of the circle. By pushing this peak outward, the concave side of the blade becomes deeper and broader, thereby intercepting more of the incoming wind. In theory, this should allow the concave surface to capture a greater volume of airflow, producing higher drag and thus generating more torque. At the same time, the convex side of the blade becomes less curved and more elongated, changing how the wind interacts with that surface. This adjustment was tested at offsets of 20 cm, 40 cm, and 60 cm from the center, and the performance of these variants was compared to that of the standard, unmodified Savonius turbine.

The turbine with a 20 cm offset demonstrated the most promising results. In fact, it even outperformed the standard Savonius turbine in several important categories by a margin of approximately 8%. Its standout feature was its rapid startup behavior. Within the first 75 seconds of simulation, it reached an angular velocity of 0.58 rad s^{-1}, which is 34% higher than that achieved by the standard design over the same period. This faster acceleration translated directly into higher power output at early times, since power depends on both torque and angular velocity. The improved startup can be attributed to the enhanced aerodynamic asymmetry created by the moderate offset: the concave surface was able to generate stronger positive drag forces while the convex side, though slightly flatter, did not yet create excessive negative drag. As a result, the net torque driving rotation was maximized in the early stages. However, after 75 seconds, the 20 cm offset turbine experienced a relatively rapid decline in torque generation. Over longer simulation times (150 seconds), its average power output fell slightly below that of the standard turbine. This suggests that while the modified geometry provided a powerful initial boost, it also introduced aerodynamic inefficiencies at higher rotational speeds, such as greater turbulent losses and less favorable flow attachment on the convex surface.

In contrast, the turbines with larger offsets of 40 cm and 60 cm performed considerably worse. At first glance, the 40 cm offset seemed promising because it recorded the highest peak torque of all tested designs. However, this peak was achieved only after a long delay, and the turbine suffered from very poor startup characteristics. The higher moment of inertia associated with the outward displacement of the blade peaks meant that more energy was required to initiate rotation. Since rotational acceleration is inversely proportional to the moment of inertia (according to Newton's second law for rotation), the heavier, more extended blades were much slower to respond to the available torque. As a result, the turbine was unable to accelerate efficiently, undermining the advantage of its higher torque capability.

The 60 cm offset turbine performed even worse, with its angular velocity still close to zero after 75 seconds of runtime. This extreme underperformance cannot be explained by moment of inertia alone. The large offset altered the convex side of the blade geometry so dramatically that it effectively became a long, flat surface facing into the wind. Rather than allowing air to smoothly slip past, this flat surface caused significant flow stagnation and pressure buildup. In aerodynamic terms, the convex side was no longer "streamlined," and the flow separated early, creating a broad wake of turbulent, high-drag air behind it. The increased pressure drag on the convex side generated a large amount of negative torque, which directly counteracted the positive torque produced by the concave surface. This destructive interference between the two sides of the blade meant that much of the energy supplied by the wind was wasted, and the turbine struggled to overcome static resistance to rotation. Figure 10 illustrates this effect, showing the large pressure distribution on the convex face.

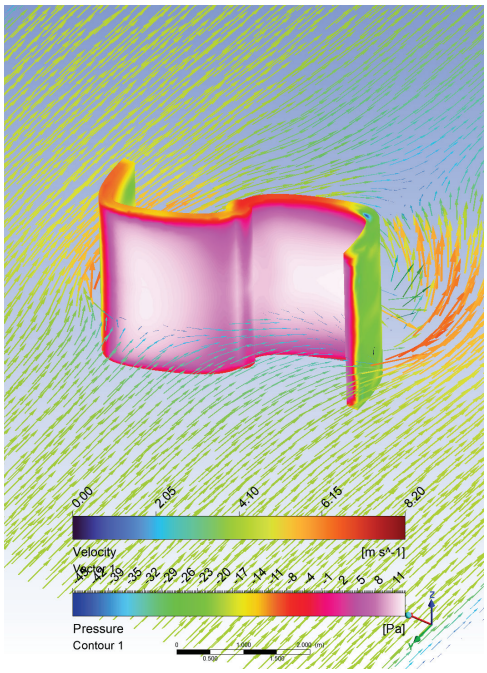

Figure 10: Pressure distribution on the turbine with a 60 cm peak offset. High pressure on the convex surface generates negative torque, significantly reducing startup performance.

A small outward offset, as in the 20 cm case, enhances moment asymmetry without excessively increasing convex-side resistance, thereby maximizing startup torque. But as the offset increases, the convex surface loses its curved, streamlined character and begins to behave like a flat plate, dramatically raising drag and producing counterproductive torques. At the same time, the greater offsets increase the turbine's moment of inertia, meaning even the torque that is available cannot translate into angular acceleration efficiently. The combination of these aerodynamic and mechanical effects explains why the 40 cm and 60 cm offsets performed so poorly in practice.

Table 2: Results of blade peak offset investigation. A 20 cm offset provides the best balance between increased torque and low moment of inertia.

Blade Offset to one side					
Amount of offset (cm)	Moment of Inertia (kg m²)	angular speed (rad s⁻¹)	Peak Moment (Nm)	Final Moment (Nm)	Final Power (W)
0.0	6,699	0.814	131.8	72.3	58.9
20.0	6,916	0.903	140.2	65.3	59.0
40.0	7,219	0.468	142.3	64.4	30.1
60.0	7,557	0.257	73.6	68.6	17.6

Overall, the offset modification demonstrated that careful geometric tuning can improve turbine performance, but only within narrow limits. The 20 cm offset represented a "sweet spot" where the increased drag asymmetry outweighed the penalties of higher inertia and convex-side drag. Larger offsets pushed the design past this optimum, creating negative aerodynamic interactions that prevented efficient startup.

4.4. Blade Depth:

The third set of modifications focused on altering the depth of the blade. The guiding idea behind these changes was to increase the difference in drag between the concave and convex sides of the blade, since this drag asymmetry is the driving force behind torque production in a Savonius turbine.

Interestingly, the standard Savonius blade performed surprisingly well. Despite having the lowest absolute drag difference of all tested geometries, it achieved the second-highest drag-to-inertia ratio. The explanation lies in its relatively low moment of inertia. Because the standard blade has a shallower depth, less of its mass is distributed far from the axis of rotation. This reduces rotational resistance, meaning that even a modest drag difference can translate into effective angular acceleration. In other words, although it does not maximize aerodynamic performance, the standard blade geometry benefits from being mechanically lightweight.

When the blade depth was increased to 1.1 meters, the performance improved significantly. This blade achieved the highest ratio score overall, outperforming the standard design. The reason was twofold: first, the convex side of the blade produced about 3.2 N less drag compared to the standard geometry. This reduction occurred because the deeper curvature of the blade promoted smoother flow separation, allowing air to slip around the convex side with less resistance. Second, the concave side experienced a slight increase in drag, which may seem counterintuitive at first. However, this is consistent with aerodynamic theory: the deeper blade provides a larger surface area for the wind to interact with, and more surface exposure typically increases form drag. Together, these changes widened the drag asymmetry, providing more useful torque without a disproportionate increase in inertia.

As blade depth continued to increase beyond 1.1 meters, the trend of larger drag differences persisted. However, the larger moment of inertia began to dominate. Since inertia grows approximately with the square of the distance of mass from the axis, deeper blades quickly became much harder to accelerate. This diminishing return meant that the deepest blades, despite having the largest aerodynamic drag differences, actually scored the lowest drag-to-inertia ratios. In practice, this highlights a key engineering trade-off: maximizing drag difference alone does not guarantee efficiency if the turbine becomes too mechanically sluggish to respond effectively to the wind.

Table 3: Results of the blade depth investigation. A blade depth of 1.1 m yields the highest drag-to-inertia ratio, indicating optimal startup efficiency.

Blade depth					
Peak Radius (m)	Moment of Inertia of full VAWT (kg m²)	Drag Frontside (N)	Drag Backside (N)	Drag Difference (N)	Ratio
1.0	6,699	108.3	45.42	62.9	0.00939
1.1	7,047	108.7	42.17	66.5	0.00944
1.2	7,741	109.2	40.32	68.8	0.00889
1.3	8,509	109.3	38.91	70.4	0.00827
1.4	9,353	111.9	37.71	74.1	0.00793

4.5. End plates:

The fourth set of modifications tested the effect of adding end plates to the blades. End plates are often used in aerodynamic design because they limit the escape of airflow around the blade tips, thereby reducing tip vortices and improving the

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effective drag on the concave side. This design was refined over three iterative steps; each balancing drag performance with moment of inertia.

The first iteration of end plates was not particularly successful. Although the plates reduced the drag on the convex side by suppressing the low-pressure wake behind it, they also inadvertently decreased the drag on the concave side. With less air circulation being trapped inside the concave surface, the pressure differential was smaller than expected. Since both drag contributions dropped, the net drag difference increased only slightly. Unfortunately, this minor aerodynamic gain was offset by the substantial increase in moment of inertia introduced by the heavy plates. As a result, this design scored lower than even the standard turbine in terms of ratio performance.

In the second iteration, many of the sharp edges of the plates were filleted, as shown in Figure 11. This adjustment made a profound difference. By smoothing the flow path, the fillets reduced turbulence around the blade and improved pressure build-up on the concave side. At the same time, the rounded geometry allowed air to pass more cleanly around the convex side, further lowering its resistance. This combination created a stronger drag asymmetry, while the reduced mass of the plates slightly lowered the turbine's moment of inertia. The result was a dramatic improvement, with the iteration achieving a ratio score nearly 37% higher than the previous design.

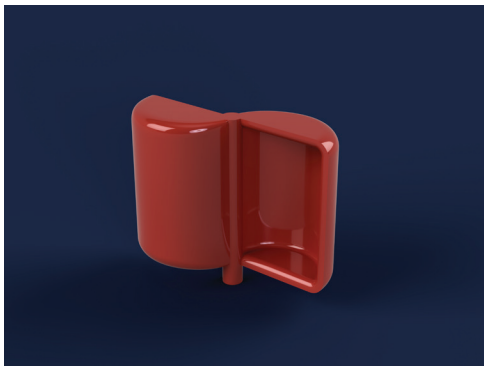

Figure 11: Second iteration of the end plate design. Filleted edges improve airflow attachment and increase drag asymmetry compared to the first iteration.

The third iteration refined the design even further by reducing the size of the plates (Figure 12). This modification sought to preserve the aerodynamic benefits of the earlier design while cutting down on mass to minimize inertia. The smaller plates maintained favorable airflow patterns, continuing to suppress turbulence and guide more wind into the concave side. At the same time, their reduced size meant that the moment of inertia was actually lower than that of the standard turbine. This combination of aerodynamic efficiency and mechanical responsiveness produced the highest ratio score of all tested geometries, outperforming the standard turbine by nearly 30% and the first plate design by an impressive 43%.

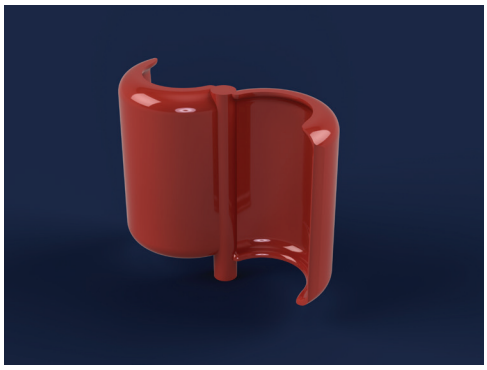

Figure 12: Third iteration of the end plate design. Reduced plate size preserves aerodynamic benefits while lowering moment of inertia, leading to improved overall performance.

Table 4: Results of the end plate study. The third iteration achieves the highest drag-to-inertia ratio by combining aerodynamic improvement with reduced inertia.

Endplates					
Design Iteration	Moment of Inertia of full VAWT (kg m²)	Drag Frontside (N)	Drag Backside (N)	Drag Difference (N)	Ratio
1	7,651	105.7	40.85	64.9	0.00848
2	7,145	109.6	26.57	83.0	0.01161
3	6,461	103.4	25.07	78.4	0.01213

4.6. Final Designs:

Drawing on the insights gained from the various geometric modifications, a final design was established by combining the most effective features: the third plate iteration, the 1.1 m blade depth, and a 20 cm peak offset, as depicted in Figure 13. In theory, this configuration should maximize drag asymmetry while limiting the mechanical downsides of an increased mass distribution, thereby producing a Savonius turbine with both strong startup torque and limited resistance to angular acceleration.

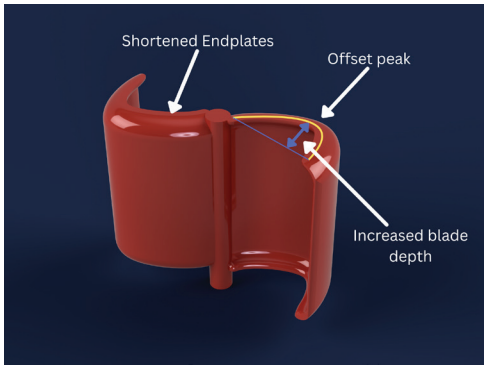

Figure 13: Final optimized Savonius turbine design. The geometry combines the most effective modifications to balance drag asymmetry and rotational inertia.

When tested, the final design did indeed outperform the standard Savonius turbine, although to a lesser degree than predicted. The optimized geometry produced a 16% higher peak torque, a 0.7% increase in peak angular velocity, and a 4% higher final power output after 150 seconds of simulation. These gains confirm that geometric refinement can yield improvements in turbine efficiency. However, the improvements

fell short of expectations, which can be attributed primarily to the higher moment of inertia introduced by the combined modifications and the standard Savonius turbine already being quite optimized as is.

From a physics perspective, the startup behavior of drag-based turbines is governed by the balance between aerodynamic drag differential (the torque-producing force) and rotational inertia (the resistance to angular acceleration). While the final design achieved the highest torque of all tested geometries, it also carried a 5% higher moment of inertia than the standard configuration. This higher moment of inertia acted as a bottleneck, slowing down acceleration and preventing the turbine from fully capitalizing on its aerodynamic improvements during the simulation time frame. The importance of this trade-off is highlighted by the performance of the 20 cm offset turbine tested earlier: despite not having the highest torque, its relatively low inertia enabled it to achieve a much higher angular velocity than other designs within the first 75 seconds, demonstrating that startup responsiveness can often outweigh peak torque in determining overall efficiency.

Conclusion

This study set out to investigate the aerodynamic optimization of Savonius-type vertical axis wind turbines (VAWTs) for potential use in low-speed, turbulent, and multidirectional urban environments, such as Berlin. Using computational fluid dynamics (CFD) simulations, several geometric modifications were tested, including variation in blade number, peak offsets, blade depth, and the addition of end plates. The results confirm that small geometric changes can have disproportionately large effects on turbine performance, particularly in the startup phase, where drag asymmetry and inertia compete to determine acceleration.

Several key findings emerged. First, reducing the number of blades to two improved startup performance by minimizing aerodynamic interference and rotational inertia, though at the cost of torque smoothness. Second, moderate peak offsets (20 cm) provided a "sweet spot" where torque was enhanced without generating excessive drag on the convex side, while larger offsets (40–60 cm) proved detrimental due to flow separation and negative torque. Third, increasing blade depth to 1.1 m improved drag asymmetry, primarily by reducing convex-side resistance, though further increases became counterproductive as inertia scaled faster than aerodynamic benefit. Finally, the addition of end plates, particularly in the third design iteration with reduced plate size and filleted edges, proved highly effective in improving drag difference while simultaneously lowering turbulence and moment of inertia.

The final optimized design, which combined these modifications, demonstrated measurable improvements in torque, angular velocity, and power output compared to the baseline turbine. However, the gains were more modest than anticipated. This result highlights the fundamental design trade-off in Savonius turbines: enhancing drag asymmetry inevitably increases mass distribution, which raises moment of inertia and limits startup acceleration. Successful optimization, therefore, requires carefully balancing aerodynamic improvements with mechanical responsiveness.

Looking forward, several directions for further research can be identified:

1. Reducing Moment of Inertia:

Future designs should aim to lower inertia without compromising structural stability, for example, by using lighter composite materials. This would improve startup performance, especially in low wind conditions.

2. Exploiting Flow Attachment Effects:

Some simulations revealed that flow attachment and redirection could dramatically enhance startup torque. Developing blade geometries that deliberately channel airflow between blades may unlock new performance gains at low wind speeds.

3. Finer Incremental Testing:

Smaller design changes (e.g., 5 cm offsets instead of 10 cm) should be tested to map performance trends with greater precision. This would help identify subtle optima that may be missed with larger increments.

4. Wake and Array Studies:

Since urban deployment often requires multiple turbines in proximity, future work should investigate the wake interactions of optimized designs. Understanding how turbines perform in series or clusters will be crucial for real-world feasibility.

5. Scaling and Dimensioning:

Finally, an important avenue is to determine the optimal size of Savonius turbines for urban areas. Larger rotors capture more wind energy but increase inertia and structural demands, while smaller turbines may respond better to turbulent urban flows.

In conclusion, while the optimized turbine presented in this study shows clear improvements over the standard Savonius design, it also underscores the complexity of balancing aerodynamic and mechanical factors in VAWT optimization. Future research that integrates aerodynamics, materials science, and urban flow modeling will be essential in developing efficient, robust, and scalable turbine solutions for the built environment.

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References

1. *World Energy Outlook 2021 – Analysis. IEA. https://www.iea.org/reports/world-energy-outlook-2021* (accessed 2025-08-22).
2. Chu, S.; Majumdar, A. Opportunities and Challenges for a Sustainable Energy Future. Nature **2012**, 488 (7411), 294–303. https://doi.org/10.1038/nature11475.
3. Tumse, S.; Bilgili, M.; Yildirim, A.; Sahin, B. Comparative Analysis of Global Onshore and Offshore Wind Energy Characteristics and Potentials. Sustainability **2024**, 16 (15), 6614. https://doi.org/10.3390/su16156614.
4. Mertens, S. Wind Energy in Urban Areas: Concentrator Effects for Wind Turbines Close to Buildings. Refocus **2002**, 3 (2), 22–24. https://doi.org/10.1016/S1471-0846(02)80023-3.

DOI: 10.36838/IJHSR811.48

5. Tsionas, I.; Llaguno-Munitxa, M.; Stephan, A. Environmental Effects of Urban Wind Energy Harvesting: A Review. Buildings & Cities **2025**, 6 (1). https://doi.org/10.5334/bc.491.
6. Wilke, A.; Shen, Z.; Ritter, M. How Much Can Small-Scale Wind Energy Production Contribute to Energy Supply in Cities? A Case Study of Berlin. Energies **2021**, 14 (17), 1–20.
7. Stathopoulos, T.; Alrawashdeh, H.; Al-Quraan, A.; Blocken, B.; Dilimulati, A.; Paraschivoiu, M.; Pilay, P. Urban Wind Energy: Some Views on Potential and Challenges. Journal of Wind Engineering and Industrial Aerodynamics **2018**, 179, 146–157. https://doi.org/10.1016/j.jweia.2018.05.018.
8. Al-Rawajfeh, M. A.; Gomaa, M. R. Comparison between Horizontal and Vertical Axis Wind Turbine. IJAPE **2023**, 12 (1), 13. https://doi.org/10.11591/ijape.v12.i1.pp13-23.
9. Berlin Climate, Weather By Month, Average Temperature (Berlin, Germany) - Weather Spark. https://weatherspark.com/y/75981/Average-Weather-in-Berlin-Germany-Year-Round (accessed 2025-08-13).
10. Accurate Berlin Wind Forecast | See Average Wind Speed. World Weather & Climate Information. https://weather-and-climate.com/average-monthly-Wind-speed,Berlin,Germany (accessed 2025-08-13).
11. Ansys Fluent – Computational Fluid Dynamics Software. Ansys Inc. https://www.ansys.com/products/fluids/ansys-fluent (accessed 2025-08-11).
12. Autodesk Fusion – Integrated CAD, CAM, and CAE Software. Autodesk Inc. https://www.autodesk.com/products/fusion-360/overview (accessed 2025-08-10).
13. Rezaeiha, A.; Montazeri, H.; Blocken, B. Towards Accurate CFD Simulations of Vertical Axis Wind Turbines at Different Tip Speed Ratios and Solidities. Renewable and Sustainable Energy Reviews **2019**, 111, 1–17. https://doi.org/10.1016/j.rser.2019.05.030.

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RESEARCH ARTICLE

AI On Trial: A Holistic Review Of The Promise And Perils Of Artificial Intelligence In The Practice Of Law

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ABSTRACT: While Artificial Intelligence (AI) holds the potential to dramatically enhance the efficiency and accessibility of legal systems, its integration into the legal field also poses deep structural and ethical challenges. This paper offers a comprehensive synthesis of the debate, bringing together three critical dimensions often examined in isolation: (1) AI's benefits in enhancing legal workflows, outcome prediction, and advanced research; (2) the threats posed by bias, opacity, and unequal access; and (3) the ethical frameworks required to govern its use. By weaving these perspectives together, the paper provides a uniquely holistic lens for understanding not only what AI can do for law but also what it risks taking away if left unchecked. Our analysis argues that any integration of AI in law must be guided by robust legal frameworks capable of embedding principles of justice, explainability, and human oversight into AI systems from the beginning. This review thus serves as both a caution and a roadmap: the goal is not to resist technological change but to ensure that it serves the values at the heart of democratic legal systems rather than undermining them, offering space for responsible innovation rooted in legal integrity and justice.

KEYWORDS: Robotics and Intelligent Machines, Machine Learning, Legal Ethics, Artificial Intelligence, Algorithmic Bias.

Introduction

Imagine a courtroom where a machine identifies the most relevant case precedents, predicts the likely verdict, and proposes the optimal litigation strategy, all within seconds. Though this may sound like a scene from a fiction movie, it reflects the accelerating reality of artificial intelligence (AI) in the legal field.

The intersection of AI and law is not new; it has a rich history that set the foundation for today's rapid advancements. Its roots extend back over half a century, from the 1970s research on legal reasoning and logic, through the 1980s development of expert systems and case-based reasoning, to even earlier inquiries by legal scholars and mathematicians like Gottfried Leibniz in the 1600s, who envisioned applying mathematical thinking to law.[1] With AI tools already automating contract reviews, aiding judicial risk assessment, and transforming litigation research, law has become a central domain of AI disruption.

Artificial Intelligence has emerged as a transformative force in the legal profession since the mid-2000s, particularly in the wake of the so-called Industry 4.0 era, which has ushered in data-driven automation across industries. As a consequence, the legal field, once characterized by time-intensive manual processes, now stands on the cusp of a major shift.[2] The most immediate and widely discussed impact of AI is its transformative potential in improving efficiency and accuracy in legal practice. Multiple studies detail how machine learning systems can streamline outcome prediction, contract analysis, and litigation strategy, opening the door to faster decision-making and cost-effective legal services.

AI-driven platforms like ROSS Intelligence, Blue J Legal, and eBrevia can process vast legal datasets at unprecedented speeds, dramatically reducing the time and cost of legal research and document analysis. For instance, JPMorgan's COIN program is able to process and extrapolate specific details from over 12,000 contracts in mere seconds, saving the firm more than 36,000 billable hours annually.[3] Predictive analytics allow lawyers to assess litigation risks more objectively, while Natural Language Processing (NLP) enables the real-time parsing of legal documents, transforming the way in which legal arguments are crafted.[3] These capabilities are not just acting as technical upgrades, but are reframing the legal landscape by enabling a more strategic and data-informed approach to law.

However, while AI technologies have already demonstrated their value in streamlining legal workflows and augmenting decision-making processes among judges and scholars alike, they also raise critical legal and ethical concerns about bias, transparency, data privacy, and due process. As pointed out in "Artificial Intelligence and Law: An Overview" by Harry Surden, current machine-learning models often operate by themselves, so that the rationale behind a prediction or decision is obscure even to its creators.[1] Thus, when courts begin to rely on algorithmic risk assessments, there is a danger that these systems may encode and reproduce the very biases present in their training data, potentially undermining the fairness of legal proceedings.

Further, the growing deference to AI-generated outputs threatens to erode the authority of human legal professionals. Legal scholars such as Rosengrün (2022) argue that AI is increasingly acting as the de facto regulator of legislation and of entire societies, shaping legal norms and decisions without democratic oversight.[4] This shift raises the question of whether AI's efficiency gains are coming at the expense of some of law's most fundamental values: accountability, interpretability, and human judgment. Additionally, legal decisions are gradually being abstracted into coded logic, making it more difficult for

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individuals to contest, or even fully understand, the processes that affect their rights.

Adding to these concerns is the issue of unequal accessibility concerning a digital divide that could exacerbate existing inequalities in access to legal representation and justice. Moreover, over-reliance on these tools may contribute to the demeaning of legal professionals, diminishing the emphasis on human reasoning and critical judgment that have long defined the legal profession.

Similarly, though these systems would require less expertise and work, without adequate oversight, AI may also embed systemic biases into legal processes, reproducing social inequalities under the guise of objectivity. In addition, issues like AI hallucinations, which are very common and not transparently noted by the system when they happen, increase the risks of untrue and unobjective facts being presented to the court.

Overall, these developments point to an urgent need for a regulatory and ethical framework that can accommodate innovation while safeguarding justice. As noted by Getman *et al.*, responsible integration of AI into the legal system requires more than technological refinement; it demands interdisciplinary engagement and normative reflection.[5]

This paper undertakes a critical analysis of the impact and ethical use of AI within the U.S. legal field, drawing examples from other jurisdictions where relevant, with peculiar attention to legal research, litigation, and decision-making. It explores the promises and perils of this shift, analyzing how AI is reshaping legal practices, where it risks undermining core legal values, and the ethical guardrails around its deployment. By drawing on both academic literature and real-world applications, the analysis aims to trace the dual-edged nature of AI's influence on legal practice, an intersection where the stakes are nothing less than the future of justice itself.

Examining AI's role in the legal profession is extremely important nowadays. Developments in AI technologies mean that algorithmic decision-making is no longer hypothetical, but it is actively shaping access to justice, the fairness of proceedings, and public trust. Without critical evaluation, the promise of AI could come at the expense of accountability and transparency; thus, understanding both its potential and perils is essential to ensuring that technological progress strengthens the core values of the legal system. Ultimately, the paper seeks to outline the existing relationship between artificial intelligence and legal practice and to present the path forward as one that embraces the opportunities of AI without losing sight of justice, fairness, and integrity.

To structure this inquiry, the exploration is divided into three thematic sections: the benefits of AI in legal practice, the threats it poses to legal institutions and professional judgment, and the principles guiding the ethical uses of AI within law. To unpack these questions, this paper adopts a critical review methodology, drawing exclusively on a wide body of scholarly work to provide a balanced and evidence-driven understanding of the intersection of AI and law.

Section I: The Benefits of AI in Legal Practice

Artificial Intelligence has already proven to be a tool that is reshaping how law is researched and argued by streamlining workflows, enhancing predictive accuracy, and expanding the scope of legal research. Consequently, these technologies are enabling law practitioners to operate with unparalleled efficiency and precision. This section examines how AI augments legal practice and argues that these benefits could wholly redefine the role of legal professionals in the 21st century. Specifically, we address the benefits of AI in: 1) enhancing efficiency in legal workflows; 2) improving the prediction of legal outcomes; and 3) enabling more advanced, data-rich legal research and problem solving. Together, these advancements point to an evolving professional ecosystem where human expertise and machine intelligence operate in tandem.

A. Enhancing efficiency in legal workflows:

The legal profession, once defined by hours of manual document review, citation checks, and precedent hunting, is undergoing a transformation powered by technological software that is automating routine tasks and dramatically reducing the time required for traditionally labor-intensive legal tasks. According to Assistant Professor Shanin Kabir, the software of Kira Systems, founded by Noah Waisberg, can speed up the process by up to 40% for first-time users and up to 90% for experienced users.[3] In addition, eBrevia, founded by Ned Gannon and Adam Ngueyn, claims to be able to review over 50 documents in under a minute with accuracy rates surpassing manual review by approximately 10%.[3] For example, Lawgeex claims to reduce contract review time by up to 80% and costs by 90%. These kinds of operational improvements free up legal professionals to focus on strategic planning rather than repetitive review tasks and save up time and resources for lawyers, clients, and law firms. According to Harry Surden, technology-assisted review and predictive coding now allow lawyers to efficiently filter through millions of documents, a process that would previously have required teams of paralegals working for weeks.[1] Consequently, these systems are not merely speeding up work but are redefining what is feasible within litigation timelines and transforming the due diligence process by raising efficiency, reducing errors, and automating various tasks.

Machine learning, which involves the development of computer systems that are able to learn and adapt without explicit instructions, is currently the most impactful approach to Artificial Intelligence. AI tools operate through machine learning systems, whose rise has been fueled by a massive increase in the amount of data on the Internet, to "learn" from user feedback and patterns and incorporate the findings into their results, and, as more data gets added over time, improve the rates of accuracy and precision. As a consequence, the results of AI research are often similar to those a human would've reached, over a much longer period of time, without ever even reaching human-level cognition. Algorithms like this can be used to assist lawyers by extrapolating the relevant information within hundred-page-long documents, identifying the core legal

principles at stake, and predicting case outcomes. In general, AI works extremely well for tasks that have clear, definite, and unambiguous patterns, such as Surden mentions, chess, fraud detection, and tumor identification. [1]

Moreover, AI's ability to assist in the drafting of legal documents is another major area of impact. Automating legal drafting through pattern recognition and data extraction enables rapid production of contracts and pleadings that comply with jurisdiction-specific requirements.[2] While human oversight remains essential, AI dramatically reduces the time needed to produce reliable, legally sound drafts.

B. Prediction of Legal Outcomes:

Beyond efficiency gains, AI's ability to analyze large datasets also enables powerful predictive tools that help lawyers forecast legal outcomes and make more data-driven strategic decisions, especially in the early stages of litigation. In their paper, Alarie *et al.* emphasize that while traditional human judgment often relies on intuition and experience, such "quick and dirty" predictions are frequently unreliable and prone to bias.[6] Drawing from decades of studies across various fields, including parole decisions, medicine, and insurance, the authors demonstrate that formal, algorithmic methods consistently match or surpass human judgment in predictive accuracy.[6] This foundational insight applies equally to the legal field, where data-driven analytics can provide more objective and reliable forecasts than lawyers working unaided by technology. One of the central challenges in applying predictive analytics to law has historically been the availability and usability of data. Nowadays, however, given that most documents are electronically published, research and discovery are way more accessible to people who don't have the resources normally required to initiate, continue, or respond to a lawsuit, including time and money. John Markoff, in fact, wrote in the New York Times that e-discovery software can analyze documents in a fraction of the time for a fraction of the cost. For instance, Blackstone Discovery of Palo Alto, California, analyzed 1.5 million documents for less than $100,000.[7] For example, Alarie *et al.* say that more than one million Canadian court and tribunal decisions are publicly accessible through platforms like CanLII.[6] Additionally, regulators such as the Canada Revenue Agency and securities commissions publish vast numbers of rulings and decisions, creating a rich dataset that far exceeds the capacity of any individual lawyer to fully absorb.[6] Thus, by processing this diverse data, AI algorithms can detect patterns and generate predictions about legal outcomes that are both faster and more accurate than human analysis alone.

Moreover, the advantages of AI-driven prediction extend beyond accuracy as they operate at a remarkable speed, delivering predictions within seconds or minutes, in stark contrast to the often lengthy deliberation human lawyers require. Furthermore, unlike humans, algorithms do not suffer from fatigue, emotional fluctuations, or inconsistent judgment, factors that could compromise decision quality. This consistency is particularly valuable in legal contexts where impartiality and fairness are paramount. In addition, Alarie and his colleague mention how machine learning algorithms, including neural networks, pioneered by experts like Professor Geoff Hinton, learned from data to identify hidden connections between variables and outcomes without relying on restrictive assumptions.[6] This is extremely useful as these algorithms automatically adapt to complex patterns, improving the precision of legal predictions.[6] The authors also caution about the importance of data quality in machine learning applications. The famous "garbage in, garbage out" principle applies: if the input data is flawed or poorly curated, the predictive model's outputs will also be unreliable. Nonetheless, with well-curated data and robust model selection, machine learning offers significant improvements over traditional statistical techniques.[6]

Looking toward the future, we can foresee an exponential increase in computing power and cognitive computing capabilities, such as natural language processing, which will enable AI systems to process data like court opinions and rulings more effectively. By analyzing millions of data points, these algorithms reduce inconsistencies and errors, helping to avoid unnecessary detentions and associated social and financial costs. Such uses of AI illustrate the broader impact of predictive tools in promoting fairness and efficiency in the justice system. Furthermore, by providing clearer predictions about likely outcomes, these technologies increase the probability of settlement and reduce litigation, focusing court resources on genuinely ambiguous cases where legal development is most valuable.[6] As machine learning tools become more sophisticated and widespread, lawyers may face legal obligations to incorporate these technologies into their due diligence processes, ensuring that advice and litigation strategies are informed by the best available data-driven predictions.

Blue J Legal:

Many aspects of the legal landscape, in its complexities, are often described as grey areas, where no single fact is dispositive, and outcomes hinge on how courts weigh an interrelated web of considerations. For lawyers, this means navigating an enormous volume of precedent cases, each with subtle factual differences that can influence the final determination. The challenge of thoroughly researching and interpreting hundreds of relevant decisions makes providing confident legal advice difficult and resource-intensive. In this context, a compelling example presented by Alarie *et al.* is Blue J Legal, a Toronto-based startup that harnesses machine learning to predict legal outcomes in Canadian courts, particularly in tax law, by analyzing thousands of past cases and identifying the patterns that underlie judicial decisions.[6] Rather than relying on simple checklists or formulas, their algorithms evaluate multiple variables simultaneously, learning from the complex interactions among factors that human researchers might overlook. This technology significantly improves the speed and accuracy of predicting case outcomes, also quantifying the likelihood of the predicted outcome, giving lawyers a powerful tool to cut through ambiguity and focus on the most relevant precedents. This capacity to model uncertainty and reveal the grey zones within the law is particularly valuable in disputes where facts may be contested or open to interpretation.

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Beyond enhancing individual case assessments, Blue J Legal's system also incorporates user feedback to refine its models continuously. By aggregating diverse professional judgments, the platform mitigates individual biases and provides a more balanced and reliable analysis over time. This decentralized learning process ensures that the tool evolves alongside the law itself, adapting to new cases and shifting legal standards. Ultimately, such innovation promises to reduce costly litigation by helping parties and their lawyers reach clearer, more informed agreements early in the process and empowering more confident and efficient legal decision-making.

C. Advanced Legal Research and Problem Solving:

AI's impact on legal research is similarly transformative. Historically, legal research was an arduous, manual endeavor, requiring hours of combing through case reporters, statutes, and secondary sources. This process, though thorough, was time-consuming, susceptible to incomplete or outdated information, and inherently limited in its capacity to explore the full breadth of available legal data. Today, AI engines not only save time but also often uncover relevant materials that traditional searches might miss, enhancing the depth and quality of legal arguments.[11] Modern AI systems bring together natural language processing (NLP), machine learning (ML), and predictive analytics to conduct complex legal research in ways that mimic, yet significantly amplify, the cognitive processes of experienced attorneys. NLP enables semantic search, allowing queries to be posed in natural language rather than through rigid keywords, while ML models learn from patterns in data to refine their results over time. Systems such as ROSS Intelligence, Lexis, and CaseMine exemplify this shift, enabling lawyers to ask sophisticated legal questions and receive highly targeted results.[11] In practice, this means lawyers can uncover precedents and legal arguments that traditional search approaches might overlook, increasing both the depth and quality of their reasoning. For instance, BakerHostetler's use of ROSS Intelligence in its bankruptcy department, navigating 27 terabytes of data and delivering rapid and precise answers, illustrates the transformative potential of such tools.[3]

The expanding range of commercial AI tools demonstrates the width of these applications and underscores how automation enhances strategic decision-making across legal practice. LEVERTON, an offshoot of the German Institute for Artificial Intelligence, uses AI-powered data extraction to process contracts in over 20 languages, extracting key financial and operational details such as rent, maintenance obligations, and expiration dates, and presenting them in a structured spreadsheet format to expedite real estate due diligence.[3] This showcases AI's ability to distill complexity into actionable understanding.

Furthermore, ThoughtRiver's Fathom Contextual Interpretation Engine, developed with Cambridge University expertise, similarly demonstrates AI's capacity to interpret nuance: by automatically flagging risky clauses and generating plain-language summaries, it enables faster and more consistent risk assessments.[3] Legal Robot and Casetext's CARA extend this capability further; the former converts legal text into numerical representations for machine analysis, automatically flagging potential issues for human review, while the latter anticipates opposing arguments and surfaces relevant precedents, aiding lawyers in proactive litigation strategy. Each of these tools exemplifies AI's ability to integrate vast, disparate legal data into coherent insights. In addition, while early systems were hampered by cost and computational limitations, modern AI systems incorporate heuristic methods that allow them to improve with use and to recognize complex, non-linear relationships in data.[8] Together, these examples reveal that AI's true advantage lies not merely in efficiency, but in augmenting the lawyer's cognitive toolkit, transforming legal research into a predictive, interpretive, and ultimately more strategic form of problem-solving.

AI's strengths also lie in enhanced information retrieval and the mechanization of juridical activities. It can quickly locate the relevant legal texts, precedents, and studies across multiple jurisdictions and levels of law while simultaneously integrating administrative regulations, judicial decisions, and academic commentary.[10] This capacity allows AI to detect contradictions between sources, reveal ambiguities in legal provisions, and even propose innovative legal solutions that advance the doctrine of law. By bridging different branches of law, AI supports a more holistic, cross-disciplinary approach to legal problem-solving, enabling insights that human researchers might overlook. Moreover, centralized legal information systems, powered by AI, could provide courts, legislatures, and administrative agencies with immediate, consistent access to the same high-quality legal data, reducing duplication of effort and fostering a more coherent application of law across jurisdictions.

In sum, the integration of AI into legal practice has already transformed the profession's capacity to work with unprecedented speed, depth, and accuracy. Taken together, these developments show that AI is not merely an auxiliary tool but a transformative force capable of redefining the very mechanics of legal work by streamlining processes and uncovering insights and connections that might otherwise remain hidden. This evolution marks a decisive shift from merely retrieving information to generating richer, more nuanced legal reasoning. Yet, as these tools become more sophisticated and deeply embedded in legal workflows, they inevitably surface new questions about their influence on the profession's methods and values that demand careful consideration in the broader conversation about AI's role in law.

■ Section II: Threats of AI on the Legal Practise

While the advantages of artificial intelligence in legal practice are compelling, its rapid adoption also introduces profound risks that threaten the integrity of the profession. These risks are not speculative but already visible in the ways AI is reshaping legal workflows, reasoning, and access to justice. Scholars warn that unchecked reliance on algorithmic systems could erode professional expertise, distort outcomes through biased or flawed data, exacerbate inequalities in access to legal resources, and undermine transparency and accountability at the core of the rule of law. These concerns reveal that AI's influ-

ence extends beyond efficiency gains into the very structure of legal reasoning and practice. In order to fully understand the stakes, it is necessary to examine the specific domains in which AI poses threats.

A. Erosion of Legal Expertise and Over-Reliance on AI:

One of the most pressing threats posed by AI in legal practices is the risk of eroding professional expertise through over-reliance on automated systems. The legal profession has long been structured around a system of apprenticeship, where junior associates traditionally develop analytical ability, familiarity with legal sources, and judgment through labor-intensive processes such as reviewing documents, cross-checking citations, and drafting pleadings under the supervision of senior colleagues. This "apprenticeship model," though repetitive and time-consuming, formed the bedrock of professional development, allowing young lawyers to cultivate the analytical habits, interpretive skills, and contextual knowledge that underpinned independent judgment. Yet, as Harry Surden observes, the rapid adoption of machine learning tools such as predictive coding, e-discovery platforms, and automated contract analysis is transforming the very work that once trained generations of lawyers.[12] While this enhances efficiency, these technologies, by processing millions of documents at speeds far beyond human capacity, are gradually supplanting the entry-level tasks that were once essential for developing professional competence.

This concern reflects a broader "deskilling" effect that legal scholars have begun to document in which lawyers become passive consumers of algorithmic outputs rather than active interpreters of legal texts. This threatens to demolish the rigor of the legal system, where the value of arguments depends not only on citing precedent but also on deploying creativity, contextual nuance, and rhetorical judgment. If AI systems are allowed to dominate core tasks, lawyers may gradually defer to machine-generated results without interrogating their accuracy or context, thus producing a generation of lawyers whose interpretive instincts are underdeveloped. AI tools such as Lawgeex or eBrevia, capable of reviewing contracts with greater accuracy and speed than human paralegals, might save clients money and streamline transactions, but they also eliminate countless hours of hands-on experience that previously helped junior associates learn how to spot subtle issues, weigh alternative interpretations, and anticipate opposite arguments. Under this lens, a legal culture shaped by over-reliance on AI risks elevating efficiency above interpretive quality, eroding the human capacities that give the law its adaptability.

Historical perspectives reinforce the gravity of this problem. Early computer scientists working on automated legal reasoning already anticipated that computers would eventually outperform humans in the speed and thoroughness of data retrieval, but they also implicitly assumed that lawyers would always remain central to the discipline.[6] If lawyers instead abdicate these interpretive responsibilities to machines, the result may be not just efficiency gains but also a narrowing of legal imagination. Additionally, humans often cannot fully articulate the reasoning rules they use when solving complex problems; thus, this inability to "teach" the computer everything makes the role of human oversight irreplaceable. Over-reliance on AI risks collapsing this delicate balance, creating a profession that prizes output speed but sacrifices intellectual depth.

This danger becomes most visible in contexts such as predictive coding and automated drafting. For instance, predictive coding software, widely used in e-discovery, can filter out millions of irrelevant documents with minimal human input, leaving lawyers with a smaller subset of potentially relevant materials.[12] While this undoubtedly increases efficiency and saves resources, it also strips lawyers of the experiential learning that comes from sifting through large volumes of material, spotting unexpected connections, and developing intuition about patterns of evidence. Similarly, AI-assisted drafting tools such as those offered by Kira Systems or ThoughtRiver use pattern recognition and clause libraries to generate contracts or risk assessments that once required hours of human labor. These outputs may be accurate within established parameters, but they deprive junior lawyers of the opportunity to practice drafting from scratch. In the short term, this saves time and reduces costs, but in the long term, it risks depriving lawyers of the opportunity to cultivate the judgment necessary to adapt forms creatively to new contexts.

Over-reliance also invites complacency at higher levels of the profession. Even experienced lawyers may be tempted to defer to machine-generated outputs, especially when these are presented with the confidence of quantitative scores or forecasts that project an aura of objectivity. Lawyers, accustomed to reasoning in qualitative, argumentative terms, may find themselves increasingly deferring to these apparently "scientific" measures. The danger is not that AI will replace judgment outright, but that it will subtly reorient decision-making around what the system identifies as most "probable" or "relevant," sidelining considerations that fall outside its parameters. This is particularly troubling in "grey area" cases, where outcomes hinge on how judges balance competing principles. If lawyers grow accustomed to leaning on these outputs without supplementing them with human interpretive skills, the profession risks narrowing its engagement with ambiguity and uncertainty. In addition, by reducing the need for armies of junior associates to conduct research and document review, AI may risk reducing job opportunities for many workers as large firms may shrink their base, relying on a smaller cadre of associates supported by powerful technological platforms. Thus, if the interpretive skills of human workers are allowed to erode under the weight of automation, the law may become faster and cheaper but also narrower, less adaptable, and less humane.

B. Bias, Error, and the Limits of Data-Driven Reasoning:

If efficiency and prediction are the headline advantages of AI in legal practice, the flip side is that these very capacities depend heavily on the quality, neutrality, and completeness of data. Unlike human lawyers, who can contextualize facts, weigh competing values, and recognize when precedent should not be followed, AI systems reason primarily by detecting patterns in historical datasets. This reliance introduces vulnerabilities that can produce errors, perpetuate biases, and distort outcomes in

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ways that threaten the legitimacy of legal decision-making. A central principle in machine learning is that outputs are only as good as their inputs (the classic "garbage in, garbage out" problem that was already mentioned).[9] If a dataset is mistaken and reflects historical inequalities, prejudiced judgments, or incomplete records, an algorithm trained on that data will reproduce and amplify those biases. Yet, when presented as "objective" or "data-driven", such outputs risk reinforcing discriminatory practices under the guise of neutrality. In law, where decisions carry immense social consequences, this is not a theoretical issue but a tangible danger.

Beyond bias, the sheer complexity of legal reasoning exposes the limits of AI's pattern-based logic. While machine learning excels in domains with clear, unambiguous rules, like chess, the law is replete with grey zones. Many disputes hinge not on straightforward fact-matching but on competing interpretations, normative judgments, and context-specific equities. For instance, two cases may share factual similarities but diverge in outcome because a court interprets a principle differently, or because broader social or constitutional values are at stake. An AI trained on surface-level textual patterns may miss these subtleties, producing results that are technically accurate in a statistical sense but shallow jurisprudentially. This limitation reveals the risk of "automation bias," in which lawyers or judges place undue confidence in outputs that seem precise but fail to capture the law's depth.[12]

Errors, too, manifest in ways unique to AI systems. Unlike human lawyers, who are constrained by rules of logic, evidence, and professional responsibility, AI models, particularly large language models, are prone to "hallucinations." This phenomenon occurs when an AI system generates information that is false but presented with the same stylistic confidence as genuine knowledge. In legal research, this can mean fabricating case law, misquoting statutes, or citing precedents that do not exist. In 2023, for example, a New York attorney was sanctioned after ChatGPT, an OpenAI algorithm, generated a legal brief citing six entirely fictitious cases.[12] Even when AI systems retrieve real cases, they may misstate holdings, omit key limiting facts, or misinterpret their doctrinal weight, producing outputs no competent human researcher would accept. The danger lies not merely in occasional errors but in the difficulty of detecting them, because, unless outputs are meticulously verified by human lawyers, hallucinations can pass unnoticed, corrupting arguments and misleading courts. For instance, the case of Mata v. Avianca brought national attention to the ethical pitfalls of using AI. In this instance, two attorneys submitted AI-generated materials in a brief, which' included six fabricated cases, resulting in a sanction under Federal Rule of Civil Procedure Rule 11.[13,14] This underscores how AI, at least at the still underdeveloped stage it is at currently, cannot replace the lawyer's fundamental duty of diligence and independent verification.

Compounding these risks is the opacity of error detections, as traditional legal research, however tedious, offers transparent lines of accountability: a lawyer cites a case, and opposing counsel or the court can verify it. With AI-driven research, by contrast, errors may be buried within opaque "black box" models that provide no clear explanation of how results were generated. Commentators stress that the lack of transparency and explainability undermines accountability, as lawyers cannot easily reconstruct the algorithm's reasoning or test its assumptions. This not only heightens the risk of unintentional reliance on flawed results but also raises difficult questions of professional responsibility, since any errors introduced by AI ultimately remain the lawyer's liability. In addition, the limits of data-driven reasoning are further highlighted by jurisdictional and linguistic complexities. AI models, trained primarily on U.S. or English-language legal data, may perform poorly in other jurisdictions, failing to capture civil law tradition or multilingual statutes.[10] Errors introduced by such blind spots could disadvantage lawyers and litigants in non-dominant legal systems, widening global inequities in access to reliable AI tools.

What makes these problems particularly troubling is the perceived authority of AI outputs because AI tools are marketed as faster and smarter than any individual. Ultimately, law is not simply the retrieval of precedent but the balancing of competing values, the weighing of fairness alongside consistency, and the capacity to innovate beyond past data. By contrast, AI's outputs are tethered to historical patterns and probabilities. This mismatch means that errors, hallucinations, and biases are not accidental flaws but structural byproducts of current AI design. Until systems can provide verifiable, context-sensitive reasoning with transparency and accountability, they will remain valuable aids, but ones whose outputs demand rigorous human oversight.

C. Bias, Inequality, and Access to Justice:

The integration of artificial intelligence into legal systems also has profound implications for fairness, equality, and accessibility. At its core, the rule of law is premised on legal certainty, equality before the law, and equal access to justice, yet AI often threatens these very principles by replicating existing biases, amplifying socioeconomic disparities, and transforming law from a system of human accountability into one governed by opaque code. Scholars warn that this shift risks moving society from a rule of law to a "rule of code," where algorithms and the corporations controlling them exercise regulatory authority without transparency or democratic oversight.[4] This transformation has practical consequences across legal practice, from automated decision-making in welfare systems to predictive policing and e-discovery, and these consequences disproportionately affect disadvantaged groups.

One of the most striking examples of algorithmic bias undermining justice comes from the Netherlands, where the SyRI fraud detection system flagged hundreds of families for welfare fraud. The algorithm disproportionately tagged lower-income neighborhoods and migrant communities, compelling many families to repay benefits they had rightfully received. Ultimately, a Dutch court struck down the system for violating privacy rights and enabling socioeconomic discrimination, underscoring the dangers of entrusting opaque algorithms with high-stakes legal determinations.[9] This example demonstrates how AI, far from correcting human error, often exacerbates ex-

isting inequalities by embedding them into technical systems presented as objective and neutral.

The reliance of AI tools on historical data also undermines the impartiality of legal decision-making. Machine learning models learn from precedent, but when that precedent reflects discriminatory practices, the models inevitably reproduce those injustices. This reliance on "the world as it was" risks turning law into a backward-looking mechanism that perpetuates entrenched inequities rather than enabling progress toward justice.[12] Far from democratizing access, automation can exacerbate exclusion by making high-quality legal services increasingly scarce and expensive while proliferating lower-quality automated alternatives for those least able to contest their shortcomings. Moreover, AI also undermines access to justice by destabilizing employment and reshaping the legal profession in ways that affect service provision, illustrating the tension between efficiency and equity. This could have serious consequences for accessibility, as fewer trained lawyers may limit the diversity and reach of legal services available to ordinary citizens.

Data privacy further complicates the picture as AI systems rely on massive datasets to function effectively, but the collection and analysis of sensitive legal information create significant risks of misuse, surveillance, and breaches of confidentiality. Legal data, including client files, case histories, and personal records, is particularly sensitive and must be handled with robust safeguards. In her paper, Dr. Madaoui Nadjia emphasizes the importance of encryption, access controls, and compliance with data protection laws such as the GDPR to prevent unauthorized access or misuse of legal information.[9] Yet the sheer volume of data required for machine learning increases the likelihood of vulnerabilities, while the opacity of many AI systems makes accountability for breaches difficult to enforce.[9] In this way, the integration of AI into legal practice can weaken client trust and undermine one of the cornerstones of the profession: confidentiality.

The broader societal consequences of AI in law highlight the risk of democratic erosion. When code begins to function as law, regulation shifts away from transparent, contestable processes toward technical architectures controlled by private corporations.[4] Search engines determine which firms and cases are visible, predictive systems shape outcomes in dispute resolution, and contract enforcement becomes automated. These developments place critical legal functions outside of public oversight, empowering corporate actors to influence legal processes in ways that may prioritize efficiency or profit over fairness and equality. Even regulatory initiatives such as the EU Artificial Intelligence Act often risk entrenching corporate control rather than limiting it, thereby legitimizing the very systems that threaten to undermine access to justice.[4] Taken together, these developments reveal that the risks of bias, inequality, and limited access to justice are not incidental side effects of AI adoption but structural consequences of its integration into law. As a result, ensuring that legal systems remain equitable and accessible will require sustained vigilance, stronger safeguards, and recognition that technological progress is not synonymous with justice.

Taken together, these concerns demonstrate that while AI offers unprecedented speed and efficiency, its unchecked integration into legal practice threatens to erode the very foundations of the professions. The keyword being "unchecked," over-reliance on automated systems risks hollowing out legal expertise, flawed or biased data undermines the legitimacy of outcomes, errors and hallucinations reveal the limits of probabilistic reasoning, and opaque, unevenly distributed technologies jeopardize transparency, fairness, and equal access to justice. What emerges is not simply a technical challenge but a structural one: the profession's ability to preserve its standards of judgment, accountability, and equality before the law is at stake. These risks underscore the urgency of ensuring that AI remains a tool subject to law and ethical oversight, rather than an obscure authority that reshapes legal practice on its own terms.

Section III: Ethics

As previously seen, artificial intelligence promises several transformative benefits for the legal profession, yet its integration raises profound ethical challenges regarding fairness, transparency, privacy, accountability, and the preservation of human judgment. As scholars have frequently emphasized, AI is not merely a neutral tool but one that can either reinforce existing inequities or help expose them. Our position on the matter is clear: AI is inevitable and potentially beneficial, but its deployment must be bounded by human oversight and guided by ethical principles.

A. Core ethical issues:

Going back to section 2, bias and fairness remain some of the most significant risks in applying AI to legal contexts. These systems risk embedding systemic injustice into legal decision-making; thus, researchers underscore that addressing such algorithmic biases requires rigorous auditing and the use of diverse, representative datasets. Indeed, as Surden notes, one of the greatest disadvantages of AI in the legal system lies in its data dependency and bias. Because AI learns patterns from historical data that may already reflect social or institutional inequalities, its outputs risk reproducing and amplifying these same biases in ways that are difficult to detect or correct, creating a dangerous illusion of objectivity.[15] Without proactive measures, algorithms may keep perpetuating socioeconomic, racial, or gender-based inequities. At the same time, AI can serve as a diagnostic tool to uncover discriminatory human patterns; thus, bias is both a threat and an opportunity in that AI can exacerbate injustice, but it can also reveal inequities that warrant reform.

Moreover, many AI systems operate as "black boxes" and lack explainability behind their decisions, which raises several concerns over the transparency of their actions and decisions. Scholars warn that explanations like " the statistical model determined this outcome" are insufficient to prove legitimacy, as legal systems demand meaningful, interpretable reasoning that respects the right to be heard. Accountability is similarly at stake. Nadjia stresses the need for comprehensive guidelines

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and codes of conduct for AI developers and legal professionals to ensure responsibility does not dissipate into technical systems.[9] When AI contributes to an unjust outcome, the question of whether responsibility lies with the developer, judge, or lawyer cannot remain unanswered; thus, clear frameworks are required to delineate responsibility and prevent the deflection of blame to the algorithm.[5]

In the legal field, particularly, privacy and data protection concerns are magnified because of the vast amount of sensitive documents and case records that are at stake. Getman and his coworkers highlight the importance of encryption, access controls, and role-based data permissions to preserve confidentiality.[5] As a result, compliance with data-protection laws such as GDPR is essential, requiring informed consent and transparency in processing.

B. Our Recommendations for Ethical AI Use:

Drawing on these concerns and the literature, we propose the following principles for responsible integration of AI into the legal system:

1. Human Oversight is Essential:

AI should augment, not replace, human judgment. Judges, lawyers, and policymakers must remain accountable for outcomes, with AI outputs treated as advisory rather than determinative. Oversight mechanisms could include mandatory human review of any AI-generated recommendation, periodic audits of AI-assisted decisions, and possibly explicit documentation of how AI influenced the decision-making process. This would ensure that professional responsibility remains central, mitigating the risk that overreliance on AI diminishes human accountability.

2. Mandated transparency and explainability:

AI systems must provide both technical transparency and user-facing explanations. Technical transparency would involve audit trails, documentation of model logic, and logging of inputs/outputs. User-facing transparency means that litigants, lawyers, and judges can understand how the AI reached its conclusions in plain language. This would address the "black box" problem, preserve trust, and ensure decisions are interpretable and contestable.

3. Rigorous bias and equity safeguards:

AI should undergo systematic bias testing before deployment and prioritize fairness to reduce the risk of perpetuating historical injustices. This involves auditing datasets for representativeness, employing fairness metrics, and running simulations to detect disparate impacts on different demographic groups. Moreover, AI can be used proactively to identify structural inequities in existing human practices. Implementation strategies include third-party bias audits, mandatory reporting of bias mitigation efforts, and continuous monitoring for emerging biases over time.

4. Strengthened Data Privacy and Security Protocols:

Legal AI systems must adhere to robust privacy standards, including encryption, access controls, anonymization, and compliance with regulations like GDPR. Additional measures could involve: role-based access to sensitive information (ensuring only necessary personnel can access specific data); secure deletion of data once the purpose of processing is fulfilled; regular penetration testing and monitoring for unauthorized access. These safeguards protect client confidentiality, uphold attorney-client privilege, and preserve trust in the legal system.

5. Clear Accountability frameworks:

This means that responsibility must be explicitly assigned at all stages of AI deployment. Judges remain accountable for rulings, lawyers for their strategic decisions, and developers for system design and implementation. Best practices include formal accountability protocols, ethical codes for AI developers, and legal requirements for documenting AI's role in decision-making. Such frameworks prevent diffuse responsibility and ensure ethical and legal recourse when AI-assisted decisions cause harm.

6. Equitable access to AI tools:

To prevent a two-tiered system, AI resources should be extended beyond elite law firms to public defenders, legal aid organizations, and courts serving marginalized populations. Mechanisms could include government-funded AI tools, shared legal AI platforms for under-resourced practitioners, and training programs to build AI literacy among public legal workers. This way, equitable access ensures that AI enhances justice rather than exacerbates disparities.

7. Training for Legal Professionals:

Effective AI integration requires that lawyers, judges, and policymakers understand both its capabilities and limitations. Mandatory training programs could cover algorithmic literacy, bias detection, privacy compliance, and ethical decision-making. Empowering legal professionals ensures that AI is interpreted correctly and applied reasonably, mitigating risks of misuse or overreliance.

8. Continuous Ethical Review:

AI evolves rapidly, so ethical review must be ongoing. Independent oversight bodies should monitor compliance with transparency, fairness, privacy, and accountability standards. Some implementation strategies could include periodic audits of AI performance and outcomes, updating ethical guidelines as AI technologies and legal practices evolve, and establishing grievance mechanisms for litigants affected by AI-assisted decisions. If applied uniformly and correctly, continuous oversight ensures that AI remains aligned with societal values and legal principles, rather than drifting toward unethical or opaque uses.

9. Ethical Use Monitoring and Feedback:

Beyond audits, AI systems should incorporate feedback mechanisms that allow stakeholders to flag errors, bias, or misuse. Real-time monitoring and corrective processes enable continuous improvement and ensure that AI outputs remain aligned with ethical and legal standards.

Discussion and Conclusion

This paper has examined the promise and perils of artificial intelligence (AI) in the legal profession, arguing that while AI is an inevitable and potentially transformative force, its integration must be bounded by human oversight and guided by ethical principles. Our central thesis has been that AI can enhance justice through efficiency, predictive accuracy, and expanded access, but with robust safeguards, it risks undermining fairness, transparency, privacy, and accountability.

Section I highlighted AI's benefits in reshaping legal practice. From accelerating document review to enabling predictive analytics and more advanced legal research, AI tools already help lawyers and judges work with unprecedented speed and accuracy. Section II, however, explored the threats AI poses to professional judgment, fairness, and access to justice. Bias embedded in training data threatens to replicate systemic inequalities, while "hallucinations" and opaque algorithms jeopardize accountability and due process. Section III turned to the ethical framework for responsible AI use, where we outlined guiding recommendations. We argued that human oversight must remain essential, and transparency and explainability should be mandatory, amongst other things. Together, these measures highlight that AI should support, not supplant, human judgment in law.

While this study offers an overview of the intersection between AI and law, it is limited by its reliance on secondary sources. Given the rapid evolution of generative and predictive AI technologies, much of the current literature may quickly become outdated, reflecting early-stage implementations rather than long-term effects. Moreover, the selected studies often emphasize Western legal frameworks, particularly those of the United States and the United Kingdom, which may not represent the diversity of global regulatory and ethical contexts. This focus introduces potential bias in understanding how AI interacts with differing legal traditions, levels of technological adoption, and societal values. Consequently, future research should aim to incorporate empirical, cross-jurisdictional, and longitudinal analyses to deepen understanding of AI's evolving role in legal systems. Though comprehensive in its nature, constraints of this study itself include limitations as to the geographical and geopolitical standings of the countries that the case studies examined refer to (mostly, again, the Westernized ones). Nonetheless, taken cumulatively, these findings suggest that the larger outcomes of AI's rise in law will depend on governance and ethics, not technological capacity alone. AI can either reinforce existing inequities or expose them for reform, depending on how it is developed, distributed, and overseen. This dual potential raises urgent questions for scholars and policymakers alike: How can we ensure equitable access to AI tools across the justice system? What methods best detect and mitigate algorithmic bias in legal contexts? Should there be international standards for transparency and accountability in legal AI systems? And how might legal education evolve to prepare future practitioners for a world where human judgment and machine intelligence must co-exist? Future research should continue to interrogate these questions, exploring interdisciplinary methods that combine computer science, ethics, and jurisprudence. In closing, this review underscores that AI's integration into the legal system is not simply a technical shift but a normative one, implicating the future of justice itself. By embracing AI with transparency, equity, and accountability, the legal profession can ensure that technology strengthens rather than subverts its most fundamental values.

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References

1. Surden, Harry, "Artificial Intelligence and Law: an Overview", *SSRN*. Published on 30 June, 2019; Last revised 6 May 2025; Last accessed on Aug. 26, 2025. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3411869
2. Agrawal, Aishwarya, "A comprehensive Review on Impact of Artificial Intelligence on Litigation", *Law Bhoomi*. Published on November 17, 2023; Last Accessed on Aug. 26, 2025. https://lawbhoomi.com/a-comprehensive-review-on-impact-of-artificial-intelligence-on-litigation/
3. Kabir, Shanin, "The role of AI technology for legal research and decision making", *International Research Journal of Engineering and Technology, Volume 10*. Published in July 2023; Last accessed on Aug. 26, 2025. https://www.irjet.net/archives/V10/i7/IRJET-V10I7148.pdf
4. Rosengrün, Sebastian, "Why is AI a threat to the Rule of Law", Volume 1, Article Number 10. Published on August 9th, 2022. Last accessed on Aug. 26, 2025. https://link.springer.com/article/10.1007/s44206-022-00011-5
5. *Getman, Yaroshenko, Shapoval, Prokopiev, Maryna Demura*, "The impact of Artificial Intelligence on legal decision-making", Mykolas Romeris University. Published Sept. 2023. Last accessed on Aug. 26, 2025. https://www.ceeol.com/search/article-detail?id=1210529
6. Alarie, *et al.*, "How Artificial Intelligence will affect the practice of law", *UTP*. Published on March 9th, 2018, in the University of Toronto Law Journal, Volume 68, Number supplement 1. Last accessed on Aug. 26, 2025. https://utppublishing.com/doi/abs/10.3138/utlj.2017-0052.
7. Markoff, John, "Armies of Expensive Lawyers, Replaced by Cheaper Software", *New York Times*. Published on March 4, 2011; Last accessed Aug. 26, 2025. https://www.nytimes.com/2011/03/05/science/05legal.html
8. Buchanan, B.G., & Headrick, T.E., "Some Speculation about Artificial Intelligence and Legal Reasoning", 23 Stanford Law Review, 40, 1970. Last accessed on Aug. 26, 2025. https://digitalcommons.law.buffalo.edu/cgi/viewcontent.cgi?article=1866&context=journal_articles

DOI: 10.36838/IJHSR811.58

9. Madaoui, Nadjia, "The Impact of Artificial Intelligence on Legal Systems". Published in 2024, Last accessed on Aug. 26, 2025.
10. Mehl, L. . " Automation in the Legal World". Mechanisation of Thought Processes conference, Teddington, England. Published in 1958
11. Patel, Shivani, "The impact of artificial intelligence on legal research and case analysis", *The Amikus Qriae*. Last accessed on Aug. 26, 2025, https://theamikusqriae.com/the-im
12. Dana, Remus & Levy, Frank, "Can Robots be Lawyers? Computers, Lawyers and the Practice of Law", SSRN. Published on Dec. 11, 2015; Last revised on Nov. 30, 2016. Last accessed on Aug. 26, 2025,https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2701092.
13. Callister, Paul D. "Generative AI and Finding the Law", *Law Library Journal*, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4608268
14. Weiser, Benjamin, "Here's What Happens When Your Lawyer Uses ChatGPT", *New York Times*. Published on May 27th, 2023, https://www.nytimes.com/2023/05/27/nyregion/avianca-airline-lawsuit-chatgpt.html
15. Surden, Harry, "The Ethics of Artificial Intelligence in Law: the Basic Questions", Chapter 38 https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3441303

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RESEARCH ARTICLE

Operational Improvements and Changes in Aerodynamics of Aircraft to Reduce the Climate Impact of Aviation

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ABSTRACT: The aviation industry serves not only as a worldwide rapid transportation network but also as a catalyst for economic and social development across the globe. As the demand for air travel continues to expand, it's critical to address the growing concerns about its impact on climate change. While various regulatory policies have promoted the use of sustainable aviation fuels, these fuel alternatives are currently challenged by production insufficiency. Therefore, strategies such as aircraft operational improvements may help mitigate CO_2 emissions in the near term. The objective of this paper is to demonstrate that operational efficiency through optimization of longer flight paths and improved aerodynamics can reduce CO_2 emissions in commercial aviation. The impact of operational management will be evaluated by collecting aircraft performance data on an existing model and analyzing how different ranges of routes impact its emissions. The impact of aerodynamic improvements will be assessed by computing the emissions per unit distance for two different aircraft models with varying wing aspect ratios and comparing their impact on the drag force. From shortest to longest flight path, the computations of the drag-based cruise method showed about 20.9% decrease in emissions per kilometer. After a complete aerodynamic comparison, the aircraft model with lower drag force appeared to release about 2.10% lower emissions due to more efficiency. These findings suggest that longer flight path optimization and aerodynamic improvements could moderately lower the effect of aviation's CO_2 on climate change.

KEYWORDS: Aerospace Engineering; Sustainable Design; Aerodynamics; Flight Route Optimization; Wing-aspect.

Introduction

It is widely known across the world that human activity is causing rapid changes to our global climate, leading to disastrous outcomes such as severe weather, wildfires, air pollution, droughts, and intensified disease transmission.[1] According to the International Energy Agency, it was reported that the aviation industry alone is responsible for nearly 2.5% of global CO_2 emissions through the usage of fossil fuels.[2] Driven by factors such as tourism, its facilitation of international trade, generation of economic growth, and global connectivity, the air transport sector is estimated to triple in size in the coming years.[3] While the demand for air travel continues to expand, it is crucial to mitigate its reputation of being one of the most carbon-intensive activities around the globe. Despite the implementation of various CO_2 reduction measures such as new technologies, more efficient infrastructure, and prospects of sustainable aviation fuels, it is likely that the industry will not meet the sustainability goals established by the Paris Agreement, an international treaty established in 2015.[4] This is because the current growth and demand of the air transport sector is simply outstripping efforts to reach net-zero carbon emissions.

Furthermore, the prospects of sustainable aviation fuels, which are comparatively low-emission biofuels, are quite uncertain considering the fact that the industry will have to increase production up to nearly 405 billion liters of fuel every year by 2050.[5] Moreover, SAF production contributed to only 0.3% of global jet fuel in 2024 and requires heavy investments as well as policy change to replace jet fuel at the current scale.6 Therefore, achieving this ambitious goal will require stronger cooperation among airlines, more technological advancements, and collaboration between governments worldwide for the construction of a powerful supply chain that can support the production of such high capacity.[6] Therefore, other feasible strategies could be utilized to reduce the carbon emissions of aviation to a moderate level.

Improvements in aircraft configurations, such as wing structures and the implementation of sustainable operational measures, can increase aerodynamic efficiency. Recently, numerous studies have indicated that changing wing aspect ratios can lead to an improvement in the fuel efficiency of an aircraft by 10%, accounting for the fact that the lift of a thinner and longer wing can reduce the drag coefficient, which decreases fuel consumption.[7] However, elongating the wings of the aircraft can make it especially vulnerable to strong gusts, turbulence, or disruptive conditions, but adding more weight to stabilize the plane will decrease flight efficiency and defeat the purpose of this modification. NASA's X-66A Transonic Truss-Braced Wing project, for instance, is a truss-braced configuration that utilizes computational fluid dynamics to reduce the weight penalty of extended wings.[4]

Operational improvements within the aviation sector can play a critical role in advancing the long-term sustainability objectives. In the context of air travel, operational managements include a wide classification of activities such as passenger and cargo unloading, optimization of processes, formation flying, effective utilization of existing resources, and the metrics/procedures used to assess and improve aircraft efficiency.[8] As asserted by the International Civil Aviation Organization (ICAO), utilizing the opportunity to improve operational

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measures might be the most successful and affordable way to reduce carbon emissions and minimize fuel consumption.[9] Not only is this approach beneficial to the environment in terms of the CO_2 emissions released, but it can also reduce costs that are associated with burning large amounts of fossil fuels. Since the promotion of operational measures does not require any new high-cost equipment or advancements in technology, this organization encouraged and developed major initiatives. In 2016, ICAO implemented the Global Air Navigation Plan (GANP) and the Aviation System Block Upgrades (ASBU) in efforts to optimize air traffic management.[9]

According to Eurocontrol's environmental assessment in 2020, inefficiencies in the European air traffic management (ATM) network cause flights to burn 8.6–11.2 % more fuel on average.[10] Optimization of flight paths is the process that can be utilized to produce the flight path that has the least impact on the climate based on emissions. Aircraft operations are generally classified into two groups: Landing and Take-off (LTO cycle) and the cruise phase of the plane. The LTO cycle includes the takeoff, climb, approach, and idle phases of the aircraft, while the cruise phase encompasses all the operations above the altitude of 30,000 feet.[11] Aircraft release the highest amount of CO_2 during the LTO phase, which account to over 10% of an aircraft's total carbon emissions.[12] According to various recent research studies, the adoption of flight route optimization over extended flight segments would distribute the landing and takeoff emissions over greater distances.[12]

While existing research has previously explored aerodynamic improvements, such as improving lift-to-drag ratios, and other studies have modeled the impact of optimizing operational measures, such as flight path planning, these fields have mostly been studied in isolation from one another.[13] There is limited empirical research that properly examines the direct impact of the drag coefficient on aircraft's carbon emissions and how optimization of long-haul flight paths can impact carbon emissions. The objective of this study is to investigate how the potential effects of optimizing longer-range flight paths and increasing aerodynamic efficiency could assist in reducing carbon emissions. By focusing on improving operational efficiency through flight route optimization and changes in aerodynamics, this study analyzes how they can mitigate the impact of CO_2 emissions on the environment.

Methods

This study uses a quantitative analytical research design, such as the utilization of performance and aerodynamic equations to calculate the fuel burn and CO_2 emissions. These computations are followed by a comparative analysis between the emissions per unit distance of two aircraft model types as a function of specific characteristics such as the drag force. The first part of this section describes the methodologies used to model the CO_2 emissions of four varying flight distances and calculate the average emissions per kilometer to examine how they balance the Landing and Takeoff Cycle (LTO) emissions and the cruise emissions of the aircraft. The purpose of this computational modeling was to showcase how optimization of longer-range flight routes can potentially reduce CO_2 emissions to a considerable extent.

Data Collection:

For the first part of this analysis, the four representative flight distances selected can be generally classified as short haul (covering 500 kilometer or less), short-medium haul (covering more than 500 but less than 1500 kilometers), medium haul (covering around 4500 kilometers), and a long haul (close to the maximum flight distance that can be covered in a flight).[14] The aircraft model A320neo with a CFM LEAP 1A engine was selected for the purpose of this study, considering the fact that it was particularly designed in efforts to decarbonize the aviation sector and offers approximately 20% of more fuel efficiency compared to previous models.[15] Table 1 displays the aircraft parameters that were utilized in this analysis, such as the values of thrust-specific fuel consumption (TSFC), cruise thrust, cruise speed, and the fuel LTO per cycle. These parameters were obtained through manufacturer specifications that were publicly available, reputable aviation databases such as the International Civil Aviation Organization (ICAO), official Airbus technical documents, and studies of credible peer-reviewed literature to ensure maximum accuracy and consistency of the technical values of this model. Furthermore, parameters such as cruise speed and cruise TSFC were collected at the standard cruise altitude of 35,000 feet, as validated by the manufacturer's spec.

Table 1: The following values are performance parameters collected for the A320neo with the CFM LEAP 1A model. These values are used as inputs for modeling CO_2 emissions over different flight distances.

Parameters	Value	Units	Source/Note
Aircraft Model	**A320neo**	**-**	**-**
Engine Type	**CFM LEAP 1A26**	**-**	**-**
Cruise TSFC	**14.43**	**g/kN-s**	[16]
Cruise Thrust (per engine)	**143.05**	**kN**	[17]
Total Cruise Thrust (both engines)	**286.10**	**kN**	[18]
Fuel LTO per Cycle	**304**	**kg/cycle**	[19]
LTO CO_2 per flight	**960.64**	**kg**	[19]
Cruise Speed	**840**	**Km/hr**	[19]

Representative flight distances include 500 kilometers (short haul), 1,500 km (short-medium haul), 4,500 km (medium haul), and 13,500 (long-haul). First and foremost, the cruise time for each distance was calculated by dividing the cruise distance by the cruise speed.

$$Cruise\ Distance \div Cruise\ Speed = Cruise\ Time \quad (1)$$

Since the true air cruise speed of A32neo is **840 km/hr**, the cruise time for 1500 km= **1.79 hr**

Since the main focus of this study is to analyze the CO_2 emissions released during the aircraft's cruise, the next computation in this method is to calculate the fuel flow (kg/hr) of the aircraft. The fuel mass flow rate of an aircraft refers to the rate of fuel consumption per unit of time during cruise. Fuel flow was calculated by taking the cruise thrust to be equal to the aerodynamic drag during steady-level cruise and then multiplying the drag by the thrust-specific fuel consumption,

which was assumed constant for this analysis. This assumption is standard for steady level flight operations because, according to the Embry Riddle Aeronautical University, the forward thrust from an aircraft's engines must balance the total balance its total aerodynamic drag to maintain constant altitude and cruise speed. Therefore, this validates fuel flow estimations that can be calculated during cruise conditions.[20]

$$T = D \quad (2)$$

In this context, the quantity T refers to the thrust. In level cruise, the engine produces enough thrust to equal the aircraft's drag. It is important to acknowledge that the cruise thrust is only equal to the drag during steady cruise, not during climb/descent or changing payloads. Thus, the drag was then computed by utilizing the conventional drag equation.

$$F_{drag} = \frac{1}{2} \times \rho \times C_d \times A \times V^2 \quad (3)$$

In this equation, the quantity ρ represents the approximation of standard air density at an altitude of 35,000 feet according to the International Standard Atmosphere (ISA) model. The quantity V is the cruise speed of the aircraft, and the quantity C_d represents the drag coefficient. Lastly, the quantity A refers to the wing area of the aircraft. The drag force was calculated after making necessary conversions. Then, the value of the A320neo with LEAP 1A engine's representative cruise TSFC was collected from the airline's official model specification sheet and multiplied by the cruise thrust (equal to drag force in level cruise) to compute the fuel mass flow.

$$\dot{m}_f = TSFC \times T \quad (4)$$

The flight fuel flow in kg/hour is $\dot{m}_f$ x 3600. Then, this value was utilized to calculate the fuel burn for each different distance. To calculate these values, the quantity $\dot{m}_f$, the fuel mass flow rate (kg of fuel burned per hour), was multiplied by the cruise time of each distance. This computed the total fuel burned for each distance, and was again utilized to further calculate the CO_2 emissions released during the cruise.

$$\textbf{Fuel Burn} = f_{cruise} \times \textit{Time} \quad (5)$$

Therefore, to calculate the CO_2 emissions for the amount of fuel burned for each distance, this formula was used to find the mass of CO_2 emissions (kg).

$$m_{CO_2} = mt \times X_c \times \frac{MW_{CO_2}}{MW_f} \quad (6)$$

In equation 6, the quantity m_{CO_2} refers to the mass of CO_2 (kg), which is what is being solved for and mt is the fuel burned, which was previously calculated. Additionally, the quantity X_c is the carbon fraction of jet fuel, which is a standard value of 0.84, and the quantity $\frac{MW_{CO_2}}{MW_f}$ refers to the ratio of molar weights for carbon, which is the value of 44/12. These values were confirmed by the International Civil Aviation Organization for estimating CO_2 emissions from aviation fuel combustion.[21]

Since the focus of this study is to analyze the balance of the CO_2 emissions, including the LTO cycle, those values were separately calculated using a similar methodology. First, the parameter for the fuel mass flow rate (kg of fuel) consumed per LTO cycle for the A320neo with the CFM LEAP 1A model was collected from a credible mechanical document from the airline's database. Then, the mass of the emissions was calculated for each LTO cycle using the CO_2 conversion formula above. The value of this calculation was **LTO cycle CO_2= 960.64 kg**. While the value of the LTO emissions may vary in real life due to engine settings, airport conditions, and the weather, a fixed value was assumed for this analysis for baseline comparison. Therefore, the value of 960.64 kg was added to the varying amounts of CO_2 (kg) released during cruise for each flight path of the aircraft to calculate the approximations for total CO_2 emissions released for all the flight distances.

$$Total\ CO2\ (kg) = LTO\ Cycle\ CO2\ (kg) + CO2\ cruise\ emissions\ (kg) \quad (7)$$

Thereafter, the average CO_2 emission per kilometer (kg/km) was computed for each distance using this equation to calculate the final values and the overall factor of CO_2 that was being released for each distance.

$$Avg.CO2\ per\ km\ \left(\frac{kg}{km}\right) = \frac{Total\ CO_2}{Total\ Flight\ Distance} \quad (8)$$

This concludes the first methodology that was used to analyze the effect of optimizing flight distance on CO_2 emissions, as the emissions released for each distance were calculated accordingly.

Limitations and Assumptions:

To produce a transparent and reproducible analysis, this study adopts a small number of simplifying assumptions. First and foremost, this analysis assumes constant thrust specific fuel consumption (TSFC) for the A320neo model LEAP 1A engine, even though TSFC might vary due to changes in altitude, flight speed, atmospheric conditions, payload, and weight reduction during flight.[22] Furthermore, the aircraft's cruise thrust was taken equal to cruise drag in steady cruise conditions; thus, climb and descent phases were not modeled separately. The Landing and Takeoff (LTO) emissions are represented by a single baseline per cycle and were calculated based on the LTO mass fuel flow rate of the A320neo that was officially published in the airline's database. However, it is important to acknowledge that LTO cycle emissions are not fixed in reality and can vary considerably depending on the thrust settings, airport location/operations.[23] The assumptions explained above were made to enable a tractable comparison using publicly available aircraft data while clearly exposing where future refinement could focus.

In the next stage of this study, a drag-based approach was employed to perform a comparative analysis between two aircraft models to calculate the fuel consumption, the CO2 emissions, and assess how differences in the wing structure of aircraft can directly impact the CO_2 emissions. Hence, the first aircraft model is the same model that was utilized in the first methodology to calculate the average (kg) of CO_2 emissions per km, which was the A320neo with the CFM LEAP 1A design model. The secondary aircraft model that was compared was the Airbus 220-300 with PW1500G. To ensure full clarity on the distinction between sourced data and computed values in this analysis of aerodynamics, Table 2 and Table 3 present the performance parameters of each aircraft, such as the fuel flow rates, wing dimensions, and maximum take-off weight (MTOW) data that were collected from credible sources of

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the aircraft models' manuals, spec sheets, and databases. After obtaining these sourced parameters, the CO_2 emissions for each of the aircraft models were computed through the methodology described above. The cruise thrust, in particular, was calculated based on the drag force and the cruise speed values, which were collected from the sources to ensure a realistic reflection of operational conditions.

Table 2: Structural and performance parameters for the A320neo with CFM LEAP 1A engine are used to calculate CO_2 emissions per flight distance. The table presents the main aerodynamic and operational parameters that directly influence fuel efficiency and emissions.

Parameter	Value	Units	Source/Note
Aircraft Model	**A320neo**	**-**	[19]
Engine Type	**CFM LEAP 1A26**	**-**	[19]
Wing Span (b)	**35.8**	**m**	[19]
Wing Area (S)	**122.4**	**m²**	[19]
Cruise Speed	**840**	**km/hr**	[19]
Fuel Flow	**1845.30**	**kg/hr**	[19]
MTOW	**79,000**	**kg**	[19]

Table 3: Structural and performance parameters for the Airbus 220-300 with PW1500G engine used to calculate CO_2 emissions per flight distance. The data displays the critical operational and aerodynamic parameters used in emission modeling.

Parameters	Value	Units	Source/Note
Aircraft Model	**Airbus A220**	**-**	[24]
Wing Span (b)	**35.1**	**m**	[24]
Wing Area (S)	**112.3**	**m²**	[24]
Cruise Speed	**871**	**km/hr**	[24]
Thrust (both engines)	**207.28**	**kN**	[24]
Engine Type	**PW1500G**	**-**	[24]
MTOW	**154,000**	**lbs**	[24]
Fuel Flow	**1850**	**kg/hr**	[24]

By using these precise values, the drag force for each aircraft mode was calculated, which led to varying results due to clear differences in factors such as wing area, which impacted the drag coefficient. The drag force was calculated using equation (2). The quantities in this equation, such as, F_{drag} refer to the drag force (N) while the quantity ρ is the air density at a specific altitude. According to the International Standard Atmosphere, 0.3099 is the standard value for this term at the standard cruise altitude of 35,000 feet. The quantity A is equal to the wing area in m^2 and V^2 is the velocity of the aircraft squared. While the precise values were not available, the drag coefficient C_d values that were utilized in this analysis were validated with representative values from similar aircraft configurations.

Using this equation and the varying values of the wingspan, drag coefficient for each model, it was calculated that the drag force of the A320neo with CFM LEAP 1A was approximately **35,522 N** and the drag force of the Airbus 220-300 with PW1500G was approximately **32,500 N**.

Subsequently, these values were used to calculate the fuel flow rate (mass of fuel per hour) by using the thrust specific fuel consumption (TSFC). By equation (3), a lower drag force requires less thrust and thereby reduces fuel per hour.

In this equation, the coefficient $\dot{m}_f$ is the fuel flow rate, and the TSFC refers to the thrust specific fuel consumption, while T equals to the cruise thrust. The value of an aircraft's cruise thrust is equal to its drag force if the aircraft is flying under steady conditions and constant speed without acceleration.[25] Thus, this research used the drag force that was previously calculated for both models to solve for the fuel flow rate of the aircraft.

After conversion of units, the fuel flow of the A320neo was **1845.30 kg/hr**. For the second aircraft model of Airbus 220-300 the value of fuel flow for this model is **1850 kg/hr**. Then, these values were divided by their respective cruise speeds to find the fuel burned per kilometer (kg/km).

$$\frac{\dot{m}_f}{Cruise\ Speed} = Fuel\ Burned\ (kg/km) \quad (9)$$

Then, the values of the fuel burned per km (kg/km) were multiplied by the standard CO_2 emission factor per kg of jet fuel of 3.15, to collect the CO_2 emissions of each different aircraft per hour.[26]

$$CO_2\ emissions\ per\ hour\ =\ Fuel\ Burned\ (kg)\ *3.15 \quad (10)$$

Following this calculation for each of the aircraft models, the final step of the methodology involved dividing the mass of CO_2 emissions per hour (kg/hr) by the cruise speed of each aircraft model, which was the main focus of the second objective of this research. The simple equation that was utilized is included below.

$$CO_2\ emissions\ per\ kilometer\ =\ \frac{CO_2\ emissions\ per\ hour}{Cruise\ Speed} \quad (11)$$

This marks the end of the methodologies that were employed to address the two main research objectives. The methodology of the primary objective involves a secondary data analysis of the A320neo with CFM LEAP 1A aircraft model by collecting publicly available performance data, such as fuel flow rates and LTO fuel cycle data, to compute emissions as a function of distance. The secondary objective of this paper was approached by performing a comparative analysis of the emissions released by two varying aircraft models and examining how differences in their wing structure affected the drag coefficient and thereby affected the amount emitted.

The results of the computations of CO_2 will be described in Section 3 through various graphs and detailed tables that will contain all the calculations and parameters, allowing for quantitative comparisons as well as visual interpretations of the emission patterns.

■ Results

The numerical values of the computations of the CO_2 emissions for the four different distances are presented in Table 4. The following values were calculated using the methodology above and will be described clearly in relation to the primary objective. For each distance, cruise time was calculated based on the cruise speed of the model. While total cruise CO_2 emissions increase with distance, the average CO_2 emissions per km decrease.

Table 4: Calculated values of the total and average CO_2 emissions (kg and kg/km) for the A320neo with CFM LEAP 1A engine across four representative flight distances (short, short-medium, medium, long haul). The computations indicate that the longest flight path of 13,500 kilometers produced the lowest average CO_2 emissions per kilometer.

Flight Distance (km)	Cruise Time (hr)	Fuel Burn during cruise (kg/hr)	CO_2 cruise emissions (kg)	LTO Cycle CO_2 (kg)	Total CO_2 (kg)	Average CO_2 per km (kg/km)
500	0.59	1098.39	3459.94	960.64	4420.58	8.841
1500	1.78	3295.18	10379.81	960.64	11,340.45	7.560
4500	5.35	9885.54	31139.44	960.64	32,100.08	7.133
13500	16.07	29656.6	93418.33	960.64	94,378.97	6.991

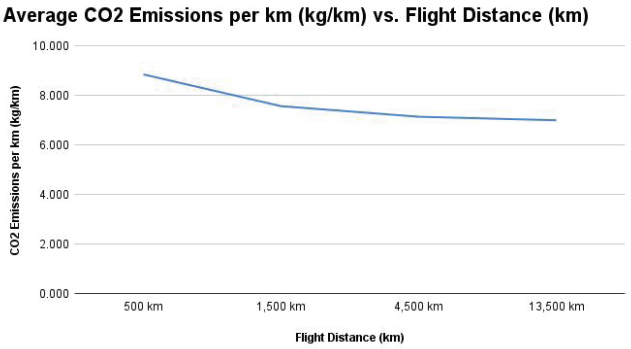

Figure 1: Average CO_2 emissions released per kilometer (kg/km) for the A320neo with CFM LEAP 1A engine across four representative flight distances (500 km, 1,500 km, 4,500 km, and 13,500 km). The results show that emissions per kilometer decrease as flight distance increases, which indicates greater efficiency on longer flights.

Figure 1 demonstrates the slight decline in the average mass of CO_2 emissions per unit distance as a result of an increase in flight distance. According to the graph above, the rate of decline is the most pronounced over the shorter range of distance, such as from 500 kilometers to 1500 kilometers, reflecting the effect of the fixed LTO cycle emissions being balanced out over fewer kilometers. The CO_2 emissions per kilometer were reported to have a 20.9% reduction from the shortest distance (500 kilometers) to the longest distance (13,500 kilometers) on the graph.

Regarding the next objective of analyzing the effects of wing-aspect ratio on the drag coefficient and carbon emissions, the findings in the analysis of both aircraft designs indicate differences between the CO_2 released per km of each model.

Table 5: Numerical values were calculated for each aircraft model using the second methodology described in Section 2. The results indicate that the Airbus 22-300 with PW1500G engine produces slightly lower CO_2 emissions per kilometer compared to the A320neo.

Aircraft Model	Wing Aspect Ratio	Drag Force (N)	TSFC (g/kN*s)	Fuel Flow (kg/hr)	CO_2 per hr (kg/hr)	CO_2 per km (kg/km)
A320neo with CFM LEAP 1A	10.471	35,522	14.43	1845.30	5831.13	6.942
Airbus 220 with PW1500G	10.971	32,500	16.01	1873.17	5919.21	6.796

The two selected aircraft models have varying wing-aspect ratios, as the Airbus 220 with PW 1500G engines has a slightly higher value of 10.970. As a result of this value, the drag force of this aircraft is considerably lower than that of the A320neo because a higher wing-aspect ratio creates less induced drag, which, in turn, reduces the drag force of the plane according to the equation utilized in the methods section. While the fuel mass flow rate and the thrust specific fuel consumption (TSFC) of the Airbus 220 appear to be higher, the cruise speed of this aircraft model is higher, with the value of 871 km per hour, because of its longer and more slender wing structure (high aspect ratio), which reduces drag and increases the efficiency of the plane.

The following bar graph shows a 2.10% reduction of CO_2 emissions per km of the Airbus 220-300 with PW1500G. Although the Airbus 220 burns more fuel per hour than the A320neo due to its high TSFC value, it has a lower drag, which increases efficiency and yields slightly lower CO_2 emissions than the A320.

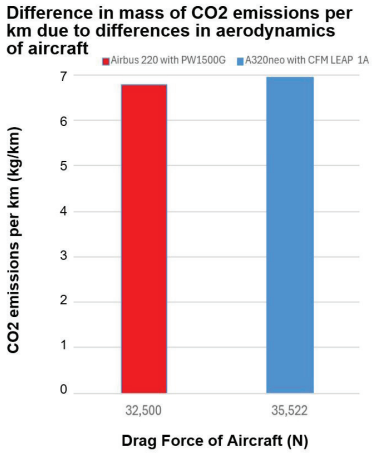

Figure 2: Comparison of CO_2 emissions per kilometer (kg/km) between the A320neo with a CFM LEAP 1A engine and Airbus 220-300 with PW1500G engine. The results show that the aircraft with a lower drag force produces slightly lower CO_2 emissions per unit distance, indicating improved efficiency.

To ensure consistency and reliability of the data, the results described in this section were verified with publicly available International Civil Aviation Organization's emission databank and were found to be within a ±10% range of reported values for similar aircraft configurations and flight profiles. While this is not a direct validation, the similarity between the values supports the credibility of this computational approach. This evidence lays the foundation for subsequent discussion and analysis, which is presented in the next section.

Discussion

Although some critics may argue that long-distance flights consume more total fuel, this study emphasizes the CO_2 emissions released per unit distance rather than just taking cruise emissions into account. According to the Intergovernmental Panel on Climate Change, landing and take-off (LTO) emissions are estimated to account for over 10% of the aviation industry's carbon emissions that contribute to climate change.27 As seen in Table 4, the impacts of LTO emissions per flight cycle are best diminished over longer distances. From the range of 500 kilometers to 13500 kilometers, there was a 20.9% reduction in the average CO_2 emissions released per kilometer (kg CO_2/km). However, it is important to interpret these results in the light of the study's assumptions that the LTO CO_2 emissions per cycle were represented by a fixed

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numerical value of 960.64 kg. It should be noted that these values might vary due to factors such as take-off and landing conditions (often determined by the airport), meteorological conditions, and other operations. It was estimated that a ±20% variation in the LTO CO_2 emissions would noticeably affect the emissions per kilometer of shorter flights but have a minimal impact on longer flights, which would still preserve the observed trend of the analysis.[28]

While analyzing the values of CO_2 emissions over longer paths and the effects of a lower drag coefficient, it has become clear that the trends and patterns of the data support the paper's hypothesis and align with its two main research objectives by showing that moderate reductions in CO_2 emissions could be achieved through operational and aerodynamic strategies. Figure 1 explicitly shows the declining trend of the average mass of CO_2 emissions per km for short-haul flights, which reflects the disproportionate contribution of LTO cycles to shorter flight routes. This supports the paper's implication that short-haul flights are less efficient in terms of carbon emissions per kilometer. For longer flight distances (4500 km -13,500 km), the curve flattens slightly because the fixed CO_2 emissions of the LTO cycle and the cruise CO_2 emissions are more proportionate. A report by the International Council on Clean Transportation validates this trend and explains that the carbon intensity (grams of CO_2 per passenger kilometer) is significantly higher for short-haul flights (< 1000 km) and gradually starts to decline from around 1500 km to 2000 km due to the balance between cruise CO_2 emissions and LTO cycle CO_2 emissions. This underscores the importance of modeling cruise and LTO cycle emissions separately when assessing operational strategies to decrease CO_2 emissions because improvements that specifically target LTO cycles could yield higher emission reduction rates for shorter flight paths.

An in-depth analysis of previous studies has indicated that aircraft emissions efficiency can substantially vary based on differences in aircraft configurations, passenger occupancy, and flight conditions.[28] This means that even small percentage improvements at the aircraft level can translate into meaningful cumulative emission savings when applied across larger fleets. To account for factors such as passenger loads while studying the impact of transportation on the environment, CO_2 emissions are also frequently measured in grams of carbon dioxide per passenger-kilometer (gCO_2/pax-km). While a detailed normalized passenger analysis was beyond the scope of this study, it represents an important direction for future work on this topic.

The secondary objective of this research was to compare the CO_2 emissions as a function of the drag coefficient of the Airbus 220-300 and the A320neo, which had differing wing aspect ratios. According to Embry-Riddle Aeronautical University, the wing-aspect ratio of an aircraft wing is the most important factor of aerodynamic analysis because it directly affects the vortex, which is also known as the drag coefficient.[29] The wing-aspect ratio of an aircraft refers to the ratio of its wing span to its mean chord, and it can be calculated by squaring the wingspan and dividing it by the wing area. High aspect ratio wings are considered to be more efficient as they generate more lift and reduce the induced drag at the wingtips of a plane.[30] By performing a comparative analysis using parameters, aspect ratios, and wing area, the CO_2 emissions per km of each aircraft model were calculated. Table 5 displays the calculations for various parameters of the two aircraft models collected through their official airline spec sheets. As shown in the table, the Airbus 220-300 has a slightly higher wing aspect ratio than the A320neo model, which resulted in a lower drag force and reduced thrust requirements to overcome air resistance. Although the fuel flow rate of the Airbus 220-300 was higher than that of the A320 due to its larger capacity, it still released fewer CO_2 emissions per km as it had a higher cruise speed. The increased cruise speed of the Airbus 220-300 was a result of superior aerodynamic efficiency because a lower drag enables the plane to maintain a higher speed at the same input of energy.

Figure 2 models the difference in the amount of CO_2 emission per km of both aircraft models and indicates a reduction of about 2.10% in the mass of the emissions. While seemingly minor, it is acknowledged by the government agency of the National Oceanic and Atmospheric Administration that even small reductions in CO_2 accumulate across fleets over time.31 It is important to mention that even just a 2.1% reduction in emissions per aircraft can represent a rough estimate of about 60 to 70 metric tons of CO_2 saved per aircraft per year when scaled to thousands of flights annually. This demonstrates how the collective impact of small operational improvements can considerably help minimize aviation's emissions that contribute to climate change.

Despite the relatively modest percentage change, these findings overall suggest that operational optimization can be important as a component of broader aviation emission reduction strategies. In the context of the aviation industry, incremental efficiency improvements remain a critical pathway for reducing emissions in the near term. Along with other emission reduction measures such as sustainable aviation fuels, improved air traffic management, and advanced aircraft structural modifications, the implementation of operational strategies such as flight route optimization and aerodynamic efficiency can lead to cumulative environmental benefits across commercial aviation fleets.

■ Conclusion

This paper assessed how optimizing longer flight paths and improving aerodynamic efficiency can help mitigate the impact of aviation's carbon emissions on the climate. By utilizing the officially published aircraft parameters of a reputable aircraft model, secondary analysis was conducted to compute the average CO_2 emissions per unit distance of four selected flight distances with varying ranges. Secondly, a comparative study was conducted between two aircraft models after the collection of their respective aerodynamic performance data to analyze the impact of the drag coefficient on the CO_2 emissions. With the trends of the data indicating a 20.9% decline in the average mass of CO_2 emissions per kilometer from the shortest flight distance to the longest flight distance, and a modest dif-

ference of about 2.10% reduction in average CO_2 emissions as a result of reduced drag and increased aerodynamic efficiency, the results aligned with the paper's initial proposition. While the benefits of flight path optimization are more apparent over shorter ranges, CO_2 reductions through aerodynamic efficiency prove to be consistent through all ranges. These findings indicate potential benefits of implementing operational efficiency improvements that encourage a decrease in CO_2 emissions through longer flight paths and increased aerodynamic efficiency. However, they should not be interpreted as direct policy changes because implementing these measures in the real world would require further advanced system-level studies that consider factors such as cost, route demand, and fleet compositions. Within these limitations, this paper provides a quantitative illustration of how longer route optimization and drag reduction could possibly contribute to aviation's ongoing efforts to achieve a greener future.

Future research in this field could aim to extend this study by analyzing the effects of both the operational strategies on the same emissions in a unified approach, while also exploring the application of these principles to a wider range of fleets to examine variations. In addition to this, there remains a significant gap in research in understanding the process of how flight management systems can integrate operational strategies and changes in aerodynamics under varying atmospheric and air traffic conditions.

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References

1. European Commission. *Causes of Climate Change*; https://climate.ec.europa.eu/climate-change/causes-climate-change_en (accessed Aug 15, 2025).
2. International Energy Agency. *Aviation*; https://www.iea.org/energy-system/transport/aviation (accessed Aug 14, 2025).
3. Braun, M.; Grimme, W.; Oesingmann, K. Pathway to Net Zero: Reviewing Sustainable Aviation Fuels, Environmental Impacts and Pricing. *J. Air Transp. Manag*. 2024, *117*, 102580. https://doi.org/10.1016/j.jairtraman.2024.102580.
4. Ting, E.; Reynolds, K. W.; Nguyen, N. T.; Totah, J. Aerodynamic Analysis of the Truss-Braced Wing Aircraft Using Vortex-Lattice Superposition Approach. In *32nd AIAA Applied Aerodynamics Conference*; American Institute of Aeronautics and Astronautics: Atlanta, GA, 2014. https://doi.org/10.2514/6.2014-2597.
5. Brueckner, J. K.; Kahn, M. E.; Nickelsburg, J. How Do Airlines Cut Fuel Usage, Reducing Their Carbon Emissions? *Econ. Transp*. 2024, *38*, 100358. https://doi.org/10.1016/j.ecotra.2024.100358.
6. International Air Transport Association. *SAF Volumes Growing but Still Missing Opportunities*; https://www.iata.org/en/pressroom/2023-releases/2023-12-06-02/ (accessed Aug 14, 2025).
7. Harrison, N. *Primary Funding Opportunities: High Aspect Ratio Wings and Dry Wings*; Aerospace Technology Institute; https://www.ati.org.uk/news/primary-funding-opportunities-high-aspect-ratio-wings-and-dry-wings/ (accessed Aug 14, 2025).
8. *Operational Improvements to Reduce the Climate Impact of Aviation—A Comparative Study from EU Project ClimOP*; https://www.mdpi.com/2076-3417/13/16/9083 (accessed Aug 14, 2025).
9. International Civil Aviation Organization. *Operational Measures*; https://www.icao.int/operational-measures (accessed Aug 15, 2025).
10. EUROCONTROL. *Inefficiency in the European Air Traffic Management Network Resulting in an Average Additional Fuel Burn of 8.6–11.2%*; https://www.eurocontrol.int/press-release/inefficiency-european-atm-network-resulting-additional-fuel-burn (accessed Aug 15, 2025).
11. Moniruzzaman, C. G.; Bowden, J.; Arunachalam, S. Aircraft Landing and Takeoff Emission Impacts on Surface O3 and PM2.5 through Aerosol Direct Feedback Effects Estimated by the Coupled WRF-CMAQ Model. *Atmos. Environ*. 2020, *243*, 117859. https://doi.org/10.1016/j.atmosenv.2020.117859.

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RESEARCH ARTICLE

Evaluating Personality-Driven Large Language Models as Simulated Users in Interactive Applications

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ABSTRACT: As the ability for large language models (LLMs) to simulate human behavior has been investigated, their ability to be used to test user interactions in an interactive application has yet to be evaluated. This potential use case raises the question if LLMs simulate user behavior when given personality traits and structured representations of an application's layout. In this paper, we evaluate whether LLMs simulate realistic user behavior with an interactive application, given a personality profile and user interface content. An LLM with a reluctant and controlled personality should interact less than an LLM with an open-minded and adventurous personality. By prompting LLMs with a personality profile and providing context for each page of the website, the LLM selects actions consistent with its profile. We measured how often each LLM interacted with elements and compared this to predictions. The findings showed High Exploration engaged more broadly, Neutral Exploration balanced fewer actions with wider coverage, and Low Exploration engaged least but scrolled farther. This demonstrates how personality conditioning shaped both action volume and style, and suggests LLMs support pre-deployment testing by simulating diverse user types.

KEYWORDS: Artificial Intelligence, Large Language Models, Human Simulation, User Interface, Interaction Simulation, Human Reasoning, LLM Reasoning.

Introduction

Creating and designing software is as much about understanding people as it is about writing code and creating mockups. Advances in large language models (LLMs) offer a new way to simulate realistic user interactions before real users ever touch the user interface.

Interacting with software such as a social media platform or banking website is not a very technically intensive task, but rather a very human one. Each user has a unique personality, way of thinking, and comfort level with technology. User Interface (UI) designers aim to account for the diverse and varying types of people interacting with their work,[1] but anticipating real user behavior is difficult without extensive user testing. Currently, this requires recruiting participants to run studies to allow for analysis of their interaction patterns. This has proved to be slow, costly, and has a lack of scalability.[2]

Some tools already exist to partially address this issue. Quin *et al.*[3] described A/B testing, or online controlled experimentation, as a way to compare two versions of software to support data-driven decisions. Their review shows that most A/B tests focus on algorithms, visual elements, and workflows, with results used for feature selection, rollout, and iterative development. Kohavi *et al.*[4] reported that companies like Microsoft, Amazon, and Google run hundreds of concurrent A/B tests daily, using them to validate ideas, identify harmful features before launch, and generate revenue gains.

However, these solutions require real users or extensive data. Solutions that provide the help designers need to reason about user behavior while in the design phase remain limited in accessibility and scope. The recent advances made to LLMs give the opportunity to leverage them to simulate human decision-making. Wei *et al.*[5] showed that prompting LLMs to generate step-by-step "chains of thought" dramatically improves their ability to solve complex reasoning tasks. Dasgupta *et al.*[6] compared LLM performance to human performance on logical reasoning tasks and found that models show similar content effects, performing better when the semantic context supports correct reasoning. Rajani *et al.*[7] created a dataset of human explanations, improving performance on commonsense reasoning benchmarks. Benharrak *et al.*[8] designed a system where writers could define AI personas to simulate different audiences and provide feedback, demonstrating that LLMs can adopt roles and perspectives in interactive settings. Their potential to simulate realistic, personality-driven users interacting within interactive interfaces remains to be systematically tested.

This investigation is at the intersection of human-computer interaction (HCI), user experience (UX), artificial intelligence, and user interface (UI) design. Recent work has explored how LLMs can simulate reasoning, decision-making, and personality-driven behavior,[6–8] their application to take the place of users during development has not yet been examined. If LLMs have the ability to simulate human behavior and interaction with real UI design and respond accordingly to different personality traits, they can become powerful tools for HCI and UX designers.

To investigate this question, the next section describes how we designed personality prompts, built an automated UI interaction pipeline, and collected interaction metrics. The Results section reports differences in these metrics across personality profiles. Finally, the Discussion interprets these findings in the

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context of UX research and outlines the possibility for future work.

In this paper, we investigate whether LLMs can realistically simulate user interactions with interactive applications when provided with a personality profile and structured UI context. This investigation focuses on the ability of LLMs to make coherent decisions that align with specific user traits while navigating websites or apps.

Methods

Personality Framework and Profile Design:

To simulate user behavior with personality influence, we adopted the Big Five personality model (OCEAN: Openness, Conscientiousness, Extraversion, Agreeableness, Neuroticism) as the basis for personality construction. The Big Five framework has been successfully applied in recent work on LLM personality assessment, which shows that models can maintain consistent traits across interactions.[9]

Three personality profiles were created to capture distinct exploratory tendencies:

- High Exploration: High Openness and Extraversion, low Neuroticism.
- Low Exploration: Low Openness and Extraversion, high Neuroticism.
- Neutral Exploration: Moderate Openness, Extraversion, and Neuroticism.

Web Interfaces and DOM Instrumentation:

We developed ten experimental websites (site1-site10) representing a range of application types, including social feeds, storefronts, dashboards, landing pages, educational platforms, and banking services. These websites were designed with interactive elements included to elicit engagement, such as navigation menus, buttons, search bars, toggles, forms, and call-to-action (CTA) prompts.[10,11]

All interactive elements were instrumented within the Document Object Model (DOM) using identifiers and semantic descriptors. For example:

```
{
"elementId": "sim-42",
"elementType": "button",
"semanticDescription": "Subscribe to newsletter",
"contextualInformation": "Located at the bottom of the landing page section",
"interactionAffordances": ["click"]
}
```

Structuring each element within the DOM allows for precise logging of every interaction and ensures reproducibility across runs.[12]

Simulation Environment and Prompting:

The simulation system used Playwright to extract visible DOM elements and assign structured identifiers. Each LLM received a structured prompt that combined personality conditioning, UI context, and a decision framework, instructing the model to select actions consistent with its personality.

The action decision protocol followed a multi-step cycle: perception of the UI state, evaluation of options, selection of an element, and execution of the corresponding action.[13,14]

The LLMs used are: Claude Sonnet 4, Gemini 2.5 Flash, Gemini 2.0 Flash, GPT OSS 20b, GPT OSS 120b, GPT 4.1 Mini, GPT 4o Mini.

Data Collection and Logged Metrics:

During each simulation run, the system monitored and logged interactions at the per-element level. The following event types were recorded:

- Clicks
- Text Inputs
- Scroll events
- Navigation events (internal page changes)
- Hover and view events with timings

Run level metrics were then calculated, including:

- Total action count per session
- Unique elements interacted with
- Unique pages visited
- Maximum scroll depth reached

All events were saved to TSV/JSON files for analysis.[15]

Replication and Control:

Each simulation took up to 20 actions per run. To increase the scope of the data, runs were replicated across multiple models (GPT, Claude, Gemini variants) and were tested against all ten websites.

Data Analysis:

Analysis was conducted over the aggregated metrics. Means and variance were then calculated for each profile's total actions, unique elements, unique pages, and scroll depth. These results were then compared to each other to find differences between the High, Neutral, and Low Exploration profiles.

Results and Discussion

Overall Interaction Patterns

Across all ten test websites, LLMs produced actions that varied by personality profile. High Exploration profiles averaged the largest number of total actions per session at an average of 15.7, compared to Low Exploration with an average of 13.4 and Neutral Exploration with an average of 12.6. This difference is further driven by the 20-action limit per trial. High Exploration profiles almost always used all 20, while Neutral Exploration left more actions unused. Interestingly, Low Exploration profiles produced slightly more actions overall than Neutral Exploration (13.44 vs. 12.56). This suggests that while Neutral Exploration profiles were less active, they distributed their interactions across a larger range of elements and pages compared to Low Exploration.

As shown in Figure 1, High Exploration consistently outpaced the other groups. Importantly, this effect persisted across sites with different purposes, from e-commerce sites (site2, site6) to dashboards (site3) and landing pages (site4).

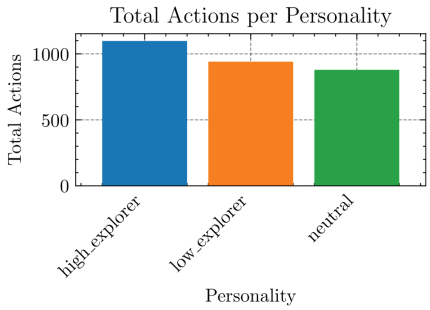

Figure 1: Total actions per personality profile across all websites. High Exploration profiles produced more actions on average than Low and Neutral Exploration profiles, indicating a higher willingness to take action.

Breadth of Interaction:

Differences were also shown in the diversity of interactions. High Exploration profiles interacted with nearly twice as many unique elements per session as Low Exploration (7.10 vs. 3.93), while Neutral Exploration fell in between with an average of 4.57. Figure 2 captures this gap, showing the gap between high and low exploration behaviors.

This breadth was not limited to single pages. High Exploration profiles visited an average of 3.36 unique pages, compared to 2.70 for Neutral and 2.31 for Low Exploration (shown in Figure 3). Sites with multiple opportunities to navigate within a site (such as the storefront in site2 and the travel planner in site8) amplified this difference, as High Exploration profiles were more willing to branch out into other areas of a site.

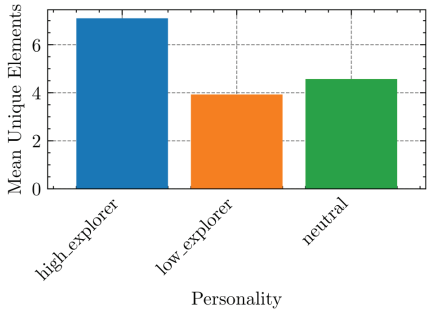

Figure 2: Mean number of unique interface elements interacted with by each personality profile. High Exploration profiles engaged with substantially more unique elements than both Low and Neutral profiles. Additionally, Neutral profiles also showed higher engagement than Low Exploration profiles, an unexpected finding given the expected relationship between Low and Neutral profiles.

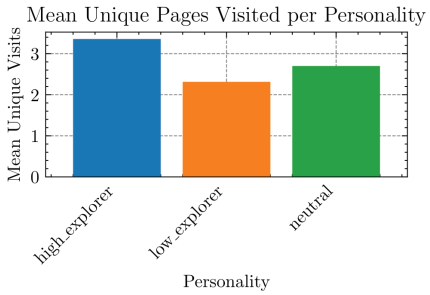

Figure 3: Mean number of unique pages visited per personality profile. High Exploration profiles visited the most pages on average, indicating a preference for navigation. The data also confirms the trend of Neutral profiles outperforming Low Exploration profiles in navigational breadth.

Depth of Engagement:

While breadth clearly distinguished the profiles, scroll behavior painted a different picture. Median scroll depth was consistent at around 200 pixels. However, the standard deviation showed that Low and Neutral Exploration profiles scrolled deeper than High Exploration (Table 1).

This pattern especially appeared on content-heavy sites such as site 10 (recipes) and site 7 (learning site with course list), where scrolling was a way to explore without executing more interactions like clicks or text inputs. High Exploration profiles tended to divert their attention to clickable elements (e.g., "Subscribe" buttons on site4 or "Add to Cart" drawers on site6) rather than continuing to scroll.

Table 1: Mean scroll depth by personality profile. Unlike their high engagement with other elements, High Exploration profiles had the lowest mean scroll depth. Low Exploration profiles had the highest mean and variance, indicating that scrolling was more characteristic of low-exploration behavior. Values are reported in pixels as mean and standard deviation across sessions.

Personality Profile	Mean (px)	SD (px)
High Exploration	228.13	230.32
Low Exploration	258.93	270.3
Neutral Exploration	256.59	255.39

Action Types and Relative Proportions:

Across all sites and personas, clicks dominated as the most common interaction type, accounting for roughly ⅔ of all actions. Scrolling followed at about 25%, with inputs, navigation, and "back" interactions adding up to less than 10%. Figure 4 shows how these proportions varied slightly by personality.

High Exploration profiles made greater proportional use of inputs and navigation than the other groups. For example, they were more likely to fill out search bars on site2 (storefront) and site8 (travel planner) or enter an email into newsletter signups on site4 (landing page). Neutral and Low Exploration profiles, by contrast, allocated an even larger share of their behavior to simple clicks and scrolls, interacting primarily with highly prominent buttons or cards.

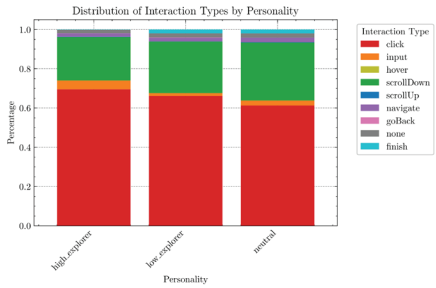

Figure 4: Distribution of interaction types by personality profile. Clicking represented the majority of actions, with scrolling as the second most common. High Exploration profiles performed proportionally more input actions than Low and Neutral profiles.

Contextual Observations by Site:

The differences in engagement style were shaped not only by personality but also by site design:

- Social Feed (site1): High Exploration profiles frequently opened modals to compose posts or clicked through sidebar items. Low Exploration mostly scrolled through content without engaging

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- Storefronts (site2, site6): High Exploration actively used filters and carts, while Low Exploration focused only on product cards.
- Dashboard (site3): Interactions were limited across profiles, but High Exploration clicked into settings more often.
- Landing Page (site4, site5): High Exploration often entered emails into signup fields, while Low Exploration only clicked prominent CTAs.
- Content-heavy sites (site7, site10): Low Exploration scrolled deeper, treating long lists or recipe grids as readable text rather than an area to interact with.

Discussion:

We hypothesized that personality conditioning would shape simulated interaction patterns, with High Exploration producing more actions and engaging more diversely than Neutral or Low Exploration. The results supported this hypothesis on the primary measure. High Exploration consistently showed more frequent and broader interaction, confirming that personality conditioning influenced not only how much LLMs engaged with an interface, but also the variety of elements and pages they explored.

The neutral profile introduced an unexpected nuance. Neutral Exploration behaved differently than predicted, producing fewer actions than Low Exploration yet covering more elements and pages. This divergence suggested that interaction volume and interaction diversity did not align simply. Instead, the Neutral Exploration profile displayed a hybrid strategy that balanced restrained overall activity with broader coverage of the interface.

Scroll behavior added another level of complexity. Low and Neutral Exploration profiles scrolled deeper than High Exploration, even though they interacted less overall. This pattern suggested that exploration can occur in multiple forms: active engagement with diverse elements or passive scanning through content. For interface evaluation, this distinction matters because designers often prioritize click-based or task-completion metrics, yet scrolling can represent a different form of engagement that deserves equal consideration.

These findings contribute to ongoing conversations in HCI and UX research about anticipating diverse user behaviors during design. Traditional methods, such as empirical usability testing, provide high-quality insight but are slow and costly to scale.[1,2] Post-launch tools like A/B testing and analytics offer systemic ways to assess design changes, but they require live users and traffic.[3,4] Our work demonstrates that LLMs can serve as personality-conditioned simulated users, providing a new pre-deployment tool that can augment established practices.

In addition, these results extend prior research showing that LLMs can simulate reasoning and decision making in non-interactive tasks[5–7] and role play as structured personas in multi-agent contexts with measurable actions, revealing that conditioning did not just influence which decisions were made but also the style of exploration itself. This underscores the potential of LLMs to model meaningful behavioral differences aligned with personality traits.

Our finding that personality conditioning shaped interaction patterns aligns with recent LLM personality research, though with important distinctions. Cohen *et al.*[16] found that Agreeableness and Extraversion significantly affect believability and goal achievement in LLM-simulated price negotiations through causal discovery methods, measuring how Big Five traits influence specific behavioral outcomes. They demonstrated that personality conditioning produces measurable behavioral variation in task-oriented contexts. However, their study focused on structured negotiation dialogues with clear endpoints, whereas our work examined exploratory UI navigation with less clearly-defined decision boundaries.

Limitations:

Several limitations constrain the generalizability of these findings. First, we lack human baseline data. While our results demonstrate that personality conditioning produces different behavioral patterns in LLMs, we cannot determine whether these patterns correspond to how humans with similar personality traits actually navigate the same interfaces. Lu *et al.*[17] found that LLMs achieved only 11.86% accuracy in multi-turn human behavior simulation in an e-commerce context. This emphasizes the gap between behavioral plausibility and accuracy.

Second, personality operationalization brings challenges. We condensed complex personalities into simplified 'exploration' profiles. Recent research by Xu *et al.*[18] demonstrated that persona conditioning introduces model-specific and context-dependent behavioral variations. They found that weakened agreeableness or conscientiousness significantly increased LLMs' susceptibility to unsafe outputs under bullying tactics. This suggests personality prompts may interact unpredictably with model architectures and situational contexts, activating behavioral patterns beyond simple trait expression. Our Neutral Exploration profile's hybrid strategy, which produced fewer actions than Low Exploration but covered more elements, may reflect similar complexity, where personality conditioning yields coherent but non-linear behavioral patterns whose psychological validity remains unclear.

■ Conclusion

Our study investigated whether LLMs could simulate personality-driven differences in user interaction when navigating web interfaces, and our findings confirmed that personality conditioning influenced both the frequency and style of engagement, supporting our central hypothesis. In particular, our study confirmed that High Exploration profiles interacted more broadly and frequently, Low Exploration profiles showed more limited engagement, while Neutral Exploration displayed a hybrid pattern, and both Neutral and Low Exploration highlighted the importance of passive engagement through scrolling.

These findings suggest that personality-conditioned LLM agents could become a valuable complement to interface evaluation processes, providing early insight into how different users

might behave through user testing, reducing the cost of user testing, and potentially reducing unethical use of human subjects. Several important questions remain, though. Do these patterns generalize to support more complex real-world applications? How closely do LLM-simulated behaviors align with those of human users who share similar personality traits as the LLMs? Which prompting strategies best sustain persona-consistent behavior across longer sessions?

We would like to propose that future research should combine simulations with human baselines, expand to richer task environments, and refine measurement methods in order to capture subjects' attention and engagement more directly. In addition, integrating personality-driven simulations with tools such as A/B testing and post-launch analytics could help determine the contexts where simulated users add the greatest value to the design and development process.

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References

1. Mao, J.-Y.; Vredenburg, K.; Smith, P. W.; Carey, T. The State of User-Centered Design Practice. *Commun ACM* **2005**, *48* (3), 105–109. https://doi.org/10.1145/1047671.1047677.
2. Karat, C.-M.; Campbell, R.; Fiegel, T. Comparison of Empirical Testing and Walkthrough Methods in User Interface Evaluation. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '92*; ACM Press: Monterey, California, United States, **1992**; pp 397–404. https://doi.org/10.1145/142750.142873.
3. Quin, F.; Weyns, D.; Galster, M.; Silva, C. C. A/B Testing: A Systematic Literature Review. *J. Syst. Softw.* **2024**, *211*, 112011. https://doi.org/10.1016/j.jss.2024.112011.
4. Kohavi, R.; Deng, A.; Frasca, B.; Walker, T.; Xu, Y.; Pohlmann, N. Online Controlled Experiments at Large Scale. In *Proceedings of the 19th ACM SIGKDD international conference on Knowledge discovery and data mining*; ACM: Chicago, Illinois, USA, **2013**; pp 1168–1176. https://doi.org/10.1145/2487575.2488217.
5. Wei, J.; Wang, X.; Schuurmans, D.; Bosma, M.; Ichter, B.; Xia, F.; Chi, E. H.; Le, Q. V.; Zhou, D. Chain-of-Thought Prompting Elicits Reasoning in Large Language Models. In *Proceedings of the 36th International Conference on Neural Information Processing Systems*; NIPS '22; Curran Associates Inc.: Red Hook, NY, USA, 2022; pp 24824–24837.
6. Dasgupta, I.; Lampinen, A. K.; Chan, S. C. Y.; Sheahan, H. R.; Creswell, A.; Kumaran, D.; McClelland, J. L.; Hill, F. Language Models Show Human-like Content Effects on Reasoning Tasks. arXiv July 17, **2024**. https://doi.org/10.48550/arXiv.2207.07051.
7. Rajani, N. F.; McCann, B.; Xiong, C.; Socher, R. Explain Yourself! Leveraging Language Models for Commonsense Reasoning. In *Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics*; Korhonen, A., Traum, D., Màrquez, L., Eds.; Association for Computational Linguistics: Florence, Italy, **2019**; pp 4932–4942. https://doi.org/10.18653/v1/P19-1487.
8. Benharrak, K.; Zindulka, T.; Lehmann, F.; Heuer, H.; Buschek, D. Writer-Defined AI Personas for On-Demand Feedback Generation. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*; CHI '24; Association for Computing Machinery: New York, NY, USA, **2024**; pp 1–18. https://doi.org/10.1145/3613904.3642406.
9. Sparrenberg, L.; Schneider, T.; Deußer, T.; Koppenborg, M.; Sifa, R. Correcting Systematic Bias in LLM-Generated Dialogues Using Big Five Personality Traits. In *2024 IEEE International Conference on Big Data (BigData)*, **2024**; pp 3061–3069. https://doi.org/10.1109/BigData62323.2024.10825941.
10. Visconti, E.; Tsigkanos, C.; Nenzi, L. Automated Monitoring of Web User Interfaces. *ACM Trans Web* **2025**, *19* (2), 10:1-10:27. https://doi.org/10.1145/3708512.
11. Dhonde, S.; Joshi, A.; Jadhav, T.; Hote, S.; Jansari, Mr. M. Automated UI Testing on Frontend of a Web Application. *Int. J. Enhanc. Res. Sci. Technol. Eng.* **2024**, *13* (05), 221–227. https://doi.org/10.55948/IJERSTE.2024.0533.
12. Abb, L.; Rehse, J.-R. A Reference Data Model for Process-Related User Interaction Logs. arXiv July 25, **2022**. https://doi.org/10.48550/arXiv.2207.12054.
13. Mehri, S.; Yang, X.; Kim, T.; Tur, G.; Mehri, S.; Hakkani-Tür, D. Goal Alignment in LLM-Based User Simulators for Conversational AI. arXiv July 27, **2025**. https://doi.org/10.48550/arXiv.2507.20152.
14. Pegoraro, M.; Uysal, M. S.; Hülsmann, T.-H.; van der Aalst, W. M. P. Resolving Uncertain Case Identifiers in Interaction Logs: A User Study. arXiv November 21, **2022**. https://doi.org/10.48550/arXiv.2212.00009.
15. Gupta, N.; Comar, P. M. Quantifying Customer Interactions on ML Optimized Page Layouts. In P*roceedings of the International Conference on Advances in Social Networks Analysis and Mining*; ACM: Kusadasi, Turkiye, **2023**; pp 502–508. https://doi.org/10.1145/3625007.3627519.
16. Cohen, M. C.; Su, Z.; Kao, H.-T.; Nguyen, D.; Lynch, S.; Sap, M.; Volkova, S. Exploring Big Five Personality and AI Capability Effects in LLM-Simulated Negotiation Dialogues. arXiv August 20, **2025**. https://doi.org/10.48550/arXiv.2506.15928.
17. Lu, Y.; Huang, J.; Han, Y.; Yao, B.; Bei, S.; Gesi, J.; Xie, Y.; Zheshen; Wang; He, Q.; Wang, D. Prompting Is Not All You Need! Evaluating LLM Agent Simulation Methodologies with Real-World Online Customer Behavior Data. arXiv June 5, **2025**. https://doi.org/10.48550/arXiv.2503.20749.
18. Xu, Z.; Sanghi, U.; Kankanhalli, M. Bullying the Machine: How Personas Increase LLM Vulnerability. arXiv May 19, **2025**. https://doi.org/10.48550/arXiv.2505.12692.

Appendix A. Additional Data

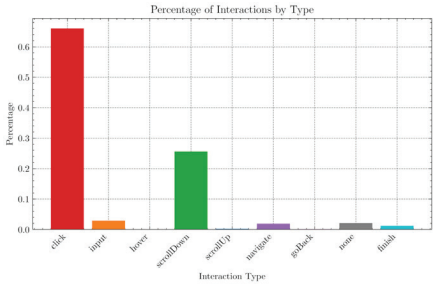

Figure A1: Normalized interaction type distribution across all profiles. Shows that LLMs tended to favor clicking and scrolling down regardless of their assigned profile.

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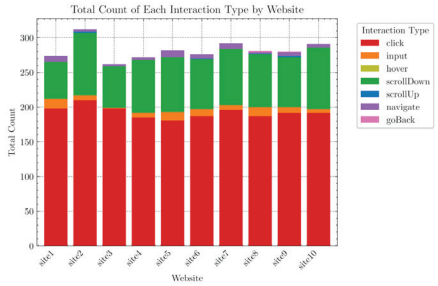

Figure A2: Interaction type counts by website. The type of website and the content shown caused variation in the way that LLMs acted and what actions were taken. This pattern replicates the way that humans interact differently depending on the website content.

Author

Isaac Robinson is a senior at Carlmont High School in California. He is a researcher focused on human-computer interaction and large language models. His work developing Mintable, a budgeting app for teens, motivated his investigation into how user interfaces are designed and how humans and AI systems interact with them.

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REVIEW ARTICLE

The Matter-Antimatter Asymmetry: A Potential Link to Dark Matter

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ABSTRACT: Matter-antimatter asymmetry is one of the biggest mysteries of the early universe. According to quantum field theory, every fundamental particle has a corresponding antiparticle with identical mass and opposite charge. Under high-energy conditions, particle–antiparticle pairs can be created, and when they come into contact, they annihilate, converting their mass into energy. But our universe proves otherwise. We only have tiny amounts of antimatter, whereas everything we observe, from microscopic molecules to humans to giant galaxies, is made of matter. How has ordinary matter not been annihilated by antimatter? Should our universe exist at all? Could there be a link to dark matter, a mysterious substance forming about 27% of our universe? In this review paper, we dive into the matter–antimatter asymmetry and explore whether it could be linked to the nature of dark matter while reviewing current findings, focusing on the Standard Model, the model that best describes the building blocks of the universe, CP [charge conjugation (C), parity (P)] violation, the violation of fundamental symmetries, and data from recent discoveries like the Euclid and Planck missions and CERN experiments. We believe this literature review will help cosmologists uncover the mysteries of dark matter and the matter-antimatter imbalance.

KEYWORDS: Physics and Astronomy, Astronomy and Cosmology, Matter-Antimatter Asymmetry, Dark Matter, CP Violation, Standard Model.

Introduction

The laws of physics as we understand them say that the universe should not exist. That is because of the Standard Model (SM), which is the most accepted theory describing the fundamental particles and forces in nature. It organizes matter into six types of quarks and six leptons, and includes various force-carrying particles (called gauge bosons) that allow these particles to interact with one another.[1,2] Quarks are the building blocks of protons and neutrons. There are 6 different types (flavors) of quarks: up, down, charm, strange, top, and bottom. They combine and form subatomic particles. Leptons include particles like electrons and neutrinos, whereas the gauge bosons include photons, gluons, and the W and Z bosons, which mediate the electromagnetic, strong, and weak forces. Quarks are the building blocks of protons and neutrons. There are six types, called 'flavors': up, down, charm, strange, top, and bottom. These combine to form subatomic particles. Leptons include electrons and neutrinos, while gauge bosons (such as photons, gluons, and W and Z bosons) mediate the fundamental forces. In short, the Standard Model organizes all known matter and interactions into these fundamental components.[3] Although CPT [charge conjugation (C), parity (P), and time reversal (T)] symmetry ensures symmetric laws for matter and antimatter, the observed imbalance requires mechanisms like CP violation to produce a net matter dominance.[4] In this view, many particles have corresponding antiparticles with opposite charges, which could annihilate each other upon contact, releasing energy. Since we are all made of matter, this annihilation did not completely eliminate matter; some particles survived, leaving behind only tiny amounts of antimatter. This imbalance is one of the biggest mysteries in cosmology. Understanding why matter dominates over antimatter could reveal gaps in the Standard Model, potentially reshaping our understanding of the universe. Antimatter makes up an extremely small fraction of the observable universe, so small that its percentage is functionally close to zero, less than 10^{-15}, making it practically nonexistent.[5]

But the enigma doesn't end there. Another mysterious component called dark matter makes up about 27% of the whole universe, far more than baryonic matter, which is only about 5%. In this paper, we explore the mystery of the matter-antimatter problem, while linking it to dark matter and analyzing current theories and hypotheses for the asymmetry problem and the possible connection to dark matter (DM).

This question is fundamental because without the answer, the Standard Model and General Relativity are incomplete. Recent experiments at CERN and Planck's data of the cosmic microwave background (CMB) are trying to find an answer or something that may be missing. We assert that during the matter-antimatter annihilation, the energy released may have formed, or have a possible link, to dark matter. We approach this hypothesis while examining current studies, theories, and data from previous papers, telescopes, and experiments.

This paper is organized as follows: In Section 2, we give background on matter-antimatter asymmetry, the Standard Model, CP Violation, and Dark Matter. In Section 3, we review current findings of CERN's latest experiment and Euclid's and Planck's data. In Section 4, we describe some of the existing theories that try to explain the asymmetry, including Baryogenesis, Leptogenesis, and the Higgs Field theories. In Section 5, we link the matter-antimatter asymmetry with dark matter through various theories, mainly Axion Quark Nuggets,

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Torsion Theory, and the hypothetical X particle. We end with the conclusion (Section 6), analyzing this hypothesis and possible future experiments to test it.

Discussion

Section 2: Matter/ Antimatter:

To understand the asymmetry problem, it is important to first define what matter and antimatter are. In physics, matter is anything that has mass and occupies space. At the most fundamental level, matter is composed of elementary particles called quarks and leptons. Quarks, as we explained before, combine to form protons and neutrons, and together with electrons (a type of lepton), they make up atoms, such as hydrogen, oxygen, and iron, which then form molecules that create complex organic and inorganic substances and all the visible matter in the universe.

Antimatter, on the other hand, is made of anti-particles, which have the same mass as particles but opposite charges.5 In 1996, scientists at CERN managed to create the first anti-atoms, specifically antihydrogen, by combining antiprotons and positrons in a lab. They used a facility called the Low Energy Antiproton Ring (LEAR), and they confirmed that the anti-atoms were real by detecting the energy signals from their annihilation.[6] (*See Table 1 for more information on particles and anti-particles*).

Table 1: Particles and their corresponding antiparticles. They have different charges: spin number, the number that shows intrinsic angular momentum; and Baryon/Lepton Number, the number that shows what type of matter it is. Note that they have the same mass but opposite charge, Baryon/Lepton Number, but the same spin number. Antiparticles are not just theoretical; they have been experimentally observed in laboratory settings, particularly at high-energy facilities like CERN.[2,7]

Particle	Charge	Spin	Baryon/Lepton Number	Anti-Particle	Charge	Spin	Baryon/Lepton Number
Electron	-1	½	Lepton +1	Positron	+1	½	Lepton -1
Proton	+1	½	Baryon +1	Anti-Proton	-1	½	Baryon -1
Neutron	0	½	Baryon +1	Anti-neutron	0	½	Baryon -1
Neutrino	0	½	Lepton +1	Antineutrino	0	½	Lepton -1

The Standard Model states that matter and anti-matter particles form in pairs, e.g., electrons form alongside positrons, the anti-particle to electrons (Table 1) and they annihilate each other immediately according to the equation below: Standard Model states that many matter–antimatter pairs, e.g. electrons and positrons, can be produced under high-energy conditions and annihilate upon contact (Table 1). They annihilate each other immediately according to the equation below:

$$e^- + e^+ \rightarrow \gamma + \gamma$$

where e^- stands for electron, e^+ for positron, and γ for photons. So when they come in contact with each other, they release two photons, or in terms of energy, we can use Einstein's equation to find the exact value:

$$E = 2 * mc^2 = 2 * (9.11 * 10^{-31} kg)(3.00 * 10^8 m/s)^2 \approx 1022 keV$$

According to particle physics, many particles and their corresponding antiparticles were created in the early universe, shortly after the Big Bang. When these particle–antiparticle pairs met, they could annihilate each other, releasing energy, which would have left a very small amount of matter. But somehow, we have more matter than antimatter. According to theoretical models supported by cosmological observations, approximately one extra matter particle per billion survived matter-antimatter annihilation after the Big Bang to create the matter-dominated universe we observe today.[7,8] This is exactly what the matter-antimatter asymmetry problem is.

Standard Model and CP Violation:

The way that scientists choose to describe the matter - antimatter asymmetry is through the CP Violation, referring to the violation of the symmetry that was thought to be in our universe of C (charge conjugation) and P (parity). Charge conjugation transforms a particle into an antiparticle, whereas P (parity) serves as a mirror while reflecting the position of the particle that we are observing. The fact that CP symmetry is violated in our universe gives rise to the matter-antimatter asymmetry. In 1964, scientists discovered CP violation in the decays of neutral kaons,[9] and later in B-meson decays at the BaBar[10] and Belle experiments[11] in 2001 (Aubert *et al.*; Abe *et al.*). Kaons and B-mesons are subatomic particles made of quarks. In this case, one quark + one anti-quark forms mesons.[3] In the 1964 and 2001 experiments, the particles decayed differently depending on whether they were a particle or an antiparticle, while proving that matter and antimatter behave differently.

CP violation stands as a perfect solution to the big question of why we have more matter than antimatter today, but there is another problem. CP violation contributes to the asymmetry, but its effect is too small to fully explain the observed dominance of matter over antimatter. While the Standard Model of Particle Physics supports the CP Violation, for example, through neutrino oscillations,[12] the effect that CP would have on the matter-antimatter asymmetry is still so small that it does not describe the matter dominance we have today.[13] This is because at very high temperatures (like during the electroweak phase transition, happening at 10^{-12} seconds after the Big Bang, when the universe cooled enough for the electroweak force to split into two separate forces)[14] studies have shown that the CP effect is about 10 billion times too small to produce the amount of matter the universe has today.[15] This gap matters because it shows that the Standard Model alone cannot explain why matter dominates, pointing to the need for new physics and guiding future experiments to search for additional sources of matter dominance.

So, there must be another component missing that would solve the matter-antimatter asymmetry. It might be a new particle in the Standard Model or, as we suggest in this paper, a possible connection with dark matter. This is why scientists are still researching, experimenting, and theorizing.

Dark Matter:

Dark Matter is one of the most mysterious substances in our universe, whose nature is still unknown to us. It makes up about 27% (as shown in Figure 1) according to Planck's data from 2018.[16] DM (Dark Matter) can be observed only by its

gravitational effects and not electromagnetic ones like we observe ordinary matter.[17, 18]

We have observed DM through:

1. Galaxy Rotation Curves – While measuring the speed of the stars' movement in galaxies, they found that the stars away from the center move faster than expected based on visible matter alone, suggesting that DM exists.[19]

2. Gravitational Lensing – Clusters of galaxies and other massive objects, bend the light due to gravity (acting like lenses) and reveal a lot about DM.[20]

3. Cosmic Microwave Background (CMB) – CMB provides information about the composition of the early universe, and missions such as Planck show that 27% of the universe is DM.[16]

4. Large-Scale Structure and Galaxy Clusters – They match simulations that include DM, proving that it plays a crucial role in universe formation.[21]

Some theories suggest that processes creating dark matter might also influence matter-antimatter asymmetry, providing a possible link between these two major cosmological mysteries.

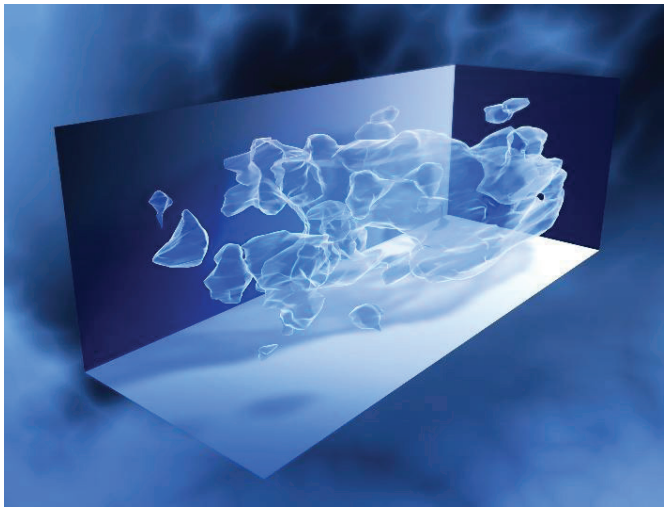

Figure 1: This figure illustrates the three-dimensional distribution of dark matter, showing that it forms complex, cloud-like structures rather than being evenly spread. These structures create a framework that influences how matter clusters and how the large-scale structure of the universe develops. (Credit: NASA, ESA).

Section 3: Current Findings:

For years, scientists have been experimenting and testing hypotheses to find a possible solution to the problem. This has been done by building huge experimental facilities like the Large Hadron Collider (LHC) at CERN and advanced telescopes such as Euclid and Planck. All these high-tech innovations have given us some incredible and physics-changing data that we describe in this section.

CERN Results:

Over the years, CERN has delivered some of the most groundbreaking discoveries (see Figure 2), including the confirmation of the Higgs boson in 2012 by the ATLAS and CMS experiments, which completed the Standard Model by explaining how particles obtain mass.[22] In March 2025, another big discovery important for the matter-antimatter asymmetry problem happened.

Scientists at the LHCb Experiment (Large Hadron Collider beauty) studied the Lambda-b (Λ^0_b), which is a baryon, consisting of a bottom (b), up (u), and down (d) quark. They also studied its antiparticle, which consists of antiquarks, and observed how these particles decay. The scientist found out that the particle and antiparticle decay in different ways. There was a measurable decay asymmetry of ~2.45%, more than 5 sigma.[23]

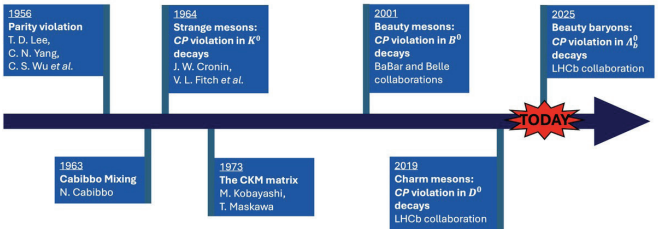

Figure 2: The figure highlights the progression and scientific significance of CERN's experiments over time. (including the latest discovery in March 2025 of LHCb for beauty baryons), Credit: CERN.

This experiment is very important because it is the first time proving that CP violation not only happens in meson decays but also in baryon decays. Even though this discovery is really crucial in understanding the asymmetry mystery, this alone cannot fully answer why matter is dominant. This is why there are other, ongoing projects and future observations being planned.

Euclid Mission:

Many projects study dark matter, and from their data, we can get crucial information that can be used towards the possible link between the matter-antimatter asymmetry and dark matter. One of these important missions is the Euclid Mission, one of the biggest telescopes that is studying dark matter. Euclid is a collaboration between NASA (National Aeronautics and Space Administration) and ESA (European Space Agency), launched on July 1, 2023. It aims to map cosmic structure via widefield optical and near-infrared imaging, covering roughly 14,000 deg^2 of the extragalactic sky. By collecting data on weak gravitational lensing and galaxy clustering, Euclid gives a very important understanding of the evolution and distribution of dark matter across half of the universe's history.[24] Studying dark matter allows great progress on the possible link between DM and the asymmetry, and Euclid is providing valuable information already. In its first data release, covering only 0.45% of its planned survey area, Euclid revealed more than 500 strong gravitational lenses, including a rare complete Einstein ring[25] and details of Abell 2390, a large galaxy cluster. An example of a recent image can be found in Figure 3. It has also cataloged over 26 million galaxies, including detailed lensing data from 380,000 galaxies, helping scientists better trace how dark matter is distributed.[26]

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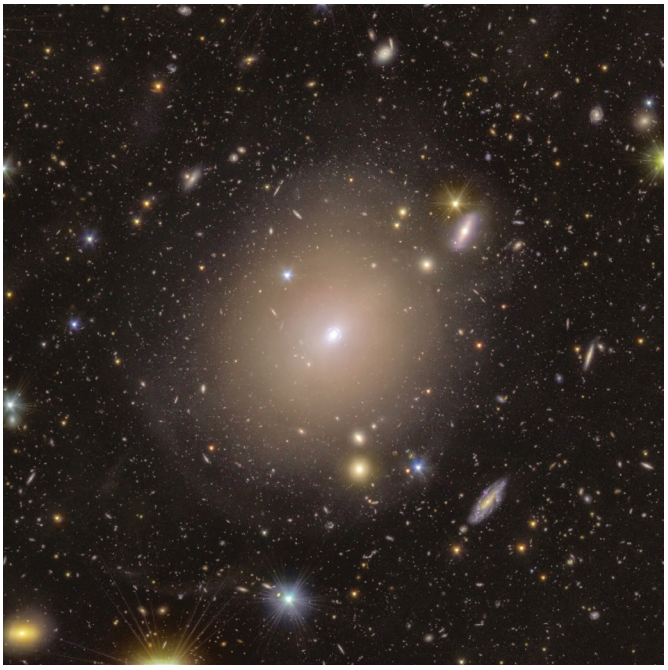

Figure 3: The Einstein Ring produced by gravitational lensing around galaxy NGC 6505. Light from a more distant galaxy is bent into a ring by the foreground galaxy's gravity, illustrating a key prediction of general relativity (Credit: Euclid).

The Planck Space Telescope:

Besides large particle colliders and missions like Euclid, scientists also study the early universe and the matter–antimatter asymmetry using data from space-based telescopes like ESA's Planck Space Telescope. According to the Planck 2018 results,[16] the universe consists of approximately 26.8% dark matter and only 4.9% ordinary (baryonic) matter.

The main goal of Planck is to study the CMB and the evolution of the early universe, which can be very useful for dark matter, asymmetry, and early universe models that scientists are currently studying. Planck has already given some really important details about our universe, which are really helpful to understand the asymmetry from the CMB anisotropies, to very small variations in temperature and density that reflect and confirm the matter-antimatter asymmetry. Moreover, its data have also been used in some proposed models and mechanism explain the asymmetry. In the upcoming sections, we are going to explain these models in a detailed way, including data that support or contradict them.

Section 4: Views on the matter-antimatter asymmetry:

The matter-antimatter asymmetry in the observable universe is usually studied within the concept of baryogenesis,[27] a process that explains an extra generation of baryons (matter) over antibaryons in the early universe. For baryogenesis to occur, certain conditions, known as the Sakharov conditions,[28] must be satisfied: baryon number violation, meaning that early-universe reactions created more matter than antimatter; C and CP violation, meaning that particles and their corresponding antiparticles behave differently; and departure from thermal equilibrium, meaning that the universe was not in equilibrium due to its rapid expansion.[4,29,30]

One promising theory within baryogenesis is Leptogenesis (subsection 3.1), which describes the matter-antimatter imbalance while focusing on the lepton asymmetry.

Leptogenesis:

We have already stated our hypothesis about connecting the matter-antimatter asymmetry to dark matter, but the imbalance mystery is an old, unsolved problem that has sparked hundreds of ideas and hypotheses about the origin of this problem. We already talked about the CP violation as a possible explanation for the problem, but since it cannot fully explain all the dominant matter, there must be other explanations. For example, one possible explanation that scientists have suggested is Leptogenesis.[31] In the Standard Model of particle physics, there are certain quantities called Baryon number (B) and Lepton Number (L), which are usually conserved.

Leptogenesis proposes that conservation of L can sometimes be violated, allowing right-handed neutrinos to decay and produce more leptons than antileptons. These lepton asymmetries can then be converted into the baryon asymmetry that we observe today. This can be a possible explanation of why there is more matter than antimatter in the universe today.[32] However, even though Leptogenesis can explain why the asymmetry exists, it has some limitations because it depends on the existence of right-handed neutrinos and specific CP-violating interactions, both of which have not yet been experimentally confirmed. Dark matter could play a complementary role in addressing these limitations, either as an independent component or as being produced alongside the lepton asymmetry.

Higgs Field and Asymmetry:

Leptogenesis is one of the most studied theories that tries to explain the asymmetry, but there are also other theories. One of them involves the Higgs field, a fundamental part of the Standard Model that gives particles their mass.[33] Scientists have suggested that after inflation in the early universe, the Higgs field oscillated in a way that violated CP symmetry, creating an imbalance between matter and antimatter similar to what we observe today. For example,[33] shows that the oscillations of the Higgs field after the inflation could have caused a lepton asymmetry of about $|nL / s| \approx 2.4 \times 10^{-10}$, a value present both in Planck data and theoretical models,[33,34] which is very close to the observed matter dominance. However, this mechanism alone cannot fully explain the matter-antimatter asymmetry, because it involves very specific conditions in the early universe, and additional components (such as dark matter) may play a role in explaining the observed asymmetry.

Section 5: How is the asymmetry linked to dark matter?:

Section 3 already gave us insight into the different theories that scientists have come up with to explain the asymmetry. In this section, we describe the connection between matter-antimatter asymmetry and DM through existing theories. However, we want to point out that it is very hard to verify them. It would require a lot of time, infrastructure, and modern equipment to prove these theories because it is very hard to de-

tect "invisible" particles, but if we do so, it will change physics as we know it.

Axion Quark Nugget (AQN) model:

The Axion Quark Nugget (AQN) model offers a potential unified explanation for both matter–antimatter asymmetry and dark matter formation. According to this theory,[35] the universe started with equal amounts of matter and antimatter, but it does not describe the antimatter as being annihilated.

It proposes that the antimatter transformed into extremely dense objects called "antiquark nuggets." These nuggets do not interact with visible light or regular matter; they are "invisible," like how dark matter behaves. At the same time, axions (very light, neutral, weakly interacting, and potential dark matter particles proposed in the 1970s to solve the CP problem)[36] are part of the model that hides antimatter in dense objects and helps support the quark nuggets (illustrated in Figure 4).

This theory is notable because it suggests that antimatter is not annihilated, but rather transformed into a hidden form.[37] However, the model relies on hypothetical particles (axions) and assumptions about quark nugget formation, and these are not yet confirmed experimentally. If this theory is correct, it would explain how the asymmetry is connected to DM, but more importantly, would solve two of the biggest mysteries in the field of cosmology: why matter won over antimatter, and what dark matter is. A strength of this model is that it links dark matter and asymmetry with a single mechanism, though its predictions are very difficult to test. Experimental tests, such as axion detection experiments or searches for quark nugget interactions, could help support or falsify this model.

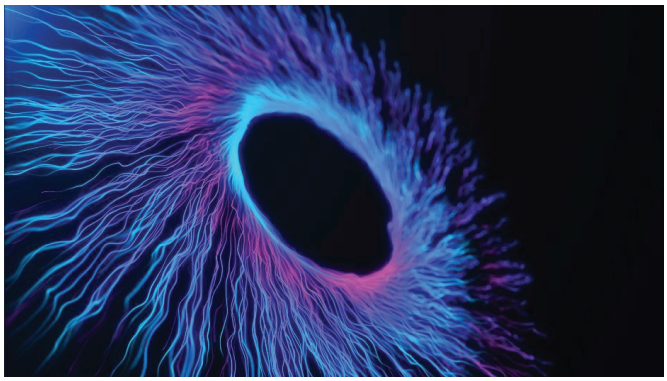

Figure 4: Conceptual illustration of axions, the target of ongoing experimental searches for dark matter (Credit: Quanta Magazine).

Subsection 5.2: Torsion Theory:

There is another theory that scientists have hypothesized to explain dark matter formation, and that it can lead to a link to the asymmetry problem. This theory uses a new branch of Einstein's Theory of Relativity. Relativity states that spacetime curves in accordance with mass and energy, which is what gravity is. But according to the theory, spacetime not only curves, but it can also twist. This twisting is what is called torsion, and it is thought to interact with particles that have intrinsic spin, such as electrons or quarks, rather than implying literal physical spinning. This theory provides a different approach from models like Axion Quark Nuggets, as it modifies spacetime itself rather than introducing new particles. Scientists research whether they can include torsion in current cosmological models, for example, in the Friedmann equations, which explain how the universe expands, and to see if there is a gravitational effect similar to that attributed to dark matter. This would be a very new and interesting approach to dark matter. They suggest that this torsion behaves like the effects of dark matter, so there are ways to describe DM without needing new particles to describe dark matter. However, these ideas remain theoretical, and future observational tests are needed to determine if torsion can indeed explain dark matter and the asymmetry problem. If torsion can explain dark matter, it could also play a role in the asymmetry problem.[38, 39] Some recent theories have speculated that torsion fields could induce CP violation or baryon/lepton number-violating processes (described in the previous section) in the early universe, by contributing this way to matter dominance. Its advantage is explaining dark matter without new particles, but the mechanism is still not experimentally confirmed. However, these ideas are still not proven experimentally and need further testing. Future observational tests may help determine if the torsion theory would be the one to solve the two biggest mysteries with just one answer.[40]

Subsection 5.3: X particle:

There is a new particle proposed that does not fit in the Standard Model called the "X" particle.[41] This particle is unique because it behaves differently from every known particle and can represent a new form of matter or maybe something that we are missing. To start with its uniqueness, the X particle decays into ordinary matter (like neutrinos), whereas the anti-X decays into "dark matter particles." This can explain matter dominance quite easily. Its mass is expected to be around 1000 GeV[41] (about a thousand times the mass of a proton), quite heavy compared to the few GeV other DM proposed particles. According to scientists, the X particle does not have to interact like the other SM particles. They actually suggest that its interactions are in a "hidden sector" with dark decay channels.[41] This particle could fill the gap between the asymmetry problem and the Standard Model. Since SM cannot fully explain the asymmetry, maybe this mysterious particle can explain it and make up most of the universe's mass, but still be invisible to us, characteristics that correspond to DM. To verify this hypothesis, scientists are still working with large experiments like CERN's LHC and investigating the properties of the X particle. The X particle model could directly show new physics, but it heavily relies on discovering a particle that has not yet been observed. If confirmed, the X particle can actually change cosmology and particle physics by solving two of the biggest mysteries and showing that DM and asymmetry correlate with each other.

This model is different from Axion Quark Nuggets and Torsion theory because it introduces a new particle instead of modifying spacetime or using dense objects. Scientists can test this idea by looking for the particle at CERN's LHC. Comparing these tests with predictions from other models can show which of these theories explains both dark matter and the matter-antimatter imbalance best.

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Conclusion

In this paper, we looked at the possible link between dark matter and the matter-antimatter asymmetry by exploring different theories that try to explain the asymmetry, starting with CP Violation in the Standard Model. We also went over the CERN, Euclid, and Planck 2018 results. Before discussing theories that connect dark matter with the asymmetry, we introduced Baryogenesis, Leptogenesis, and the Higgs Field theory, which try to explain the asymmetry without involving dark matter. Finally, we explored beyond Standard Model ideas, including Axion Quark Nuggets, Torsion, and the X particle.

Each model has its own strengths and weaknesses. The Axion Quark Nugget model links dark matter and asymmetry with a single mechanism, though it's hard to test. Torsion Theory can explain dark matter without new particles, but it's still theoretical. The X particle could reveal completely new physics, but it depends on finding a particle that hasn't been observed yet.

All of these theories need experimental proof, but future projects give hope. The Nancy Grace Roman Space Telescope, with its advanced gravitational lensing and stellar analysis, will map dark matter in the universe. The Vera C. Rubin Observatory will perform a 10-year survey, giving detailed data about both the early and current universe. Together, these studies might help figure out which models, or combination of models, best explain the matter-antimatter asymmetry and dark matter.

In short, there's still a big gap between theory and experiment, but upcoming projects like the Roman Space Telescope and the Vera C. Rubin Observatory could lead to discoveries that change our understanding of cosmology, astrophysics, and particle physics in the next few decades.

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I attest that the ideas, graphics, and writing in this paper are entirely my own. All figures, data, and sources used in this review have been properly cited and credited.

Thank you!

References

1. Talios, V. The Standard Model Theory [May Be] a Wrong Theory. *J. High Energy Phys., Gravitation Cosm.* 2023, *9*(3), 602–610. https://doi.org/10.4236/jhepgc.2023.93050
2. Particle Data Group; Tanabashi, M.; Hagiwara, K.; Hikasa, K.; Nakamura, K.; Sumino, Y.; Takahashi, F.; Tanaka, J.; Agashe, K.; Aielli, G.; Amsler, C.; Antonelli, M.; Asner, D. M.; Baer, H.; … Schaffner, P. Review of Particle Physics. *Phys. Rev. D* 2018, *98*(3), 030001. https://doi.org/10.1103/PhysRevD.98.030001
3. Griffiths, D. *Introduction to Elementary Particles*, 2nd ed.; Wiley: New York, 2008.
4. Lehnert, R. CPT symmetry and its violation. *Symmetry* 2016, *8*(11), 114. https://doi.org/10.3390/sym8110114
5. Dine, M.; Kusenko, A. Origin of the matter-antimatter asymmetry. *Rev. Mod. Phys.* 2003, *76*(1), 1–30. https://doi.org/10.1103/RevModPhys.76.1
6. Baur, G.; Boero, G.; Brauksiepe, S.; Buzzo, A.; Eyrich, W.; Geyer, R.; Grzonka, D.; Hauffe, J.; Kilian, K.; LoVetere, M.; Macri, M.; Moosburger, M.; Nellen, R.; Oelert, W.; Passaggio, S.; Pozzo, A.; Röhrich, K.; Sachs, K.; Schepers, G.; … Wolke, M. Observation of antihydrogen production in flight at CERN. *Hyperfine Interact.* 1997, *109*(1), 191–203. https://doi.org/10.1023/A:1012609601849
7. Canetti, L., Drewes, M., & Shaposhnikov, M. (2012). Matter and antimatter in the universe. *New Journal of Physics*, *14*(9), 095012. https://doi.org/10.1088/1367-2630/14/9/095012
8. Steigman, G. Primordial nucleosynthesis in the precision cosmology era. *Annu. Rev. Nucl. Part. Sci.* 2007, *57*, 463–491. https://doi.org/10.1146/annurev.nucl.56.080805.140437
9. Cronin, J. W. The Discovery of CP Violation. *Eur. Phys. J. H* 2012, *36* (4), 487–508. https://doi.org/10.1140/epjh/e2011-20057-4
10. Aubert, B.; BABAR Collaboration. Observation of CP Violation in the B^0 Meson System. *Phys. Rev. Lett.* 2001, *87* (9), 091801. https://doi.org/10.1103/PhysRevLett.87.091801
11. Belle Collaboration; Abe, K.; Abe, K.; Abe, R.; Adachi, I.; Ahn, B. S.; Aihara, H.; Akatsu, M.; Alimonti, G.; Asai, K.; Asai, M.; Asano, Y.; Aso, T.; Aulchenko, V.; Aushev, T.; … Žontar, D. Observation of Large CP Violation in the Neutral B Meson System. *Phys. Rev. Lett.* 2001, *87* (9), 091802. https://doi.org/10.1103/PhysRevLett.87.091802
12. Particle Data Group. Review of Particle Physics. *Prog. Theor. Exp. Phys.* 2024, *2024* (1), 083C01. https://pdg.lbl.gov/
13. Willmann, L.; Jungmann, K. Matter-Antimatter Asymmetry—Aspects at Low Energy. *Ann. Phys.* 2016, *528* (1–2), 108–114. https://doi.org/10.1002/andp.201500008
14. Morrissey, D. E.; Ramsey-Musolf, M. J. Electroweak Baryogenesis. *New J. Phys.* 2012, *14* (12), 125003. https://doi.org/10.1088/1367-2630/14/12/125003
15. Huet, P.; Sather, E. Electroweak Baryogenesis and Standard Model CP Violation. *Phys. Rev. D* 1995, *51* (2), 379–394. https://doi.org/10.1103/PhysRevD.51.379
16. Aghanim, N.; Akrami, Y.; Ashdown, M.; Aumont, J.; Baccigalupi, C.; Ballardini, M.; Banday, A. J.; Barreiro, R. B.; Bartolo, N.; Basak, S.; Battye, R.; … Zonca, A. Planck 2018 Results—VI. Cosmological Parameters. *Astron. Astrophys.* 2020, 641, A6. https://doi.org/10.1051/0004-6361/201833910
17. Randall, L. What Is Dark Matter? *Nature* 2018, 557 (7704), S6–S7. https://doi.org/10.1038/d41586-018-05096-y
18. Oks, E. Brief Review of Recent Advances in Understanding Dark Matter and Dark Energy. *ScienceDirect* 2021, December. https://www.sciencedirect.com/science/article/abs/pii/S1387647321000191
19. Bergström, L. Dark Matter Evidence, Particle Physics Candidates and Detection Methods. *Ann. Phys.* 2012, 524 (9–10), 479–496. https://doi.org/10.1002/andp.201200116
20. Clowe, D.; Bradač, M.; Gonzalez, A. H.; Markevitch, M.; Randall, S. W.; Jones, C.; Zaritsky, D. A Direct Empirical Proof of the Existence of Dark Matter. *Astrophys. J.* 2006, 648 (2), L109. https://doi.org/10.1086/508162
21. Lee, S. M.; Oda, K.; Park, S. C. Spontaneous Leptogenesis in Higgs Inflation. *J. High Energy Phys.* 2021, 2021 (3), 83. https://doi.org/10.1007/JHEP03(2021)083

22. Chatrchyan, S.; Khachatryan, V.; Sirunyan, A. M.; Tumasyan, A.; Adam, W.; Aguilo, E.; Bergauer, T.; Dragicevic, M.; Erö, J.; Fabjan, C.; Friedl, M.; Frühwirth, R.; Ghete, V. M.; Hammer, J.; Hoch, M.; Hörmann, N.; Hrubec, J.; Jeitler, M.; Kiesenhofer, W.; … Wenman, D. Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC. *Phys. Lett. B* 2012, 716 (1), 30–61. https://doi.org/10.1016/j.physletb.2012.08.021
23. Aaij, R.; Abdelmotteleb, A. S. W.; Abellan Beteta, C.; Abudinén, F. J.; Ackernley, T.; Adefisoye, A. A.; Adefisoye, A. M.; Adeva, B.; Adinolfi, M.; Adlarson, P. H.; Agapopoulou, C.; Aidala, C. A.; Ajaltouni, Z.; Akar, S.; Akiba, K.; Albicocco, P.; Albrecht, J.; Alessio, F.; Alexander, M.; … Zunica, G. Observation of Charge-Parity Symmetry Breaking in Baryon Decays. *Nature* 2025, 643 (8074), 1223–1228. https://doi.org/10.1038/s41586-025-09119-3
24. Euclid Collaboration; Mellier, Y.; Abdurro'uf; Acevedo Barroso, J. A.; Achúcarro, A.; Adamek, J.; Adam, R.; Addison, G. E.; Aghanim, N.; Aguena, M.; Ajani, V.; Akrami, Y.; Al-Bahlawan, A.; Alavi, A.; Albuquerque, I. S.; Alestas, G.; Alguero, G.; Allaoui, A.; Allen, S. W.; … Zumalacarregui, M. Euclid: I. Overview of the Euclid Mission. *Astron. Astrophys*. 2025, 697, A1. https://doi.org/10.1051/0004-6361/202450810
25. O'Riordan, C. M.; Oldham, L. J.; Nersesian, A.; Li, T.; Collett, T. E.; Sluse, D.; Altieri, B.; Clément, B.; Vasan, K. G. C.; Rhoades, S.; Chen, Y.; Jones, T.; Adami, C.; Gavazzi, R.; Vegetti, S.; Powell, D. M.; Barroso, J. A. A.; Andika, I. T.; Bhatawdekar, R.; … Dannerbauer, H. Euclid: A Complete Einstein Ring in NGC 6505. *Astron. Astrophys*. 2025, 694, A145. https://doi.org/10.1051/0004-6361/202453014
26. Euclid Collaboration; Bisigello, L.; Rodighiero, G.; Fotopoulou, S.; Ricci, F.; Jahnke, K.; Feltre, A.; Allevato, V.; Shankar, F.; Cassata, P.; Dalla Bontà, E.; Gandolfi, G.; Girardi, G.; Giulietti, M.; Grazian, A.; Lovell, C.; Maiolino, R.; Matamoro Zatarain, T.; Mezcua, M.; Prandoni, I.; … Scott, D. Euclid Quick Data Release (Q1). Extending the Quest for Little Red Dots to z < 4. *Astron. Astrophys*. 2025. https://doi.org/10.1051/0004-6361/202554537
27. Bödeker, D.; Buchmüller, W. Baryogenesis from the Weak Scale to the Grand Unification Scale. *Rev. Mod. Phys*. 2021, *93* (3), 035004. https://doi.org/10.1103/RevModPhys.93.035004
28. Sakharov, A. D. Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe. *Sov. Phys. Usp*. 1991, *34* (5), 392. https://doi.org/10.1070/PU1991v034n05ABEH002497
29. Alpher, R. A.; Marx, G. The Creation of Free Energy. *Vistas Astron*. 1992, *35*, 179–214. https://doi.org/10.1016/0083-6656(92)90014-W
30. Pereira, D. S.; Ferraz, J.; Lobo, F. S. N.; Mimoso, J. P. Baryogenesis: A Symmetry Breaking in the Primordial Universe Revisited. *Symmetry* 2024, *16* (1), 13. https://doi.org/10.3390/sym16010013
31. Mavromatos, N. E. Violation of CPT Invariance in the Early Universe and Leptogenesis/Baryogenesis. *J. Phys.: Conf. Ser.* 2013, *447* (1), 012016. https://doi.org/10.1088/1742-6596/447/1/012016
32. Buchmuller, W.; Peccei, R. D.; Yanagida, T. Leptogenesis as the Origin of Matter. *Annu. Rev. Nucl. Part. Sci*. 2005, *55* (1), 311–355. https://doi.org/10.1146/annurev.nucl.55.090704.151558
33. Enomoto, S.; Cai, C.; Yu, Z.-H.; Zhang, H.-H. Leptogenesis due to Oscillating Higgs Field. *Eur. Phys. J. C* 2020, *80* (12), 1098. https://doi.org/10.1140/epjc/s10052-020-08672-7
34. Lee, S. M.; Oda, K.; Park, S. C. (2021). Spontaneous leptogenesis in Higgs inflation. *J. High Energy Phys. 2021*, *2021*(3), 83. https://doi.org/10.1007/JHEP03(2021)083
35. Zhitnitsky, A. Axion Quark Nuggets: Dark Matter and Matter–Antimatter Asymmetry—Theory, Observations and Future Experiments. *Mod. Phys. Lett. A* 2021, 36 (18), 2130017. https://doi.org/10.1142/S0217732321300172
36. Marsh, D. J. E. Axion Cosmology. *Phys. Rep*. 2016, 643, 1–79. https://doi.org/10.1016/j.physrep.2016.06.005
37. Ge, S.; Lawson, K.; Zhitnitsky, A. Axion Quark Nugget Dark Matter Model: Size Distribution and Survival Pattern. *Phys. Rev. D* 2019, *99* (11), 116017. https://doi.org/10.1103/PhysRevD.99.116017
38. Shapiro, I. L. Physical Aspects of the Space–Time Torsion. *Phys. Rep*. 2002, *357* (2), 113–213. https://doi.org/10.1016/S0370-1573(01)00030-8
39. Pereira, S. H.; Vicente, A. M.; Jesus, J. F.; Holanda, R. F. L. Dark Matter from Torsion in Friedmann Cosmology. *Eur. Phys. J. C* 2022, 82 (4), 356. https://doi.org/10.1140/epjc/s10052-022-10317-w
40. Mishra, S. S.; Mandal, S.; Sahoo, P. K. Constraining f(T, T) Gravity with Gravitational Baryogenesis. *Phys. Lett. B* 2023, *842*, 137959. https://doi.org/10.1016/j.physletb.2023.137959
41. Bödeker, D.; Buchmüller, W. Baryogenesis from the Weak Scale to the Grand Unification Scale. *Rev. Mod. Phys*. 2021, *93* (3), 035004. https://doi.org/10.1103/RevModPhys.93.035004

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RESEARCH ARTICLE

U.S. Geography & Healthcare: Infrastructure and Outcomes

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ABSTRACT: Health disparities in the United States are often attributed to income, education, and race, but geography is a less studied dimension of inequity. This paper examines rurality on health conditions, outcomes, and infrastructure across over 3,000 U.S. counties. Using county-level data on chronic disease prevalence, mortality, life expectancy, infant mortality, and healthcare access, we ran regression models to examine the relationship between the rural population share and these health measures. Results show that rural and urban populations are equally likely to face chronic conditions such as obesity, diabetes, and high blood pressure. However, rural counties exhibit worse outcomes, with higher all-cause mortality, modestly shorter life expectancy, and especially elevated infant mortality. Preventive care also shows a rural disadvantage: cholesterol screening rates decline consistently with rurality, while other access measures, such as insurance coverage and doctor visits, remain stable. These findings indicate that rurality is linked to differences in health outcomes even when underlying health conditions appear similar. While the mechanisms behind these associations cannot be determined from the present data, the patterns highlight the need for further research into healthcare capacity, preventive services, and maternal care in rural communities.

KEYWORDS: Behavioral And Social Sciences, Sociology, Public Health, Public Policy, Geography.

Introduction

U.S. health disparities have long been a central research and political topic. Across the population, substantial differences in health outcomes are observed along social, economic, and geographic lines, contributing to persistent gaps in life expectancy, mortality, and quality of life. While overall national health indicators have improved over the past several decades, these gains have not been distributed equally. Specific populations continue to experience disproportionate burdens of disease and premature death, underscoring the importance of identifying and addressing the structural determinants of health inequity.

Robust research has demonstrated that socioeconomic factors are among the most powerful predictors of health outcomes. It has been shown that adults with lower levels of educational attainment experience higher mortality rates and shorter life expectancy across gender and racial groups.[1] Additionally, life expectancy among the wealthiest Americans exceeded that of the poorest by more than a decade, with the gap widening over time and varying substantially across regions, particularly for low-income populations.[2] There are still persistent differences in life expectancy by race and ethnicity between 2000 and 2019, with American Indian and Alaska Native populations showing slight improvements over time.[3] Similarly, there are also disproportionately higher cause-specific mortality rates among Black, American Indian, and Alaska Native populations relative to White populations, reflecting the cumulative effects of structural racism and unequal access to care.[4] This literature demonstrates that health outcomes are socially patterned, with socioeconomic status and race serving as well-established axes of inequality in the U.S.

Although socioeconomic and racial disparities are well-documented, rural-urban differences have often been treated as secondary variables rather than primary drivers of health outcomes. However, recent studies suggest that rurality may be more significant than previously assumed. It has been found that infant mortality rates are significantly higher in rural areas than in urban counties, with rural infants facing persistent disadvantages even after accounting for maternal demographics.[5] Furthermore, rural counties have consistently elevated mortality rates and shorter life expectancy than urban areas, and this gap has widened over the past several decades.[6] In a CDC guest editorial, it has also been stated that rural counties face persistent challenges such as limited access to physical and mental health care and inadequate infrastructure.[7] The above research suggests that rurality may play a bigger role in explaining health disparities than previously thought. We seek to add to this literature by examining whether rurality alone impacts health outcomes or if it compounds existing socioeconomic factors in ways that consistently disadvantage rural communities.

This paper examines rurality as a less-explored dimension of U.S. health disparities to clarify its role for policymakers. Analyzing county-level data on chronic conditions, mortality, life expectancy, infant mortality, and healthcare infrastructure asks whether geography predicts health outcomes. The results show that rural and urban residents are equally likely to face common chronic conditions, but rural counties experience measurably worse outcomes, particularly in mortality and infant survival. This suggests that the disparity arises less from underlying health status than from differences in healthcare infrastructure and the quality of care. Recognizing geography as an underexplored but policy-relevant factor can help design interventions that improve not only access, but also the effectiveness of care in rural communities.

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Data

We draw the data on the rural population percentage in each mainland U.S. county from the 2020 Census Bureau on Urban vs. Rural areas in the U.S. This will allow us to directly examine the correlation between rurality and different health outcomes across the country.

CDC's PLACES database gives us data on Heart Disease (CHD), Diabetes, High Blood Pressure (HBP), Obesity, Cholesterol Screening (CS), Lack of Health Insurance (LHI), Routine Doctor Check-ups (RDC), and High Blood Pressure (HBP) Medication use. The data are presented as percentages of the adult population, and we use age-adjusted statistics for standardized comparisons. NIH's HDPulse database, updated in 2025, provides the Age-Adjusted All-Cause Mortality Rate (ACMR) per 100,000 by county. Lastly, we use the CountyHealthRankings 2025 data release for Life Expectancy (in years) and Infant Mortality Rate (IMR) per 1000 by county.

Method

We analyze data on health outcomes and ruralness by running single-variable linear regressions to examine the correlation between the percentage of the rural population and each health category. The results are correlation-only, and no inference of cause-and-effect is possible.

CHD, Diabetes, HBP, and Obesity are proxies for the health of the population in each county. These four health conditions were selected because they are not heavily influenced by genetics. For example, 90-95% of diabetes patients are Type 2, which is caused primarily by lifestyle choices. These common health conditions allow us to assess whether a rural population is healthier than an urban one, or vice versa, without accounting for genetic influences. The analysis of 3,144 counties helps smooth out any outliers or genetic fluctuations.

ACMR, Life Expectancy, and IMR can provide great insights for healthcare quality. The ACMR and Life Expectancy can give us clues about the overall quality of healthcare support one receives. IMR can have direct implications for prenatal, infant, and specialized healthcare.

Lastly, we chose CS, LHI, RDC, and HBP Medicine as representations for healthcare accessibility. CS and HBP medications are selected because they directly correlate with the health outcomes we are measuring. We also chose RDC and LHI as measurements because they are the most basic forms of healthcare.

Because of the U.S.'s many county outlining and planning systems, we imported all relevant data into a single master database and sorted the states and their respective counties alphabetically. Accordingly, we added each corresponding health data for that county in the succeeding columns. However, many rows are missing one or more data points in the database, as each database uses a different method to measure counties, municipalities, and urban planning regions. So, although there are 3144 official U.S. counties, our database contains more than 3264 rows due to the multiple differences in county criteria. For example, Baltimore County is the official census county. However, CountyHealthRankings treats Baltimore County and Baltimore City as separate entities, each with its own values, creating gaps in data when different databases are combined. We account for this by including all possible counties in each dataset and filling in the corresponding data, leaving entries blank if one database does not cover that county. These blanks are not included in our regression models, so they will not affect our results.

Results

Health Conditions:

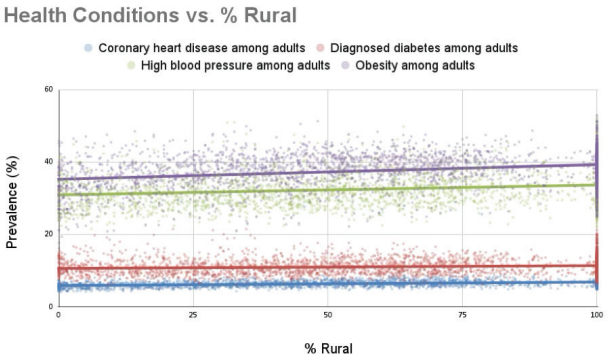

Figure 1: Scatterplots and linear regressions showing the association between county rural population share and four chronic conditions (obesity, high blood pressure, diabetes, and coronary heart disease). All correlations are weak, with small effect sizes. These results indicate that chronic disease prevalence is broadly similar across rural and urban counties, with only minimal increases as rurality rises.

Figure 1 above shows the correlations between the percentage of the rural population and the four health conditions we measured. The purple datapoints and trendline are for obesity (slope = 0.041), the blue for HBP (slope = 0.027), the red for diabetes (slope = 0.0077), and the green for CHD (slope = 0.0099). These regressions show minimal to modest urban-rural differences across chronic health conditions. For every percent increase in ruralness, there is only about a 0.01% increase in CHD, and only about 13.5% of the variations in CHD between counties are explained by ruralness (R^2 = 0.135). The trend is the same with diabetes: every percentage increase in ruralness correlates with a 0.008% increase in diabetes prevalence, and only 1.3% of the variation is explained by rurality (R^2 = 0.013). HBP rose marginally with ruralness, with each percentage increase in ruralness correlating with a 0.03% increase in prevalence, but ruralness accounted for only 3.8% of the variance (R^2 = 0.038). Obesity had the strongest correlation, with every percentage increase in ruralness associated with a 0.04% increase in obesity prevalence, though rurality explained only 8.8% of the variation (R^2 = 0.088). These results show that chronic conditions differ only slightly across rural and urban counties, and ruralness explains a small proportion of the observed variation. This suggests that, for the conditions measured, rural populations are not markedly different in underlying chronic disease prevalence, although these analyses cannot capture all dimensions of health.

Health Outcomes:

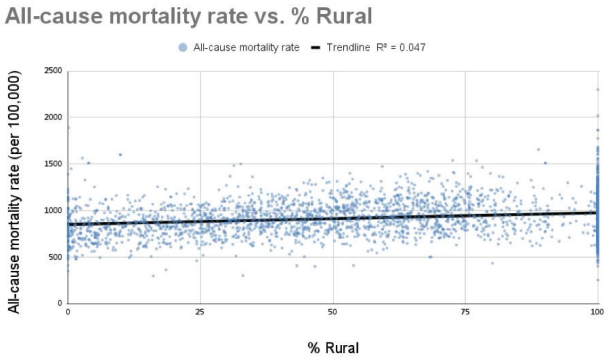

Figure 2: Scatterplot and linear regression illustrating the association between rural population percentage and age-adjusted all-cause mortality per 100,000 residents. A modest positive correlation is observed. This suggests that more rural counties experience higher mortality rates, even though the strength of the relationship remains modest.

The correlation between ACMR per 100,000 and rurality is shown in Figure 2 above. The slope of the trendline is 1.25, meaning that for every increase in rural percentage, the mortality rate increases by 1.25 per 100,000. Since typical urban-rural counties differ by 20-40% in ruralness, this corresponds to 25-50 more deaths per 100,000 people in rural counties than in urban ones. However, rurality is not the major driver of this increase in mortality rate, accounting for only 4.7% of the variation (R^2 = 0.047). These findings show a modest positive association between ruralness and mortality. When viewed alongside the weak correlations in Figure 1, this suggests that differences in mortality do not directly mirror differences in chronic condition prevalence. Because these data are correlational and lack socioeconomic and demographic controls, the underlying reasons for this pattern cannot be determined here.

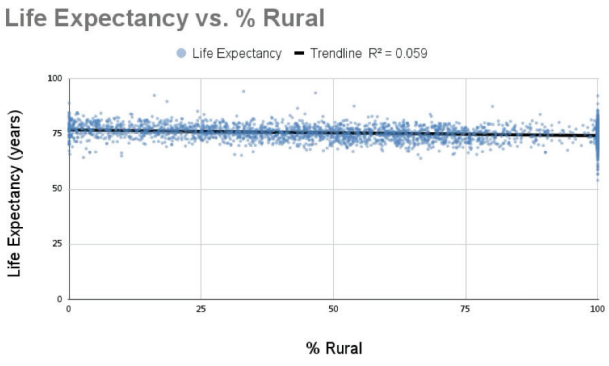

Figure 3: Scatterplot and linear regression between county rural population percentage and life expectancy at birth. The regression indicates a small negative correlation. This indicates that life expectancy tends to decline as rurality increases, though rurality explains only a small portion of the variation.

Figure 3 above shows the association between Life Expectancy (in years) and the percentage of the rural population. The trendline's slope is -0.026, meaning that each additional percentage of ruralness is associated with a decrease of around 9.5 days in life expectancy (0.026*365 ~ 9.5). Rural counties have life expectancies up to 2.6 years shorter (0.026*100 = 2.6). However, rurality alone only accounts for 5.9% of the variance (R^2 = 0.059). This finding aligns with the ACMR results in indicating that life expectancy tends to be lower in more rural counties, although the explanatory power is modest. As with other outcomes, these correlations do not indicate causation, and additional factors not included in this study likely play substantial roles.

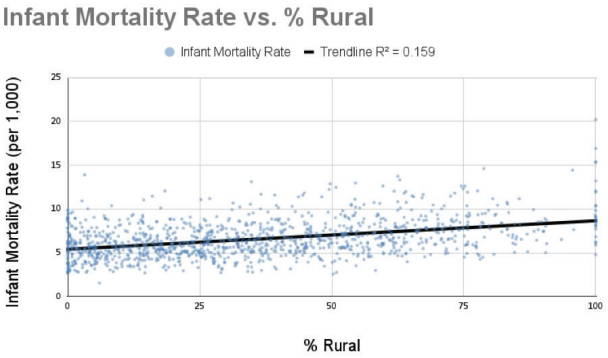

Figure 4: Scatterplot and linear regression showing the relationship between rural population percentage and infant mortality (deaths per 1,000 live births). This is the strongest correlation among the measured outcomes, though it remains modest. This highlights that infant mortality is the outcome most strongly associated with rurality, suggesting potential disparities in maternal or specialized care.

Figure 4 above shows the association between IMR per 1000 and ruralness. The slope of the trendline is 0.033, meaning that for each increase in rural population percentage, there is an additional 0.033 infant death per 1000 live births. In a county that's 40% more rural, there will be 1.3 more deaths per 1000, which is a 23% increase over the U.S. average of 5.6 per 1000. Furthermore, rurality alone accounts for 16% of the variance (R^2 = 0.16), far more than any other metric we measured. IMR shows the strongest association with rurality, matching previous research on geographic differences in infant outcomes. While this association is notable, this analysis cannot determine underlying mechanisms, and factors such as socioeconomic conditions, maternal characteristics, and healthcare access may contribute to the observed pattern.

Health Infrastructure:

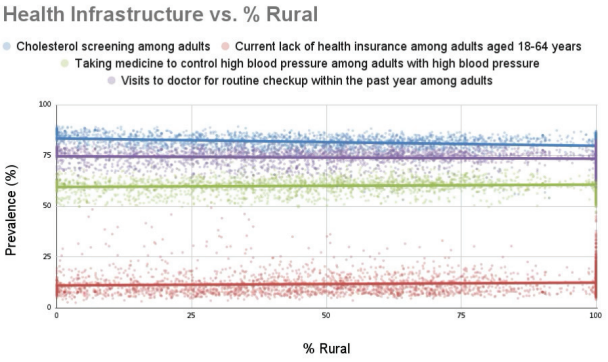

Figure 5: Scatterplot and linear regression between rural population percentage and four access measures (cholesterol screening, routine doctor checkups, lack of health insurance, and high blood-pressure medication use). Most indicators show minimal correlation, except for a modest decline in cholesterol screening. These results suggest that most basic healthcare access measures are similar across geographies, with the main difference appearing in preventive care such as cholesterol screening.

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Figure 5 above shows the correlation between CS, RDC, LHI, and HBP Medication and the percentage of the rural population. The blue datapoints and trendline are for CS (slope = -0.036), purple for RDC (slope = -0.012), red for LHI (slope = 0.014), and green for HBP medication use (slope = 0.012). The very flat slopes mean that the healthcare infrastructure we measured showed minimal association with rurality, with the only modest association being CS, where every percent increase in ruralness correlates to 0.036% fewer adults screened for cholesterol. This means that in a county that's 40% more rural, roughly 1.4% fewer adults will be screened. Rurality also accounts for 11.9% of the variance (R^2 = 0.119). These findings suggest that basic healthcare access indicators such as insurance coverage, doctor visits, and medication use are relatively similar across geographies. The modest association with cholesterol screening indicates possible differences in preventive care, but the dataset does not allow us to determine the causes of these differences.

Discussion

In this study, we present the correlation between four health conditions (Diabetes, Obesity, HBP, and CHD), three health outcomes (ACMR, Life Expectancy, and IMR), and four health infrastructures (CS, LHI, HBP medication, and RDC) and rurality.

Results Implications:

When we look at the chronic conditions, ruralness only shows weak correlations. The R^2 values never exceed 0.135, indicating that geography alone accounts for only a slight increase in chronic disease prevalence. In other words, the chronic conditions measured here do not differ substantially between rural and urban residents. Additionally, the breadth of healthcare infrastructure is essentially the same across urban and rural counties, with access to insurance, medication, and doctor visits very similar across geographies; the only difference is preventive services, such as cholesterol screening, where there is a noticeable decline in rural counties. However, health outcomes differ between urban and rural counties despite similar levels of health and healthcare access. ACMR rises noticeably, life expectancy declines modestly, and IMR increases most strongly with rurality. These findings show that rurality is associated with worse outcomes even when underlying chronic disease prevalence is similar, though the data cannot determine the specific causes behind these patterns.

Although structural features of the rural healthcare environment, such as longer distances to hospitals, fewer specialists, or limited facility capacity, may contribute to these differences, this interpretation cannot be confirmed from the available data. The contrast between similar prevalences of chronic illnesses and worse health outcomes suggests that qualitative differences in healthcare contexts may play a role. Still, unmeasured socioeconomic and demographic factors are also likely to be important. The elevated IMR, which may reflect gaps in specialized or preventive prenatal care, along with the decline in CS prevalence, suggests that preventive care may be less accessible in rural counties. However, this remains a correlation rather than evidence of a direct causal relationship. These preventive services are important for reducing health risks and detecting diseases early, but our county-level data cannot determine how much they contribute to outcome disparities.

However, despite the outcome differences, the low R^2 values (never exceeding 0.16) show that rurality itself explains only a small portion of the variation. This suggests that other socioeconomic factors remain more significant determinants of health disparities, consistent with previous research. Rather than acting as a primary cause, rurality appears to be linked with broader social and structural conditions that may amplify existing inequalities. Overall, the results reveal a clear pattern: Rural and urban populations are similarly healthy in terms of chronic conditions, yet rural areas face worse health outcomes, especially in mortality rates and infant survival. This divergence indicates that health disparities are shaped by a combination of geographic context and factors not captured in this analysis. Future research that includes individual-level data, richer measures of healthcare capacity, and multivariable models would help clarify the mechanisms behind these associations.

Policy Implications:

These findings have several policy implications. First, they suggest that simply expanding healthcare access, such as increasing insurance coverage or the number of available doctors, may not, on its own, close the urban-rural health disparity. Instead, policymakers may need to focus on strengthening the overall capacity and quality of rural healthcare systems, as well as improving the reach of preventive and maternal care. Efforts such as expanding telehealth services, supporting rural hospitals, and incentivizing specialized healthcare practices in rural areas could help address some of the differences observed in health outcomes, even though this study cannot determine the specific causes behind those differences. Public health programs like mobile screening clinics or subsidized preventive check-ups may also help offset geographic barriers and improve service availability.

Additionally, the results highlight the need for more consistent and standardized data collection practices. For example, Connecticut reports both counties and planning regions, which complicates comparisons across datasets, and Florida does not provide HBP or HBP medication data, which limits the completeness of county-level health analyses. Policymakers could support the development of standardized guidelines for collecting and reporting county-level health data, which would help future researchers more reliably organize, compare, and analyze health indicators across states. Clearer, more uniform data standards would strengthen the evidence base needed to better address rural-urban health disparities.

Limitations:

This study has several limitations. Firstly, our data are limited to the percentage of the rural county population and do not include potential confounding factors such as income, education, race, or gender. As a result, the associations between ruralness and health outcomes cannot be interpreted causally, since many unmeasured socioeconomic and demographic factors may play

a more substantial role. Based on the available data, rurality can be viewed only as correlated with existing inequities, rather than as an independent driver of them. Secondly, our county-level data may hide disparities within counties. Because counties differ widely in size, population, and demographic composition, reducing each county to a single aggregate value may overlook important community-level variation and introduce the possibility of ecological fallacy. Lastly, the Census measure of rurality, defined only as the percentage of residents living in rural areas, does not capture structural factors such as provider availability or travel distance. For these reasons, the present analysis should be interpreted cautiously, as the findings are descriptive rather than definitive. Future research using individual-level data, multivariable models, and richer measures of healthcare capacity would help clarify the mechanisms underlying the observed geographic patterns.

■ Conclusion

This study shows that rural residents are not substantially less healthy than urban residents with respect to the chronic conditions measured. However, they face worse outcomes, including higher mortality, shorter life expectancy, and elevated infant mortality. These patterns may reflect differences in preventive care or healthcare environments, though the present analysis cannot determine the specific causes. The findings suggest that geography is associated with variations in outcomes even when chronic conditions appear similar, underscoring the need to better understand the factors shaping rural health. For policymakers, this means that improving rural health may require not only maintaining access but also strengthening preventive services, maternal care, and the overall capacity of local healthcare systems. Addressing these challenges will be important for reducing persistent inequities and supporting healthier, longer lives for rural communities.

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■ References

1. Montez JK, Hummer RA, Hayward MD. Educational attainment and adult mortality in the United States: a systematic analysis of functional form. Demography. 2012 Feb;49(1):315-36. doi: 10.1007/s13524-011-0082-8. PMID: 22246797; PMCID: PMC3290920.
2. Chetty R, Stepner M, Abraham S, Lin S, Scuderi B, Turner N, Bergeron A, Cutler D. The Association Between Income and Life Expectancy in the United States, 2001-2014. JAMA. 2016 Apr 26;315(16):1750-66. doi: 10.1001/jama.2016.4226. Erratum in: JAMA. 2017 Jan 3;317(1):90. doi: 10.1001/jama.2016.18691. PMID: 27063997; PMCID: PMC4866586.
3. GBD US Health Disparities Collaborators. Life expectancy by county, race, and ethnicity in the USA, 2000-19: a systematic analysis of health disparities. Lancet. 2022 Jul 2;400(10345):25-38. doi: 10.1016/S0140-6736(22)00876-5. Epub 2022 Jun 16. PMID: 35717994; PMCID: PMC9256789.
4. GBD US Health Disparities Collaborators. Cause-specific mortality by county, race, and ethnicity in the USA, 2000-19: a systematic analysis of health disparities. Lancet. 2023 Sep 23;402(10407):1065-1082. doi: 10.1016/S0140-6736(23)01088-7. Epub 2023 Aug 3. PMID: 37544309; PMCID: PMC10528747.
5. Ely DM, Driscoll AK. Infant Mortality in the United States, 2022: Data From the Period Linked Birth/Infant Death File. Natl Vital Stat Rep. 2024 Jul 25;(5):10.15620/cdc/157006. doi: 10.15620/cdc/157006. PMID: 39412861; PMCID: PMC11513748.
6. Singh GK, Siahpush M. Widening rural-urban disparities in life expectancy, U.S., 1969-2009. American Journal of Preventive Medicine. 2014 Feb;46(2):e19-29. DOI: 10.1016/j.amepre.2013.10.017. PMID: 24439358.
7. Matthews, K. A.; Spears, K. S.; Anderson-Lewis, C. Rural Health Disparities: Contemporary Solutions for Persistent Rural Public Health Challenges. Prev. Chronic Dis. 2025, 22, 250202. https://doi.org/10.5888/pcd22.250202

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A Weapon of Mass Distraction: Misinformation in the Russian-Ukrainian Conflict

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ABSTRACT: Tackling the misinformation crisis is a perennial challenge that has stumped policymakers for decades. With the advent of social media, this issue has become even more pertinent for discussion. Extensive research has been conducted to broadly assess the misinformation crisis or recommend specific policies in unique circumstances. Yet there has been little investigation into specific case studies of misinformation to determine the future of misinformation regulation. As such, this research paper will predominantly use the context of the Russian-Ukrainian war to discuss the scope and magnitude of the misinformation crisis. Subsequently, it discusses the strengths and limitations of current misinformation regulation before providing a general direction for future regulation, drawing on lessons from the Russian-Ukrainian War.

KEYWORDS: Behavioral and Social Sciences, Algorithms, Russian-Ukrainian War, Misinformation.

Introduction

Digital misinformation has emerged as one of the most destabilising forces in the last decade, no longer confined to slow-moving rumors or hearsay.[1] Through a hyper-connected digital ecosystem, misinformation now fuels the agenda of bad actors, sows the seed of fear among the populace, and even threatens to destroy the social fabric of society as we know it today. It is uniquely characterized by its speed, reach, and integration with an indispensable part of our lives – social media.[2] As such, misinformation has been transformed from a peripheral risk into a systemic threat that requires immediate attention. This is particularly evident in the 2022 Russian-Ukrainian war, which has even been described as the "first social media war" in history.[3] While misinformation exists on both sides of the conflict, this research will predominantly analyze pro-Kremlin misinformation, as misinformation has been used as a strategic weapon to influence public sentiment in favor of Russia in order to project military power.[4]

Existing scholarship has examined the role of digital platforms in shaping the spread and governance of misleading information. For instance, Tucker, Theocharis, Roberts, and Barberá demonstrate how social media platforms facilitate the rapid diffusion of political misinformation,[5] while scholars such as Tarleton Gillespie[6] and Evelyn Douek[2] have explored how platform governance and content moderation influence the circulation of misleading content online. However, much of this literature tends to focus either on the technological mechanisms of misinformation spread or the regulatory frameworks designed to address it. Relatively little research employs qualitative case-study analysis to examine how misinformation and regulation operate in practice within a specific geopolitical context. Therefore, this paper adopts a qualitative case-study methodology, using the Russian-Ukrainian war, to examine the dynamics of misinformation. By analyzing documented instances of misinformation throughout the conflict and situating them alongside existing scholarship on social media governance, this research paper identifies recurring patterns in the types, methods, and platforms through which misinformation can spread. Ultimately, this research paper aims to answer the central question: What does the Russian-Ukrainian war teach us about how misinformation operates across platforms, and how can regulation address it? By the end of the investigation, the research paper proves that the misinformation in modern conflicts is not merely the result of individual actors spreading false information. Instead, it is amplified by the structural features of social media platforms and the current inadequacies of self-regulation and state-run regulation. By situating these empirical observations within the broader debate over platform self-regulation and state intervention, the research paper also aims to derive broader insights from the Russian-Ukrainian conflict that can inform future approaches to regulating misinformation.

Section 1 will first define the scope of misinformation, concretizing the distinction among misinformation, disinformation, and misleading information. Subsequently, it will lay out the magnitude of harm caused by misinformation, namely through the creation of inaccurate narratives and the formation of echo chambers. By further examining the international scale and deep-rooted tensions surrounding the Russian-Ukrainian war, this section will also stress why regulation has become a pressing necessity.

Building on this foundation, Section 2 will analyze the two main types of misinformation, military-related and political-related, in the Russian-Ukrainian war. While this research has already established that misinformation is systematically amplified by social media algorithms, engineered to provoke emotional responses, and capable of influencing millions, this section seeks to evaluate the various methods and media used to spread misinformation in a contemporary geopolitical landscape. Lastly, Section 2 will introduce society's current

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response to misinformation and ultimately demonstrate that the absence of social media regulation will inevitably lead to its spread.

Section 3 directly examines the contentious debate over social media regulation, evaluating the strengths and limitations of self-regulation and state regulation. Through global case studies and examples from the Russian-Ukrainian war, Section 3 will highlight the trade-off between freedom of speech and efforts to reduce harmful misinformation. This sheds light on the complex and dynamic challenge of misinformation regulation while considering the various motivations of stakeholders.

Finally, Section 4 will consolidate the findings from the first three sections and holistically analyze the nuances of the misinformation crisis in the Russian-Ukrainian war. This paper will not only evaluate current efforts to regulate misinformation but also discuss a sustainable path forward. This paper aims to inform efforts to strengthen global resilience to misinformation, thereby protecting the social fabric that underpins both democratic governance and civic stability.

SECTION 1: THE MISINFORMATION CRISIS:

To understand the importance of misinformation regulation, Section 1 will outline what constitutes misinformation, before further contextualizing it in relation to the Russian-Ukrainian war. This section aims to fulfill these objectives by elucidating the detrimental impacts and immense scale of the misinformation crisis. Coupled with the complicating factors of the Russian-Ukrainian war, the need for social media regulation will become apparent.

Section 1.1: The scope of misinformation:

Caldwell University defines misinformation as the spread of misleading information without deceptive intent. Additionally, it defines disinformation as "false or misleading information shared with the intent to mislead, confuse, or deceive people."[7] While intent to mislead distinguishes misinformation from disinformation, discerning intent in the real world is challenging. In the context of the Russian-Ukrainian war, for instance, isolated instances of misleading content often circulate online without clear attribution. Thus, it is difficult to determine whether the misinformation stems from genuinely misinformed individuals or from Russia's state-sponsored disinformation campaigns. These campaigns are strategically designed to manipulate public perception on a large scale, giving them far greater reach than independent sources of misinformation. Yet, these same campaigns also disguise disinformation as the personal views of independent, concerned netizens. This further obscures the origins of misleading narratives, making it extremely difficult to distinguish between organically spreading misinformation and coordinated disinformation efforts based on intent.

Therefore, in order to facilitate discussion, this paper defines misinformation as false or inaccurate information, regardless of intent. Given that the primary focus of this paper is the mechanics of regulating misleading information on social media platforms, exploring intent would be unproductive and would require separate research. Therefore, by addressing both unintentional and malicious fake news, this streamlines the discussion of information classification (whether it is traditionally considered misinformation or disinformation), enabling more in-depth evaluation of both forms of misinformation.

Section 1.2: The magnitude of harm caused by misinformation:

The danger of misinformation lies in its ability to remain indistinguishable from factual information. Given that it is premised on misguided or misleading information, it often relies on emotional manipulation to erode our ability to gather accurate and reliable information. Its harms manifest in two dominant ways, namely the clouding of objective facts and the creation of echo chambers.

Firstly, misinformation clouds objective facts by creating inaccurate narratives. It is significantly easier to produce misinformation than factual information, because factual information requires testing and verification, whereas misinformation relies on emotional rhetoric to appeal to the audience. This results in a greater volume of misinformation than of factual information, leading to oversaturation on social media. This information overload leads the audience to deprioritize the veracity of claims, focusing instead on features that improve audience retention, such as emotive language. This clouds objective facts and makes the audience more susceptible to believing misinformation.

Secondly, misinformation is problematic because it creates echo chambers. Social media algorithms work by recommending to users what they most likely want to watch. This means that the platform prioritizes content that garners user engagement – regardless of its accuracy. Consequently, users are drawn into information silos, where they are exposed only to content that already reinforces their preexisting beliefs, even when those beliefs were borne of misinformation.[8] At the same time, echo chambers surround users with a community that shares and legitimizes the same views, making it harder for them to recognize that some content is misinformation.

Apart from the apparent problems propagated by misinformation, identifying whether a particular piece of information constitutes misinformation is also frustratingly obtrusive. One possible reason for this could be the blurry line between fact and opinion. Just as it is difficult to discern the intent behind spreading misinformation, it can be difficult to distinguish between facts and opinions. When an individual wants to present an objective fact on social media, there are still countless subjective decisions to make, such as the language used to demonstrate the point, the description of the fact, or even the balance between textual and visual elements.[9] There is a non-zero chance that the resulting content is misinformation, especially since these subjective elements can be interpreted differently based on a viewer's worldview or lived experiences, thereby leading to inaccurate interpretations of the information.[10]

Another reason for this difficulty stems from the difficulty of discerning fact from fabrication. By definition, short-form content on social media can only provide abridged explanations

or descriptions. For instance, this could look like thirty-second videos with three to four lines of speech explaining why climate change is a hoax, as well as posts featuring aesthetic infographics on healthy eating that claim to be based on "scientific research."

Although these simplified narratives have innocuous intentions, they can cause significant issues when trying to substantiate broader, more nuanced arguments. With the information posted being highly generalized, it is hard to determine whether the content is based on semblances of the truth or pure fabrication.[11]

Section 1.3: The scale of harm caused by misinformation:

Beyond the immense magnitude of harm it can cause, the speed and scale of misinformation's spread underscore the need for social media regulation. According to Pew Research Center research, social media now plays a central role in news consumption. In 2024, fifty-four percent of American adults get their news from social media, underscoring how digital sources have become an essential part of individuals' news diets.[12]

This is especially relevant when discussing misinformation stemming specifically from the Russian-Ukrainian conflict. With millions of lives displaced, global supply chain disruptions, and shifting global power dynamics, the Russian-Ukrainian conflict is one of the highest-stakes conflicts of recent history. Given that nationalistic sentiments are being fuelled by strong emotions such as pride and fear, online discourse around this conflict becomes emotionally charged. This subconsciously influences individuals to take sides in the conflict, leading to a high degree of politicization on social media platforms.[13]

Even though many other conflicts in recent history have suffered heavy casualties (such as the Yemen or Ethiopian crisis), none have had media coverage on par with that of the Russian-Ukrainian conflict. As such, the Russian-Ukrainian war has been described as the first "social media war" in history.[14] Every development, atrocity, and counter-narrative is broadcast worldwide through social media, with posts and comments providing additional updates on the war. The virality of such content produced by Ukrainians, Russians, and their respective sympathizers makes the situation even more volatile, demonstrating the global reach of the Russian-Ukrainian conflict.

To the global community, the Russian-Ukrainian war is more than a regional conflict. It has the potential to escalate to an international conflagration with superpowers taking sides.[15] However, one must also recognize that the tensions between the two countries have existed long before Russia's direct invasion of Ukraine in 2022. This means that there has been, and will continue to be, exceptional scrutiny of the Russian-Ukrainian conflict, thereby increasing demand for information and the reach of misinformation surrounding this issue. Therefore, now more than ever, it is crucial to keep misinformation under control to prevent its harmful effects from affecting a significant portion of society that relies on social media for news.

However, this will be challenging given recent discoveries regarding the spread of misinformation. A study conducted by MIT reveals how false news spreads much faster than real news by a substantial margin. Across all categories of information, falsehoods diffused significantly faster, deeper, and farther than factual information.[16] To rationalize these findings, this paper provides two possible explanations.

On one hand, the emotional charge of misinformation may drive audience engagement. Unlike factual information, which should always aim to make a rational point, misinformation leverages the power of strategic narratives to appeal to viewers' emotions.[17] Effectively, instead of convincing users with logic and facts, misinformation taps into emotions to blur the line between reality and fabrication, thereby facilitating easier message retention. Thus, even if viewers doubt the accuracy of such content, the emotional rhetoric leaves a lasting impression.

Alternatively, it can also be argued that platforms themselves facilitate the spread of misinformation. This is because social media companies are inherently profit-driven. Given that these companies can only achieve their goals by increasing users' time spent on social media platforms, they would naturally prioritize user engagement. Yet this creates a perverse incentive to share content indiscriminately, regardless of quality or accuracy, because misinformation can be more engaging for the reasons stated earlier.[18] Therefore, this paper posits that the spread of misinformation may also be encouraged at a systemic level.

SECTION 2: QUANTIFYING THE PROBLEM:

Building on the earlier characterization of misinformation, Section 2 explores the different types of misinformation in the status quo. It will also discuss the methods and media used to spread misinformation, as well as other difficulties in regulating the status quo. This will effectively illustrate the problem of misinformation, providing context on its various forms and the public's response to it in the status quo.

Section 2.1: Types of misinformation:

Misinformation can vary in type and nature. From inaccurate data in viral videos to doctored images on social media posts, there are countless ways in which misinformation has emerged in the Russian-Ukrainian war. Nevertheless, for the sake of discussion, this paper has identified two dominant categories of misinformation: Military-related misinformation and political misinformation. These categories are not merely academic; they encapsulate real events.[4]

On one hand, military-related misinformation deserves particular attention in this conflict. Given the direct military confrontation taking place in Ukraine, it is only logical that misinformation regarding the war efforts starts to spread through social media. Without being physically present in Ukraine, the international community lacks firsthand knowledge about the conflict. Instead, they are forced to piece together scraps of information from social media to better understand the conflict's developments.[4] This information vacuum creates fertile ground for the spread of misleading claims about military events. Users may misinterpret footage,

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circulate outdated images from unrelated conflicts, or fabricate battlefield developments in an attempt to contribute to online discussions about the war. Additionally, countries themselves may also exploit this uncertainty. Studies have shown that Russia has strategically used social media to amplify misleading narratives about military developments, portraying its forces as liberators while discrediting NATO and Western institutions as imperialist aggressors. In such uncertain environments, individuals often accept misleading claims rather than remain without information. As Greenhill and Oppenheim argue, the absence of direct evidence can lead audiences to adopt unverified narratives as plausible explanations. Once internalised as truth, these narratives may then be reshared by ordinary users, allowing misinformation about military developments to spread widely across social media platforms.

Political misinformation is another category for consideration. Beyond misinformation directly targeting the war efforts in Ukraine, there is also misinformation regarding the context of the conflict. Russia spreads narratives of its country being the heroic victor of World War II, and Ukraine betraying its historical roots by aligning with the West. This narrative becomes even more believable when considering that some of the accusations against Ukraine have proven true. The Azov Brigade, for example, was accused of having Nazi connections given its contentious use of Nazi-related symbols, and members of its unit committing human rights violations.[19] This has led to the rampant spread of misinformation, whether intentionally by the Russian government or unintentionally by members of the public, that the rest of Ukraine is similarly fascist or has Nazi connections. Regardless of intent, this misinformation has tainted Ukrainian leaders with suspicious historical connections.[4] The scandalous nature of such claims has further spread misinformation. Even though a claim may be supported by dubious sources or fabricated evidence, the initial outrage still garners traction on social media, depicting Ukraine as an illegitimate and morally gray country.

Both political and military misinformation pose a similar threat to society. They tend to promote pro-Kremlin narratives, conveying the consistent narrative that Russia will eventually "liberate" Ukraine, whether it is by exaggerating the overwhelming military resources of the Russians, or tainting the image of Ukrainian leaders through unsavory historical connections.[4] Thus, these two types of misinformation will be referenced throughout the rest of the research.

Section 2.2: Methods of misinformation:

Even on social media, misinformation can be spread through various methods. Among the most common are repurposed photos and videos, fake eyewitness accounts, and internet trolls. Each of these methods contributes to misinformation on social media in its own way.[6]

Firstly, recontextualized images from unrelated sources are used to support false narratives, misdirecting viewers and leading them to form incorrect conclusions. For instance, a war photo in 2014 was falsely circulated as proof that Ukrainian soldiers injured a twelve-year-old boy in Sloviansk, thereby acting as evidence of Ukrainian aggression in Sloviansk. However, it was later revealed that the photo was actually a 2013 photo from the Syrian War, with no connection to the supposed Ukrainian aggression.[6] This method of misinformation is particularly effective due to the well-documented Picture-Superiority Effect (PSE). First discovered by Paivio and Csapo in 1973, PSE is a cognitive bias in which images are more likely to be internalised than text on a screen.[20] Even for bite-sized information where both text and image are easily remembered in immediate recall, images were found to be significantly more memorable in delayed recall.[21] At the same time, unlike other methods of misinformation, which present facts and data to viewers, images serve as visual stimuli that influence viewers' interpretation of the situation. Using contextual clues from the surrounding text, viewers form connections between text and image, under the tacit assumption that images must be relevant to the accompanying text.[22] However, when images are recontextualized, their context is misrepresented. Viewers end up with an inaccurate interpretation, thereby propagating misinformation.

Additionally, fake eyewitness accounts lend a false sense of legitimacy, further propagating misinformation.6 In 2014, a self-proclaimed pro-Russian emergency doctor, Igor Rozovskiy, reported on Facebook that Ukrainian nationalists did not allow him to help other injured pro-Russian demonstrators after a fire at the Trade Unions House. The story was reposted thousands of times and even translated into different languages before it was realized that Rozovskiy was not an emergency doctor but a dentist. Additionally, his Facebook account was created only immediately before he published that story and was deleted soon after that truth was revealed.[6] While the truth was eventually revealed, it was not before thousands believed the fabricated incident. What makes this method of misinformation especially problematic is the lack of readily available corroborative evidence. To correct misinformation, the correction needs to be specific enough for the public to understand which aspect of the claim is being refuted.[23] However, in the case of the Russian-Ukrainian War, verifying or refuting statements is challenging due to the conflict's isolated nature. Therefore, so long as the information seems logically congruent, individuals tend to believe the claim, regardless of its actual veracity.

Nevertheless, the most pervasive source of misinformation remains internet trolls. Internet trolls provoke social discord by expressing disagreement toward the subject matter through a combination of insults, jokes, and unhelpful comments.[24] Such trolls have various motivations for spreading misinformation, ranging from being excessively opinionated to being state-sponsored agents or simply wanting to seek entertainment. Russia has repeatedly denied the existence of state-sponsored internet trolls, but the discovery of a "troll factory" situated near St. Petersburg suggested otherwise. Regardless of whether the Russian government indeed paid the trolls, their disruptive effect is undeniable. The Guardian reported coordinated attacks on its Russia and Ukraine articles, facing up to forty thousand troll comments per day.6 Internet trolls are particularly effective as they rely on quantity, rather than the quality of information. By flooding comment sections, mass-report-

ing posts, and asserting unsubstantiated claims, internet trolls drown out legitimate, factual information, thereby enabling the rapid spread of misinformation.[25]

Section 2.3: Media of misinformation:

At the same time, this paper acknowledges that not all social media platforms are identical: some platforms, like Telegram, are vastly different from others, such as Instagram or TikTok. Understanding these differences will be crucial, as they have significant implications for social media regulation and will inform policy decisions on how best to regulate misinformation across platforms.

One medium for misinformation is social messaging applications, such as Telegram. The platform has been widely used during the Russian-Ukrainian war to disseminate information and boost morale. Over the last few years, the Russian government has flooded the platform with over three hundred thousand inauthentic comments under the guise of seeking peace and cooperation.[26] These comments promote pro-Russian ideology and anti-Ukrainian narratives targeted at Ukraine's occupied territories, fuelling the government's efforts to control the narrative by framing the Russian-Ukrainian war as a "special military operation." Telegram's structure creates favorable conditions for the circulation of misleading information. This is primarily due to end-to-end encryption, which ensures that messages are unreadable by third parties, including fact-checkers who would otherwise be able to track the content being shared.[27] As such, the platform's decentralized communication model allows messages, images, and videos to spread rapidly across channels with minimal oversight. Nevertheless, this medium for misinformation has the lowest impact. This is because the spread of misinformation through this medium is reliant on the viewer's interest in the subject. Unlike algorithm-based platforms, Telegram requires users to actively join channels or group chats to receive information.[28] Therefore, if an informed individual recognizes the risk of misinformation from a specific source, they will consciously choose not to join the channel, thereby breaking the chain of misinformation.

Another medium for misinformation is media-sharing platforms like Instagram and TikTok. These platforms are highly visual and prioritize user engagement through their algorithm-driven recommendation system. Additionally, studies have shown that user engagement is prolonged by emotionally charged, shocking, or even polarising elements.[29] Thus, it is unsurprising that there have been numerous instances in which these platforms have been used to post aestheticized war footage with misleading captions and edited clips from interviews with government officials. Investigations by BBC Verify have revealed videos on TikTok that misleadingly portray Ukrainian President Volodymyr Zelensky as profiting from the war while remaining detached from the suffering of Ukrainian civilians.[30] The spread of misinformation through this medium is especially detrimental, as the algorithm-based recommendation system is highly likely to continue exposing users to misleading political content, even without seeking it out, so long as they have watched similar content on the Russian-Ukrainian conflict.

Another medium for misinformation is discussion forums, including Twitter (now known as X) and Reddit. These platforms offer a conversation-like format for individuals to share opinions, view links, and join communities based on various topics.[31] In the context of the Russian-Ukrainian conflict, this manifests itself in users sharing absurd claims such as the Russian-Ukrainian War being fake.[32] Unlike the other two mediums, misinformation is not directly forwarded to users or recommended by the algorithm. Instead, users actively choose the topic of discussion and interact with other users on the platform. Consequently, emotionally charged or politically polarising claims may gain visibility if they resonate with a particular online community. Over time, repeated exposure to these claims within a discussion forum can contribute to the formation of collective narratives that reinforce misinformation, as long as enough community members upvote them.[33]

Section 2.4: The current response to misinformation:

Given the variety of misinformation types, methods, and media, how does society currently respond to the misinformation crisis?

Firstly, bad actors increasingly weaponize social media to spread misinformation. These actors recognize how social media enables them to create spectacle rapidly, while drawing emphasis away from the lack of veracity of some of these claims.[19] As a result, misinformation has become more pervasive than ever. These actors continue to blur the boundary between truth and fiction, creating a post-truth environment where emotional appeal dominates social media.

As for regular social media users, a growing proportion of society is cognizant of the pro-Kremlin disinformation campaign and remains largely skeptical of information from Russian sources.[18] Given how this is not the first wave of misinformation, communities are already beginning to tackle misinformation through crowdsourced projects. For instance, StopFake was launched in 2014 in Kyiv to combat misinformation across various sources, including social media.[6] Although it started as a small grassroots initiative to debunk, it has since been joined by numerous professionals, growing into a vibrant community and symbolizing a new wave of citizen accountability in digital spaces. Although efforts thus far have been largely uncoordinated, the mere presence of such crowdsourced projects indicates an increasing desire to weed out misinformation.[6] At the same time, more vulnerable members of society continue to fall prey to misinformation. Based on research by Erlich and Garner, individuals who are less politically astute, identify with Russian ethnicity and language, and are demographically older tend to be more susceptible to misinformation. Parallels can be drawn to the status quo, with youths forwarding misleading reels on Instagram, or elders sending chain letters in their family WhatsApp chats.4

In all cases, it is evident that some form of intervention is necessary, whether by the government or by social media companies. When left to their own devices, social media users often fall victim to misinformation. Even within the subset

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of users that recognize the importance of tackling misinformation, crowdsource projects are currently uncoordinated and ineffective.

SECTION 3: REGULATION IN THE STATUS QUO:

The question of social media regulation has sparked immense discussion and controversy. Striking the right balance between protecting freedom of speech and curbing harmful misinformation requires both platform self-regulation and government-led regulation. Although both approaches have yielded some results, neither is without shortcomings. Section 3 will explore the state of regulation in these two areas, drawing on case studies and regulatory policies worldwide.

Section 3.1: Self-regulation:

Social media companies are keenly aware of the misinformation crisis that plagues their platforms. As a result, companies engage in self-regulation, voluntarily identifying and removing misinformation without direct state intervention. Self-regulation often involves internal rules and regulations adopted by companies on their own accord. For example, this could include protocols for scrutinizing advertisement placements, services, and fact-checking mechanisms.[34] At the same time, self-regulation is often guided by international frameworks and codes of conduct. In line with the EU Code of Practice on Disinformation being revised in response to concerns about Russian propaganda during the war, social media platforms such as YouTube and TikTok committed to more accountable content moderation in line with the code.[49] This policy builds on years of past self-regulatory efforts by social media companies, streamlining such policies on an international scale.

Social media companies have an active incentive to self-regulate for various reasons. Some platforms conduct content moderation out of a sense of moral responsibility.[35] For other social media companies like YouTube and Twitter, establishing free-speech norms is crucial to maintaining their identities. As such, they have established community guidelines on misinformation that align with the company's values and goals.[36] Even for social media companies that may not have a strong orientation toward managing content quality, content moderation will be necessary to prevent backlash from allowing misinformation to spread unchecked across the platform.[52] More compelling, however, are the economic incentives. Although corporate responsibility exists, the main reason most companies continue to regulate misinformation is the risk of losing potential profits. This is because allowing misinformation to propagate on the platform can lead to the alienation of users and advertisers, especially given the highly politicised and divisive nature of the Russian-Ukrainian war. This can lead to direct revenue losses when users leave the platform.[52] Therefore, to retain user engagement and protect the company's profitability, social media companies have an incentive to implement an effective content moderation system.

There are many examples of self-regulation by social media companies. For instance, when companies identify misinformation, most social media algorithms actively reduce its visibility by not recommending it to users, thereby limiting its spread and disincentivising users from posting it.[37] In more serious cases, companies also have the power to swiftly and comprehensively take down malicious content.[38] Nevertheless, beyond reactionary measures, companies also implement preventive safeguards to reduce the spread of misinformation. Through partnerships with fact-checkers across languages, social media platforms ensure quick verification of content flagged as potentially misleading. Companies like TikTok have even launched media literacy campaigns across Europe to help users, especially younger audiences, critically assess content, identify misinformation, and access reliable sources.[39]

Given the immense scale of misinformation on social media, platforms cannot have human moderators screen content before it is published. Instead, most companies utilize automated moderation systems to identify misinformation ex ante, helping prevent its spread before it reaches the public.[40] However, automated moderation runs the risk of over-censorship, especially when a post blurs the line between what is acceptable and what is not. Only the most harmful forms of misinformation are immediately removed by the platform, while less severe cases are instead made less visible to users.

From these measures, this paper posits an implicit hierarchy of misinformation in the eyes of social media companies. For outright harmful rhetoric likely to gain traction, social media companies may prioritize moderation through automated algorithms, ensuring that the post has zero reach. However, for more nuanced and contentious issues, the social media company may allow the content to circulate, relying on human moderators to sift it for misinformation.[41]

Unfortunately, the current system of self-regulation still has significant limitations. Across the industry, platforms often have different interpretations of the hierarchy of misinformation, leading to varying degrees of content moderation. Some companies choose to err on the side of caution, removing most content that they deem as misleading or malicious. Other companies prefer to disregard controversial cases to prevent backlash from wrongly labeling content as misinformation.[42]

Even within the platform, content moderation can be inconsistent. One striking example is Twitter's treatment of US President Donald Trump's tweets. When President Trump made the controversial tweet "when the looting starts, the shooting starts" in 2020, the company did not restrict it, and no further action was taken against his account. This matter has already raised questions about whether Trump should be prosecuted, given that public officials should be held to a higher standard. However, when another Twitter account copied the same message, the account was promptly suspended within three days.[43] This double standard reveals a lack of accountability in self-regulation: Social media companies often regulate misinformation based on context, allowing it to continue spreading.

At the same time, all social media platforms are driven by profit. Social media companies earn revenue by maximizing viewer engagement. Therefore, companies have an incentive to provide users with content they want to see, regardless of whether the information is true or false. Social media algorithms are trained to feed us with information that reinforces

what we already believe, thereby increasing our satisfaction by limiting our exposure to new, disruptive viewpoints.[44] Moreover, to maximize profit, these companies have an incentive to restrict content regulation. By adding more content to the platform, the company earns more from advertising revenue. Therefore, sole reliance on social media companies to regulate misinformation is also insufficient, as these companies benefit from the spread of misinformation insofar as content gains traction and generates advertising revenue.

Section 3.2: State-run regulation:

State-run regulation, on the other hand, is vastly different. Instead of directly labeling information as misinformation, governments like the EU and UK have created frameworks to regulate misinformation from the Russian-Ukrainian war. Unlike social media companies, these governments do not have access to social media algorithms or back-end systems to remove misinformation from social media platforms. Thus, state-run regulation rarely addresses individual cases of misinformation, as it cannot directly control the content available on its platforms. Instead, they use a variety of methods to enforce regulations set by social media platforms.[45] For instance, governments may enact legislation compelling social media companies to promptly identify and remove misinformation.[46] By holding social media companies liable for misinformation on their websites, state-run regulation compels them to implement procedural measures to address it.

The government has an active incentive to implement state-run regulation for several reasons. From a principle perspective, the government has a duty to ensure democratic participation through all media, including cyberspace. Therefore, especially when misinformation directly targets other individuals and inhibits their ability to share their views freely online, the government has a moral responsibility to intervene.[47] From a practical perspective, current attempts at self-regulation are insufficient. Even though each social media platform regulates misinformation independently, state-run regulation is still necessary to establish a common standard for platforms to work toward. This standardization helps social media platforms to regulate misinformation within a set framework, rather than continuously treading the line between over-censorship and allowing misinformation to run rampant.[47] The government is also incentivized to regulate due to the unique context of the Russian-Ukrainian War. As the first "social media war" in history,[48] Ukraine recognizes the need to keep its citizens well-informed by combating the threat of misinformation. As much as the Russian-Ukrainian War is a physical battle of arms, it is also a battle of narratives.

State-run regulation is one of the most effective ways to tackle Pro-Kremlin misinformation. This is because government policies, unlike self-regulation, are legally binding. For instance, when Russia first invaded Ukraine in 2022, the EU and the United Kingdom took drastic action by banning the Russian state broadcaster RT in their respective territories.[1] This limited European citizens' exposure to Russian propaganda, thereby reducing the spread of pro-Russian misinformation. This demonstrates that the government has the legal mandate to regulate misinformation by any means necessary, even if that means complete censorship of information channels. When direct government intervention is not required, state-run regulation can also provide an impetus for social media companies to act. Through advisories or direct legislation, state-run regulation acts as a strong signal of the government's attitude toward this serious issue. This can push social media companies to review user content more regularly and thoroughly, in line with the guidelines and direction provided by the state-run regulation.[49]

However, implementing broad-level state-run regulation alone is insufficient. By using frameworks to shape expectations, governments can only offer implementation suggestions.[50] This includes examples such as the European Commission's voluntary Code of Practice on Disinformation, which sets out commitments by social media platforms to combat fake news.[51] While such frameworks are a step in the right direction, they lack legally binding enforcement mechanisms. Thus, they are unable to hold social media companies to account effectively.

On the other hand, the government can wield its executive power and implement direct state-run regulation. This typically manifests as governments compelling social media platforms to remove content deemed misleading, though the process remains subject to judicial review. However, this raises concerns about excessive control over the flow of information. When governments are granted the authority to determine what constitutes misinformation, critics argue that such powers may risk suppressing legitimate political expression. This emphasizes the importance of judicial oversight, helping ensure that state-run regulation remains accountable. Ultimately, even though stronger regulatory frameworks may help curb the spread of misleading information, excessive intervention risks suppressing legitimate political discourse. As Stefan Theil argues, even in this extreme case of state-run regulation, governments must navigate a balance between safeguarding against misinformation while preserving the democratic principle of free speech.[52]

Most countries currently fall somewhere between the two opposing approaches: broad-level regulation and direct state-run regulation. Vietnam, for instance, has reached an agreement with Facebook to expedite content-removal requests from Vietnamese government ministries. Turkey has sought to compel social media platforms like Twitter and YouTube to remove defamatory content about Mustafa Kemal Atatürk, a renowned national figure often hailed as the founder of modern Turkey, but with little success.[53] Additionally, the United States is even proposing new legislation to crack down on social media bots and online political falsehoods.[54]

In the case of the Russian-Ukrainian war, both broad-level and direct state-run regulation have been employed to combat misinformation. On a broader level, the European External Action Service's East StratCom Task Force launched the EUvsDisinfo initiative, intending to issue guidelines and reports in response to the Russian government's disinformation campaign. This influences platform behavior and public awareness, helping to reduce the spread of pro-Kremlin disinformation without legal compulsion.[55] At the same time, the EU has also taken concrete steps to directly remove pro-Kremlin misinfor-

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mation sources. Following the invasion of Ukraine in 2022, the EU banned pro-Kremlin news outlets RT and Sputnik across all member states, regardless of content.[56]

This further broadens the concern about state-run regulation. Beyond accounting for differing treatments toward the gray area of misinformation, we must also consider the possibility of a government outright censoring clearly valid information. Some sacrifices should be made when considering freedom of speech, but it must definitely not become a weapon of oppression in the hands of the government. Going one step further, governments themselves can serve as sources of misinformation. In the Russian-Ukrainian war, Russia has repeatedly framed the invasion of Ukraine as a "special military operation" aimed at protecting Russian-speaking populations. In such cases, state-run regulation is ineffective, since the government can freely spread false narratives and conveniently decide what constitutes misinformation. State-run regulation provides a legitimate means for bad actors to censor information that contradicts their narrative, labeling it "misinformation." This makes it difficult to hold governments accountable, especially when they have a vested interest in spreading misinformation.

SECTION 4: CONCLUSION:

With a better understanding of the misinformation crisis and the current global response, it is apparent that more must be done to prevent the spread of harmful misinformation. Although misinformation continues to plague the international community, current efforts to regulate misinformation have been disorganized and ineffective. Section 4 aims to outline a path forward, offering preliminary guidance on improving the current status quo.

Section 4.1: Lessons from the past:

Based on Sections 1 to 3, it is apparent that the misinformation crisis is multifaceted. As evident in the Russian-Ukrainian war, misinformation has taken many forms, communication methods, and dissemination platforms.

Ranging from doctored battlefield videos being uploaded onto Telegram to misleading political narratives spread through Reddit forums, there are endless ways for misinformation to manifest.[57] At the same time, misinformation spreads farther, deeper, and more widely than the truth. The culmination of these factors has created a systemic misinformation epidemic. Platforms have implemented algorithmic filters and fact-checkers, but they continue to lag behind the viral falsehoods that plague the internet.[17] State-run regulation is also being explored, but its heavy-handed nature makes it difficult for countries to implement effectively without being accused of abusing their executive power. To move forward, society cannot simply repeat ineffective policies. We must create a robust strategy that addresses the multifaceted nature of the issue.

There are two main ways to address the misinformation crisis surrounding the Russia-Ukraine war. The first approach places the blame for misinformation squarely on platform users. This approach treats the spread of misinformation on social media as a reflection of society and, by extension, of human behavior. During the Russian-Ukrainian war, some users shared misinformation to gain attention; others chose not to fact-check before sharing. Therefore, it does not matter if the system is changed, because people will continue to spread misinformation.[59] The second approach involves treating social media as the source of the issue. Given that social media algorithms are built for sensationalist headlines and short-form content, they naturally favored emotionally charged narratives about the death of innocent civilians or the pain of wounded soldiers, rather than logical reasoning and detailed explanations. As such, social media platforms are mainly responsible for creating a systemic framework that prioritizes misinformation. Hence, without greater algorithmic transparency, efforts to change people's mindset will be ineffective in curbing the spread of misinformation.[12]

However, neither approach alone tells the whole story. The former approach ignores algorithms that systematically recommend misinformation.[76] Without social media algorithms, malicious users would be able to amass only hundreds of views, thereby exponentially slowing the spread of misinformation. On the other hand, the latter approach fails to account for why individuals find misinformation memorable. Without users clicking on misinformation that pops up in their feeds, social media algorithms would also be unable to catalyze its spread.[60] As such, treating the misinformation crisis as purely a matter of human behavior or algorithmic bias will lead to a myopic outcome. Instead, this paper purports that the proper solution could stem from a combination of both approaches. Even though some users have malicious intent, social media places these perspectives on a pedestal, amplifying misinformation that does not represent society as a whole.

As evident in Section 3, self-regulation and state-regulation are both limited in isolation but undeniably crucial for curbing the spread of misinformation. To address this issue, a hybrid approach that accounts for the unique strengths and limitations of both actors is necessary. Self-regulation can be used as the first line of defense against misinformation. This is because social media companies have the exclusive ability to implement technical interventions, such as deprioritising misleading posts and flagging suspicious content.[61] With complete access to the algorithm, social media companies will be able to adapt misinformation regulations to swiftly overcome platform-specific challenges. This can be complemented by state-run regulation in more critical situations, where the potential for public harm is immediate and severe. In these cases, the government must rely on its executive powers to regulate misinformation related to high-stakes issues, such as false claims about public health data or emergency-response news. Nevertheless, the government should also exercise restraint in cases involving national sensitivities. As evidenced through the case study of Mustafa Kemal Atatürk in Turkey, governments must not compel social media companies to remove uncomfortable content from their platforms. Instead, it must be keenly aware of the risk that state intervention crosses the line into authoritarian overreach.[62]

However, the isolated efforts of individual countries may be insufficient to solve the misinformation crisis. With its international reach and extensive viewership, social media platforms have effectively become superstate actors who transcend geo-

graphical boundaries.[63] As such, no single nation can exercise complete control over content posted on social media platforms, nor can it unilaterally enforce accountability on platforms beyond its jurisdiction. To address this power imbalance, the next logical step is for the international community to move toward multilateral cooperation and international treaties. By establishing global standards, countries can create a standardized regulatory framework that all social media companies must adhere to. This allows for more straightforward guidelines on the scope of regulation and on how to hold social media companies accountable through self-regulation agreements and state-regulated directives. Even if multilateral forums seem unproductive, they still offer an essential avenue for discourse.[64] This allows countries to voice regulation concerns in a cordial setting, preventing disagreements from escalating into global tensions or censorship wars.

Section 4.2: Envisioning the future:

Going one step further, this paper argues that a long-term solution requires not just an effective response to misinformation after it has spread, but also an emphasis on preventing its spread on social media platforms in the first place. This is because it is exponentially harder to reverse the effects of misinformation after it has gone viral. Therefore, fact-checking and takedown efforts, while necessary, are too late to fully neutralize the harms caused by misinformation. Incorporating a preventive framework in the future can reduce the burden on reactive regulation systems.[52] There are a few key characteristics of this proposed long-term solution.

Firstly, social media companies must prioritize accuracy over sensationalism. While it is unavoidable for social media algorithms to promote content based on popularity, companies must also take steps to verify content accuracy. For instance, social media companies could implement a tiered verification system that involves expedited fact-checking for viral posts. This means that, even as social media algorithms prioritize engaging content, there will be a parallel mechanism to ensure content accuracy. This prevents misinformation from spreading by ensuring that a heightened sense of responsibility over content accuracy accompanies the extensive reach of social media.[65]

Secondly, users must evolve from passive consumers to active stakeholders. While the government and social media companies may enact joint regulation through state-level and international-level treaties, users must also collaborate with both stakeholders. On the one hand, social media users must work with companies to effectively moderate social media platforms. One good example of this is TikTok's efforts to collaborate with researchers and fact-checkers. By partnering with users in all official EU languages, the company ensures swift responses to international misinformation reports.[66] On the other hand, social media users must also be receptive toward the government's misinformation education efforts. Through which, users will be incentivized to recognize and call out potential instances of misinformation.

Lastly, this paper also reveals the need for greater transparency and accountability across all stakeholders. At its core, the misinformation crisis cannot be solved without genuine collaboration between stakeholders. Social media companies must strive for complete transparency about their algorithms. Through regular accountability reports, third parties can hold social media companies to account, ensuring that they take adequate measures to combat harmful content on their platforms. Additionally, the need for governmental transparency is twofold. While the government should be transparent about how it chooses to regulate and enforce platform obligations, it must also be transparent about its decision-making process regarding government censorship.[67]

The long-term solution described in this section is merely a guide to the path forward. It serves as guidance for governments, given the current landscape of the misinformation crisis. More importantly, however, social media companies must remain open to new developments in the misinformation crisis while remaining unwavering in their support for regulation. Ultimately, the fight against misinformation cannot be merely a series of reactive measures against falsehoods. Instead, the collective efforts of all stakeholders must be geared toward cultivating a proactive digital environment that calls out misinformation and embraces the truth.

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■ References

1. Dean Jackson and Jon Bateman, "Countering Disinformation Effectively: An Evidence-Based Policy Guide," Carnegie Endowment for International Peace, accessed October 21, 2025, https://carnegieendowment.org/research/2024/01/countering-disinformation-effectively-an-evidence-basedpolicy-guide?lang=en.
2. Evelyn Douek, "Content Moderation as Systems Thinking," *Harvard Law Review* 136, no. 2 (2022).
3. Dan Ciuriak, "The Role of Social Media in Russia's War on Ukraine," SSRN Scholarly Paper no. 4078863 (Social Science Research Network, April 8, 2022), https://doi.org/10.2139/ssrn.4078863.
4. Aaron Erlich and Calvin Garner, "Is Pro-Kremlin Disinformation Effective? Evidence from Ukraine," *The International Journal of Press/Politics* 28, no. 1 (2023): 5–28, https://doi.org/10.1177/19401612211045221.
5. Joshua A. Tucker *et al.*, "From Liberation to Turmoil: Social Media and Democracy," *Journal of Democracy* 28, no. 4 (2017): 46–59, https://doi.org/10.1353/jod.2017.0064.
6. Tarleton Gillespie, *Custodians of the Internet: Platforms, Content Moderation, and the Hidden Decisions That Shape Social Media* (Yale University Press, 2018), https://doi.org/10.12987/9780300235029.
7. Kelcy Mathurin, "Misinformation & Disinformation," EN 101: The Process of Writing, Caldwell University Jennings Library, February 26, 2026, https://libguides.caldwell.edu/EN101/misinformation-disinformation.
8. Megan Kurten, "Why We Fight for Fractured Truths – How Misinformation Fuels Political Violence in Democracies," *MediaWell*, January 9, 2025, https://mediawell.ssrc.org/research-reviews/why-we-fight-forfractured-truths-how-misinformation-fuels-political-violence-in-democracies/.

DOI: 10.36838/IJHSR811.93

9. Stefania Farace *et al.*, "Standing Out While Fitting In: Visual Design of Text Overlays in Social Media Communication," *Journal of Marketing*, February 12, 2025, https://doi.org/10.1177/00222429251322773.
10. Shiqi Yi *et al.*, "Is Information Evaluated Subjectively? Social Media Has Changed the Way Users Search for Medical Information," *Digital Health* 10 (September 2024), https://doi.org/10.1177/20552076241259039.
11. Sierra L. Lawson and Steven W. Ramey, "Sourcing Stereotypes: Constructing and Challenging Simplified Knowledge," *Culture and Religion* 19, no. 4 (2018): 416–34, https://doi.org/10.1080/14755610.2018.1505759.
12. Pew Research Center, "Social Media and News Fact Sheet," *Pew Research Center*, September 17, 2024, https://www.pewresearch.org/journalism/fact-sheet/social-media-and-news-fact-sheet/.
13. Gianella Pena Barbery, "*The Role of Communication in 21st Century Nationalism: A Tool of Influence and Manipulation*," Identity Hunters, April 30, 2025, https://identityhunters.org/2025/03/30/the-role-of-communicationin-21st-century-nationalism-a-tool-of-influence-and-manipulation.
14. Dan Ciuriak, "Social Media Warfare Is Being Invented in Ukraine," *Centre for International Governance Innovation*, n.d., accessed April 21, 2025, https://www.cigionline.org/articles/social-media-warfare-is-beinginvented-in-ukraine/.
15. Malaka Gharib, "Not Every War Gets the Same Coverage as Russia's Invasion — and That Has Consequences," Ukraine Invasion — Explained, *NPR*, March 4, 2022, https://www.npr.org/sections/goatsandsoda/2022/03/04/1084230259/not-every-war-gets-the-same-coverage-asrussias-invasion-and-that-has-consequenc.
16. Peter Dizikes, "Study: On Twitter, False News Travels Faster than True Stories," *MIT News*, March 8, 2018, https://news.mit.edu/2018/study-twitter-false-news-travels-faster-true-stories-0308.
17. Irina Khaldarova and Mervi Pantti, "Fake News: The Narrative Battle over the Ukrainian Conflict," *Journalism Practice* 10, no. 7 (2016): 891–901, https://doi.org/10.1080/17512786.2016.1163237.
18. Gizem Ceylan, "How Social Media Rewards Misinformation," *Yale Insights*, March 31, 2023, https://insights.som.yale.edu/insights/how-social-media-rewards-misinformation.
19. Al Jazeera, "Profile: Who Are Ukraine's Far-Right Azov Regiment?," Al Jazeera, March 1, 2022, accessed October 5, 2025, https://www.aljazeera.com/news/2022/3/1/who-are-the-azov-regiment.
20. Abd Allah Aljalabneh, "Visual Media Literacy: Educational Strategies to Combat Image and Video Disinformation on Social Media," *Frontiers in Communication* 9 (November 2024), https://doi.org/10.3389/fcomm.2024.1490798.
21. Terry L. Childers and Michael J. Houston, "Conditions for a Picture-Superiority Effect on Consumer Memory," *Journal of Consumer Research* 11, no. 2 (1984): 643–54, https://doi.org/10.1086/209001.
22. Eryn J. Newman and Norbert Schwarz, "Misinformed by Images: How Images Influence Perceptions of Truth and What Can Be Done about It," *Current Opinion in Psychology* 56 (April 2024): 101778, https://doi.org/10.1016/j.copsyc.2023.101778.
23. Toby Prike and Ullrich K. H. Ecker, "Effective Correction of Misinformation," *Current Opinion in Psychology* 54 (December 2023): 101712, https://doi.org/10.1016/j.copsyc.2023.101712.
24. Evita March and Jessica Marrington, "A Qualitative Analysis of Internet Trolling," *Cyberpsychology, Behavior, and Social Networking* 22, no. 3 (2019): 192–97, https://doi.org/10.1089/cyber.2018.0210.
25. Flemming Splidsboel Hansen, "Trolls in Your Feed: Russian Disinformation," DIIS, 2019, accessed October 5, 2025, https://www.diis.dk/en/trolls-in-your-feed-russian-disinformation.
26. Atlantic Council, "Digital Occupation: Inside Russia's Telegram Battle in Ukraine," July 16, 2025, https://www.atlanticcouncil.org/event/digital-occupation-inside-russias-telegram-battle-in-ukraine/.
27. BBC, "Ukraine Bans Telegram Use on State-Issued Devices," September 21, 2024, https://www.bbc.com/news/articles/c78dwepw95do.
28. Telegram, "Telegram Channels," accessed October 6, 2025, https://telegram.org/tour/channels.
29. Zicheng Cheng and Yanlin Li, "Like, Comment, and Share on TikTok: Exploring the Effect of Sentiment and Second-Person View on the User Engagement with TikTok News Videos," *Social Science Computer Review* 42, no. 1 (2024): 201–23, https://doi.org/10.1177/08944393231178603.
30. BBC, "*Ukraine War: How TikTok Fakes Pushed Russian Lies to Millions*," December 15, 2023, https://www.bbc.com/news/world-europe-67687449.
31. Katie Elson Anderson, "Ask Me Anything: What Is Reddit?," *Library Hi Tech News* 32, no. 5 (2015): 8–11, https://doi.org/10.1108/LHTN-03-2015-0018.
32. Alistair Coleman and Shayan Sardarizadeh, "*Ukraine War: Viral Conspiracy Theories Falsely Claim the War Is Fake*," BBC, February 27, 2023, https://www.bbc.com/news/world-europe-64789737.
33. Holly Haney, "Systems of Upvoting and Their Implications (Term Paper)," *Medium*, December 16, 2015, https://hollyhaney.medium.com/systems-of-upvoting-and-their-implications-term-paper-1954a004e916.
34. Ekin Balkan and Sinan Ülgen, "The Role of Self-Regulation and Regulation in Combating Disinformation," EDAM, 2023, https://edam.org.tr/uploads/yukleme_resim/Report-The-Role-of-Self-Regulation-and-Regulationin-Combating.pdf.
35. Jeffrey Howard, "The Ethics of Social Media: Why Content Moderation Is a Moral Duty," *Journal of Practical Ethics* 11, no. 2 (2024), https://doi.org/10.3998/jpe.6195.
36. Kate Klonick, "The New Governors: The People, Rules, and Processes Governing Online Speech," *Harvard Law Review* 131, no. 6 (2018): 1599–670.
37. Tarleton Gillespie, "Do Not Recommend? Reduction as a Form of Content Moderation," *Social Media + Society* 8, no. 3 (2022): 20563051221117552, https://doi.org/10.1177/20563051221117552.
38. Paul M. Barrett, "The Supreme Court Protects Social Media Platforms' Ability to Filter Out Harmful Content," NYU Stern Center for Business & Human Rights, n.d., accessed October 6, 2025, https://bhr.stern.nyu.edu/quick-take/the-supreme-court-protects-social-media-platforms-ability-to-filter-outharmful-content/.
39. TikTok, "Protecting the Integrity of TikTok during the Czech Parliamentary Elections," TikTok Newsroom, n.d., accessed October 6, 2025, https://newsroom.tiktok.com/protecting-the-integrity-of-tiktok-during-the-czechparliamentary-elections?lang=en-150.
40. Alessia Zornetta, "Online Misinformation: Improving Transparency in Content Moderation Practices of Social Media Companies" (LL.M. thesis, McGill University, 2022), accessed October 21, 2025, https://escholarship.mcgill.ca/concern/theses/rf55zd782.
41. Zornetta, "Online misinformation."
42. Thomas James Vaughan Williams *et al.*, "Policy vs Reality: Comparing the Policies of Social Media Sites and Users' Experiences, in the Context of Exposure to Extremist Content," *Behavioral Sci-*

ences of Terrorism and Political Aggression 17, no. 1 (2025): 110–27, https://doi.org/10.1080/19434472.2023.2195466.
43. Donie O'Sullivan, "Mark Zuckerberg Silent as Trump Uses Facebook and Instagram to Threaten 'Looting' Will Lead to 'Shooting'," CNN, May 29, 2020, https://www.cnn.com/2020/05/29/tech/facebook-violence-trump.
44. Harvard Law School, "The Changing Ecosystem of News and Challenges for Freedom of the Press," *Harvard Law School*, 2018, accessed October 21, 2025, https://hls.harvard.edu/bibliography/the-changingecosystem-of-news-and-challenges-for-freedom-of-the-press/.
45. Ben Sperry, *Knowledge and Decisions in the Information Age: The Law & Economics of Regulating Misinformation on Social-Media Platforms* (International Center for Law & Economics, 2024), https://laweconcenter.org/resources/knowledge-and-decisions-in-the-information-age-the-law-economics-ofregulating-misinformation-on-social-media-platforms/.
46. Howard Tumber and Silvio Waisbord, eds., *The Routledge Companion to Media Disinformation and Populism*, (Routledge, 2021), accessed October 21, 2025, https://www.routledge.com/The-Routledge-Companion-to-Media-Disinformation-and-Populism/Tumber-Waisbord/p/book/9780367704919.
47. Robyn Sanders and Ashleigh Maciolek, "The Government Shouldn't Be Barred from Countering False Information," Brennan Center for Justice, September 12, 2025, https://www.brennancenter.org/ourwork/analysis-opinion/government-shouldnt-be-barred-countering-false-information.
48. Ciuriak, "Social Media Warfare Is Being Invented in Ukraine."
49. Amélie Heldt, "Reading between the Lines and the Numbers: An Analysis of the First NetzDG Reports," *Internet Policy Review* 8, no. 2 (2019), published June 12, 2019, https://doi.org/10.14763/2019.2.1398.
50. Paul Henman, "The Big Question," UQ Contact Magazine, 2019, accessed October 21, 2025, https://stories.uq.edu.au/contact-magazine/2019/big-question-social-media-regulation/.
51. European Commission, "The 2022 Code of Practice on Disinformation | Shaping Europe's Digital Future," accessed October 21, 2025, https://digital-strategy.ec.europa.eu/en/policies/code-practice-disinformation.
52. Stefan Theil, "Private Censorship and Structural Dominance: Why Social Media Platforms Should Have Obligations to Their Users under Freedom of Expression," The Cambridge Law Journal 81, no.3 (2022): 645–672, https://doi.org/10.1017/S0008197322000484.
53. Daphne Keller, "Internet Platforms: Observations on Speech, Danger, and Money," Hoover Institution, accessed October 21, 2025, https://www.hoover.org/research/internet-platforms-observations-speech-dangerand-money.
54. Ariel Shapiro, "Democratic Sen. Warner Has a New Policy Paper with Proposals to Regulate Big Tech Companies," CNBC, July 30, 2018, https://www.cnbc.com/2018/07/30/sen-warner-proposes-20-ways-toregulate-big-tech-and-radically-change.html.
55. EEAS, "EUvsDisinfo," European External Action Service, n.d., accessed November 23, 2025, https://www.eeas.europa.eu/delegations/china/euvsdisinfo_en?s=166.
56. Gergely Ferenc Lendvai, "Media in War: An Overview of the European Restrictions on Russian Media," *European Papers - A Journal on Law and Integration* 2023 8, no. 3 (2024): 1235–45, https://doi.org/10.15166/2499-8249/715.
57. Clothilde Goujard, "YouTube's Algorithm Pushes Hateful Content and Misinformation: Report," *Politico*, July 7, 2021, https://www.politico.eu/article/mozilla-firefox-report-youtube-algorithm-pushes-hateful-contentmisinformation/.
58. Robin Ramcharan, *Fake News and Elections in Southeast Asia: Impact on Democracy and Human Rights*, 1st ed. (Routledge, 2022), https://www.routledge.com/Fake-News-and-Elections-in-Southeast-Asia-Impact-on-Democracy-and-Human-Rights/Gomez-Ramcharan/p/book/9781032379821.
59. Tucker *et al.*, "From Liberation to Turmoil."
60. Franziska Zimmer *et al.*, "Fake News in Social Media: Bad Algorithms or Biased Users?," Korea Institute of Science and Technology Information, June 30, 2019, https://doi.org/10.1633/JISTaP.2019.7.2.4.
61. Corinne Tan, "Regulating Disinformation on Twitter and Facebook," *Griffith Law Review* 31, no. 4 (2022): 513–36, https://doi.org/10.1080/10383441.2022.2138140.
62. Tech Against Terrorism, "The Online Regulation Series | Turkey," October 23, 2020, accessed November 7, 2025, https://techagainstterrorism.org/news/2020/10/23/the-online-regulation-series-turkey.
63. Suvojit Bandopadhyaya, "Transcendence through Social Media," *Journal of Media and Communication Studies* 8, no. 3 (2016): 25–30, https://doi.org/10.5897/JMCS2015.0469.
64. UNESCO, "Online Disinformation: UNESCO Unveils Action Plan to Regulate Social Media Platforms," November 6, 2023, accessed November 7, 2025, https://www.unesco.org/en/articles/online-disinformationunesco-unveils-action-plan-regulate-social-media-platforms.
65. Otávio Vinhas and Marco Bastos, "Fact-Checking Misinformation: Eight Notes on Consensus Reality," *Journalism Studies* 23, no. 4 (2022): 448–68, https://doi.org/10.1080/1461670X.2022.2031259.
66. Caroline Greer, "TikTok's Continued Commitment to Combating Disinformation Under the EU Code of Practice," September 24, 2024, https://newsroom.tiktok.com/tiktoks-continued-commitment-to-combatingdisinformation-under-the-eu-code-of-practice?lang=en-150.
67. Mark MacCarthy, "Transparency Is Essential for Effective Social Media Regulation," *Brookings*, January 11, 2022, https://www.brookings.edu/articles/transparency-is-essential-for-effective-social-media-regulation/.

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RESEARCH ARTICLE

An Environmental and Economic Analysis of the Practicality of Incorporating Boundary Layer Ingestion

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ABSTRACT: Aerodynamic drag (e.g., wave drag, induced drag, and skin friction/boundary layer drag) has long remained and continues to be a caveat in aircraft fuel efficiency, despite decades of advancements in propulsion and design. However, boundary layer ingestion (BLI) propulsion systems have shown promising results in improving aircraft fuel efficiency through ingesting the lower velocity boundary layer air to reduce wake kinetic energy and overall power requirements. This study addresses the economic and environmental benefits of BLI integration in commercial aircraft through the use of power balance calculations, analysis of published computational data, and performing economic and environmental analyses through calculated performance results. We believe that BLI integration has the benefits that make it practical for commercial use, and using force coefficient data from fully coupled aerodynamic propulsion simulations, we calculated reductions of shaft power requirements up to ~1021 hp relative to conventional podded configurations. This corresponds to estimates around a 7-10% lower fuel burn and annual savings of ~$400,000 to $560,000 per BLI aircraft configuration. These savings also correspond to CO_2 emissions reductions of up to 3.4 million lb per aircraft, which result in more than ~100.0 million lbs of CO_2 over the course of its life cycle. However, challenges like fan efficiency, which require strict design requirements to mitigate, and challenges in structural integration of the system can lead to high developmental costs. Despite this, because of a rapidly increasing aircraft carbon footprint, the benefits that BLI provides ultimately prove the developmental costs to be superficial in light of achieving ambitious sustainability goals.

KEYWORDS: Boundary Layer Ingestion (BLI), Computational Fluid Dynamics (CFD), Pressure Ratio (FPR), Power-Balance, Thrust Specific Fuel Consumption (TSFC), Power Specific Fuel Consumption (PSFC).

Introduction

Despite decades of advancements in aircraft technology in terms of propulsion efficiency and design, there remain aerodynamic inefficiencies that limit improvements in fuel efficiency and environmental factors. Aerodynamic drag—especially induced drag during takeoff and landing, wave drag at transonic cruise, and skin-friction drag due to turbulent boundary layers—remains a dominant factor in fuel consumption. Confronting these issues is rather important, particularly considering ambitious targets such as ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), NASA's N+3 goal of a 70% reduction in fuel burn by 2035, and ACARE's 75% CO_2 emission reduction goal by 2050.[1,2]

A possible solution to reducing drag and improving overall aircraft efficiency would be Boundary Layer ingestion (BLI) systems, which, unlike traditional podded engine systems, BLI ingests the lower velocity boundary layer air either from the fuselage or over the airfoil, reducing the aircraft's power requirement.[2] This approach has been explored in configurations such as NASA's STARC-ABL and MIT/NASA's D8 Series, both incorporating aft-mounted BLI systems. Some models highlight up to 15% reductions in power for the D8 concept.[3] Furthermore, computational studies using the common research model (CRM) geometry also showed that BLI systems can reduce engine power requirements by as much as 15.6% while also reducing drag compared to podded engine systems.[4] These improvements are also linked to how the BLI system utilizes the fuselage wake, which reduces the required jet propulsive power.[4]

However, BLI is not without its limitations. Engine inlet distortion reduces fan efficiency by 0.5–5%.[5] Additionally, structural complexities arise from propulsion system and airframe integration, particularly for embedded or aft-mounted systems.[6] The D8 aircraft concept also shows that BLI systems cannot just be fitted onto any airframe, as in its design, the fuselage and propulsion system were designed specifically to utilize the thickened boundary layer.[6,7] Additionally, simulation modeling can be rather difficult for BLI systems. To accurately highlight the effects of BLI systems, Gray *et al.* suggest a coupled modeling of both the airframe and propulsion system rather than the traditional approach to design separately, in cases when the propulsion system is placed in free-stream air. The assumption that small changes to either system do not affect each other no longer applies to BLI systems, as fully integrated simulations (such as those used in NASA's STARC-ABL and MIT's D8 studies) show that these small changes to either system can significantly affect BLI engine performance.[3,8] Because of these challenges with research and development, the costs for developing BLI systems may be higher than the development costs of other aircraft.

Despite the extensive research into BLI systems and their benefits in fuel efficiency, there has not been significant discussion on the costs and practicality of actually incorporating BLI systems for commercial use. On top of the additional research

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and developmental costs that are a product of complexities with simulation and incorporation of BLI systems, there may also be additional maintenance and production costs due to the incorporation of an additional aft-mounted BLI propulsor.

That is why, when given the tradeoff between potential aerodynamic improvements and the challenges of incorporating BLI systems, it is necessary to assess the system's impact and practicality through performance-based analysis. This paper aimed to address the environmental and economic benefits of boundary layer ingestion (BLI) systems compared to standard podded configurations through the use of published data, power balance calculations, fuel consumption calculations, and emissions conversions. We hypothesize that the integration of BLI systems can produce reductions in propulsive power requirements, fuel burn & fuel cost, and CO_2 emissions that outweigh its integration and design challenges.

Background

2.1. Aerodynamic Drag in Aircraft:

In the case of aircraft, drag comes in the form of aerodynamic drag, which is the resistive force an aircraft experiences as it cruises through the atmosphere. For commercial transport aircraft, total drag is composed primarily of:

-Induced drag, which is mainly from lift generation (when the flaps extend out and down to produce lift via Newton's 3rd law and Bernoulli's principle), is mainly present during takeoff, aircraft climb, and landing.

-Wave drag, which is caused by compressibility effects of the air and shockwaves (where airflow locally exceeds the speed of sound) at transonic flight.

-Skin friction drag, which results from within the turbulent boundary layer along the fuselage and wings.

These forms of drag directly influence the thrust required for cruise flight, and as a result, they also bring about a plethora of other issues, such as effects on the fuel requirements/efficiency and the environmental impact of the aircraft. Even with advances in aerodynamics and propulsion integration, these forms of drag are still major inhibitors to operational efficiency.[2]

2.2. Boundary Layer Ingestion:

BLI is a propulsion system where the engine inlets ingest the lower velocity boundary layer air from the fuselage or wing surface rather than the free stream air, as seen in traditional engine configurations. As a result, this reduces wake kinetic energy and recovers momentum that would be otherwise lost to drag, as seen in Figure 1.[2,3]

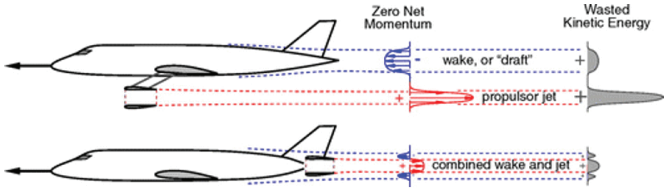

Figure 1: By absorbing the boundary layer air, the wake kinetic energy is reduced, thus reducing the energy required.

Computational fluid dynamics (CFD) studies have shown that BLI has reduced propulsive power requirements:

-The D8 concept estimates up to a ~15% cruise power reduction from twin rear-mounted fans ingesting a thickened boundary layer, and Common research model (CRM) based simulations done by NASA highlighted up to a 15.6% reduction in engine power at cruise.[3]

However, BLI also introduces challenges. Engine inlet distortion, which is caused by ingesting low-energy boundary layer air, resulting in deviations in pressure from the ideal condition, can reduce fan efficiency by up to 0.5-5%. Furthermore, there are difficulties in the integration of BLI systems, as oftentimes, they cannot just be retrofitted onto legacy frames.[5-7] Additionally, in the case of the D8 study, the airframe had to be specifically designed to produce a boundary layer profile to optimally match the propulsor inlet, as the fuselage shape was essential to the projected gains.[3]

Methodology

3.1. Research Approach:

This study uses CFD simulation data to calculate the power requirements of BLI systems and thus determine the propulsive benefits of Boundary Layer Ingestion systems relative to podded engine systems. Fully coupled aerodynamic propulsion data from Gray *et al.* for the STARC-ABL configuration (Figure 2) are analyzed to determine the changes in net axial force from BLI and podded systems. The data is then used to calculate the power requirements, which we then cross-compare with data for the Airbus A320 Neo (a narrow-body aircraft with roughly the same size as the STARC-ABL configuration). We will then use the calculated power requirements to compute CO_2 reductions, Fuel burn, and estimated life cycle cost analysis.

Figure 2: Simulation render of the STARC-ABL configuration. An aft-mounted electric BLI propulsor (powered by the podded engines) ingests the boundary layer air.

Figure 3: Rendering of Airbus A320-200 NEO. An incremental development aircraft part of the A320 aircraft family. This aircraft is fitted with next-generation engines, improving the aircraft's fuel efficiency.

3.2. Flight Conditions:

Both configurations in Gray *et al.* (2018) share the same cruise conditions as well as reference area (A = 1400 ft^2)

1. Baseline: Conventional twin podded turbofans
2. BLI: STARC-ABL configuration with an aft-mounted BLI system supported by podded turbofans for takeoff and climb

Cruise conditions:[8, 9]

- Mach: M∞=0.72
- Altitude: 37,000 ft
- ρ∞=0.0008 slug/ft3
- V∞=707.3 ft/s

3.3.: Force to Power Conversion

Net axial force coefficient for the propulsor ($C_{fx\text{-}prop}$) is defined as

$$C_{F_{x-prop}} = \frac{2(Thrust - Drag)}{\rho V^2 A_{ref}} \#(3.1)$$

Net axial force coefficient for the fuselage ($C_{fx\text{-}fuse}$) is defined as:

$$C_{F_x-fuse} = \frac{2(F)}{\rho V^2 A_{ref}} \#(3.2)$$

Where F is composed of pressure and viscous forces that contribute to drag

This is a simplified version of the integration done in Gray *et al.*, as in the $C_{Fx\text{-}prop}$, drag is composed of outer nacelle pressure and viscous forces, as well as "ram drag" (the momentum deficit to suck in air flow). Thrust is composed of the jet momentum.

(Note the row and V values are still the freestream values from the cruise conditions listed above)

Step 1: Force

$$F_x = C_{F_x} \cdot \frac{1}{2} \rho_\infty V_\infty^2 A_{ref} \#(3.3)$$

The net force F_x is calculated using the net force coefficient (C_{Fx}), which is the combined force coefficient of the fuselage and propulsor. This coefficient is then multiplied by the free stream air density ρ_∞ at 37,000 ft, the free stream air velocity V_∞, and the reference wing area A_{ref}.

Step 2: Power

$$P_{net} = F_x \cdot V_\infty \#(3.4)$$

This is the standard formula for net power, which is calculated by multiplying the net force F_x by the free stream air velocity V_∞.

Step 3: Fuel Burn

$$\dot{m_{fuel}} = \frac{PSFC \times \Delta P_{net}}{6.71} \#(3.5)$$

This is the equation for calculating the fuel burn reductions $\dot{m}_{fuel}$, with PSFC being the power specific fuel consumption (which we calculate from thrust specific fuel consumption) multiplied by the difference in net power between the BLI systems and Podded configurations. It is then divided by 6.71, which is the lbs per gallon of Jet A-1 fuel.

3.4. Economic and Environmental Factors:

1. Fuel cost: Jet fuel price ~$3.00/gal (Jet A-1 6.71 lb/gal).[10]
2. CO_2 Factor: ~21 lb CO_2 per gallon burned.[10]

3.5. Integration Costs:

Despite the many benefits that BLI provides, there are also limitations when it comes to the integration of BLI systems. As mentioned previously, BLI systems cannot simply be fitted onto standard airframes, and there are structural modifications required to integrate them. Additionally, since BLI is designed to ingest and accelerate the slower-moving boundary layer air, the engine fans experience distortion, so to tolerate that distortion, specialized fan/inlet designs are also required.

Results

4.1. Force Coefficients:

Table 1: Given and calculated metric values for the comparison between BLI and Podded Configurations (The counts are the net axial force coefficients * 10^4).

Configuration	FPR	Fuselage Force (lbf)	Fuselage (counts)	Propulsor Force (lbf)	Propulsor (counts)	Net Force (lbf)	Net (counts)	Net Power (hp)	Net Power (kW)
Podded	-	-2331	-83.21	1893	67.57	-438	-15.65	-564	-420
BLI	1.35	-2101	-75.00	2307	82.35	206	7.35	265	197
BLI	1.20	-1990	-71.03	2345	83.71	355	12.68	457	341

The force coefficient and FPR (fan pressure ratio) values are taken directly from experimental results in Gray *et al.*, in which they conducted a fully coupled simulation on the STARC-ABL BLI system. This data shows that for both BLI configurations, power requirements were significantly reduced (with BLI at FPR 1.35 producing 197 kW of excess power, and BLI at FPR 1.20 producing 341 kW of excess power).

Using eq 3.3 and eq 3,.4 we were able to calculate the net axial force (lbf) and thus the net power requirement

4.2. Analysis:

For the Podded configuration (reference), the combined fuselage + podded propulsor has a net backward force (negative F_x). Converting that residual drag to power gives about 564 hp that the podded engines must additionally provide just to hold cruising speed on top of anything else they're doing. Comparatively, with the BLI configurations (paired 3500 hp aft-mounted boundary layer electric propulsor), the net force Fx (propulsor + fuselage) is positive. The BLI systems produce an excess of ~265 hp at 1.35 and an excess of ~457 hp at FPR = 1.20 (see Table 1).

With podded configurations, the podded under-wing engines must cover 564 hp just to cancel the system's residual drag. With BLI in the STARC-ABL configuration, the podded under-wing engines can throttle back by the BLI surplus, which is ~265-457 hp, because the system is already accelerating forward. Relative to the podded case, BLI improves the propulsive power balance by ~829 hp at FPR 1.35 and ~1021 hp at FPR 1.20.

In the BLI, the aft propulsor itself is being driven at a fixed 3,500 hp shaft, which is powered by the electric power gener-

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ated by the under-wing engines (which also provide the cruise thrust), so the generated power benefits are not a result of an additional power source.

4.3. Fuel and CO2 Savings Estimates:

We will be estimating PFSC (power specific fuel consumption) based on NASA's Glenn Research Center's reference of TFSC for turbofan values as 0.5 at sea level static environments.[11] It is important to note, however, that this value can vary with factors like altitude, velocity, and engine design, so we will be proceeding further with caution. Despite this, these values should be sufficient to serve as a basis for our estimates.

TFSC conversion to PSFC:

$$PSFC\ [lb/(hp\ \times\ hr)] = \frac{TSFC\ [lb/(lbf\ \times\ hr)] \times 550}{V\ [ft/s]} \#(4.1)$$

Through this, we find our PSFC to be

$$PSFC = 0.389\ [lb/(hp \times hr)]$$

We will be using the Airbus A320 NEO (Figure 3) cruising at 37,000 ft as our reference model since it is in the relatively same class size based on wingspan and passenger load as the STARC ABL model. We find that in a standard 7-hour flight, the Airbus A320 NEO model burns ~4732 gal.[12-14]

Now using eq 3.6 to calculate fuel savings per hour, we find:

- BLI at FPR 1.35 (Δ = 829 hp)
  - o Fuel savings (gal/hr) ~ 48.09 gal/hr
  - o CO_2 savings ~ 1009.26 lb/hr
- BLI at FPR 1.20 (Δ = 1021 hp)
  - o Fuel savings (gal/hr) ~ 59.19 gal/hr
  - o CO_2 savings ~ 1243.00 lb/hr

And adjusting for the 7-hour flight, we find that the BLI configurations can save an estimated ~7-10% in fuel burn per flight, and flying ~2700 flight hours per year, we find that the savings on fuel total up to around ~$400,000 - $560,000 per configuration each year.[15,16] Additionally, if we consider the reduction in carbon emissions, we find an estimated reduction in CO_2 by up to ~3,356,000 lb CO_2 per configuration each year.

The STARC-ABL configuration utilizes a 3rd aft mounted BLI propulsor, unlike the 2 narrowbody engines seen in the Airbus A320 NEO. Since there is no available data on the price for the tailcone propulsor, as it is still in the research and development phase, we will estimate the cost by aligning it with the cost of a Pratt & Whitney PW1100 (~$12,000,000 USD) as seen in an A320 NEO model. It is to be noted, however, that the price of the actual BLI propulsor may vary higher or lower than the estimated price.[17-19]

Discussion

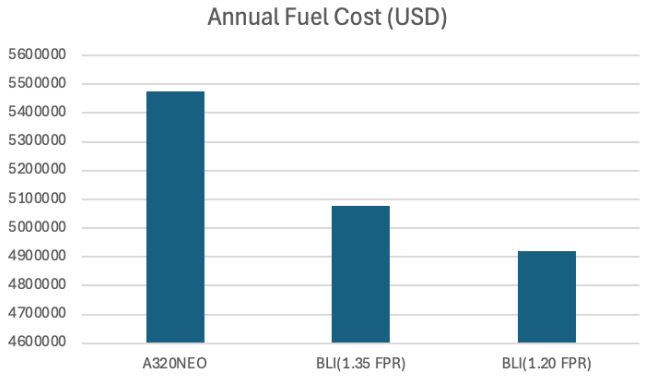

Figure 4: Fuel Cost comparison across A320NEO and 2 BLI Configurations. This data shows that both BLI configurations have significantly reduced fuel costs (upwards of 10%) when compared to their podded A320 counterpart.

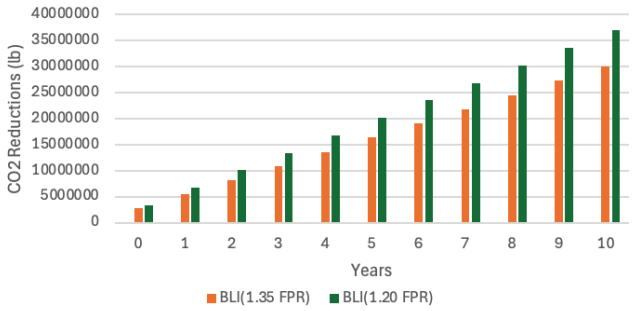

Figure 5: Reductions in CO_2 emissions for BLI at FPR 1.20 and at FPR 1.35 over the course of 10 years. This data shows that when compared to the A320 Neo configuration, both BLI configurations demonstrated significant CO_2 reduction (up to ~375 million lbs over the course of 10 years). It is also to be noted that BLI at an FPR of 1.20 is shown to be more efficient when compared to BLI at FPR 1.35.

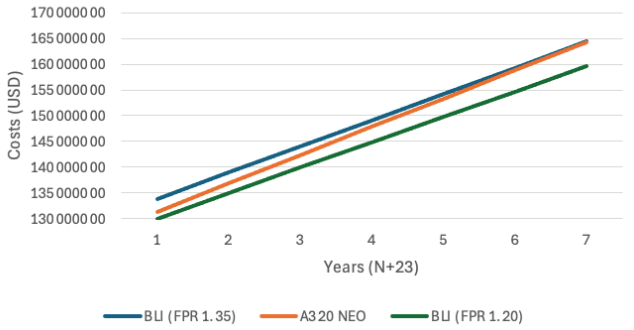

Figure 6: Lifespan cost assessment for the BLI systems and A320 NEO configuration, accounting only for the fuel burn savings and cost of an additional propulsor. This data predicts that over the course of a 30-year life-cycle for all three configurations, their life-cycle costs will remain roughly similar. BLI at FPR 1.20 is the cheapest to maintain, while the A320 Neo and BLI at FPR 1.35 have roughly similar life-cycle costs.

From the analysis of the STARC-ABL BLI configuration (see Figure 2) in Table 1, we find that under the realistic cruise conditions presented in section 3.2, BLI reduces shaft power by ~829-1021 hp compared to conventional podded systems. This

translates to ~7-10% fuel savings. Figures 4-6 provide an overview of the results we found from our additional calculations. BLI in both FPR scenarios demonstrates significant benefits compared to standard podded configurations in several environmental and economic parameters. The BLI configuration's fuel efficiency improvements have led to significant reductions in estimated annual fuel costs and fuel burn. Furthermore, as a result of fuel burn reductions, BLI has been estimated to reduce CO_2 emissions by up to 35,000,000+ lbs of CO_2 per configuration over the course of 10 years and potentially triple that number over the course of its lifespan. However, in the STARC-ABL configuration, there is an additional propulsor configuration, but as demonstrated in Figure 6, BLI in both configurations is seen to nullify or even improve on that cost deficit over the course of its lifespan (30 years).[20] It is to be noted that in the case of BLI, which is a technology still in the research and development phase, there is no concrete value on the actual price of the propulsor, and as a result, the actual developmental value can vary significantly from our predicted value.

Additionally, this figure does not consider maintenance costs for these aircraft, as it is assumed that for all 3 configurations, it would be the same. This is because both the BLI configurations and podded configurations are roughly the same in aircraft size, and thus, maintenance costs should correlate.[21] However, this figure does not account for the maintenance cost of the additional aft-mounted propulsor in the BLI configurations, so our estimated costs for the BLI configurations are probably greater than the value we predicted for the total lifecycle cost.

Despite this, in the bigger picture, the difference in costs between the systems is ultimately going to be negligible. It is important to acknowledge, however, that despite the benefits, there are also significant challenges that come with the incorporation of BLI. Our use of a fixed TSFC value to calculate our PSFC introduces uncertainty, as fuel consumption changes varyingly on altitude and engine design. Additionally, with the incorporation of an additional aft-mounted electric propulsor, integration issues and complexities arise. For example, the developmental requirements needed to mitigate fan inlet distortion from ingesting the slow-moving boundary layer air can significantly increase research and developmental costs, as special inlets need to be designed to prevent performance deterioration or stalling. Adding on, additional maintenance systems such as a cooling system for the aft-mounted propulsor are also required, which will increase the cost and maintenance complexity even more.[22] Aircraft development programs can cost upwards of billions of USD to develop, making the financial commitment to realizing BLI quite extensive (notably seen in the Boeing-737 MAX with R&D costs estimated to be well over $2 billion USD).[23-25] However, with sustainability goals like NASA's N+3 target of fuel burn and NO_x reductions, and ACARE's 75% CO_2 emissions reductions by 2050, BLI serves as a promising tool to help meet those goals.

Conclusion

In this study, we utilized fully coupled CFD simulation data to support our power balance calculations, from which we were able to deduce that BLI improves on standard podded configurations in several important sustainability parameters, including fuel efficiency, fuel burn reductions, and CO_2 reductions. BLI has achieved ~7-10% reductions in fuel burn corresponding to up to ~$560,000 in annual savings per configuration, and they also reduce CO_2 emissions of up to +3,000,000 lbs. per configuration each year as well. From the rough estimate for a 30-year life cycle cost assessment, we found that the BLI systems cost less or roughly the same as a standard podded configuration despite having an extra BLI propulsor. It should be noted that this result is an estimate. It does not incorporate maintenance costs in the calculation, which may result in costs for BLI systems being higher because of the additional propulsor. Furthermore, since the technology is still in the research and development phase, it is hard to really put a concrete number on the exact cost of incorporating a BLI system, but with the integration and developmental complexities that come with BLI, the financial burden for research and development can be quite extensive.

However, in light of ambitious sustainability goals with NASA's N+3 target of 70% fuel burn improvement and 75% reduction in NO_x emissions by 2035, along with ACARE's 75% CO_2 emissions reductions by 2050, BLI demonstrates potential to help meet those sustainability goals. While significant research and development are still needed to address the challenges, BLI is ultimately something that should be pursued for research, development, and widespread incorporation.

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References

1. International Civil Aviation Organization (ICAO). (2019). CORSIA. https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx
2. Lv, P., Gangoli Rao, A., Ragni, D., & Veldhuis, L. (2016). Performance analysis of wake and boundary-layer ingestion for aircraft design. Journal of Aircraft, 53(5). https://doi.org/10.2514/1.C033395
3. Uranga, A., Drela, M., Greitzer, E. M., & Titchener, N. (2014). Preliminary experimental assessment of the boundary layer ingestion benefit for the D8 aircraft. 52nd Aerospace Sciences Meeting. https://doi.org/10.2514/6.2014-0906
4. Blumenthal, B. T., Elmiligui, A. A., Geiselhart, K. A., Campbell, R. L., Maughmer, M. D., & Schmitz, S. (2018). Computational investigation of a boundary-layer-ingestion propulsion system for the Common Research Model. Journal of Aircraft, 55(3). https://doi.org/10.2514/1.C034454
5. Hardin, L., Tillman, G., Sharma, O., Berton, J., & Arend, D. (2012). Aircraft system study of boundary layer ingesting propulsion. In 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference (AIAA 2012-3993). American Institute of Aeronautics and Astronautics https://arc.aiaa.org/doi/abs/10.2514/6.2012-3993

DOI: 10.36838/IJHSR811.104

6. Hall, D. K., Huang, A. C., Uranga, A., Greitzer, E. M., Drela, M., & Sato, S. (2017). Boundary layer ingestion propulsion benefit for transport aircraft. Journal of Propulsion and Power, 33(5). https://doi.org/10.2514/1.B36321
7. Hendricks, S. E. (2018). A Review of Boundary Layer Ingestion Modeling Approaches for Use in Conceptual Design. NASA Technical Report. https://ntrs.nasa.gov/api/citations/20180005165/downloads/20180005165.pdf
8. Gray, J. S., Mader, C. A., Kenway, G. K. W., & Martins, J. R. R. A. (2018). Modeling boundary layer ingestion using a coupled aeropropulsive analysis. Journal of Aircraft, 55(3). https://doi.org/10.2514/1.C034601
9. Gray, J. S., Martins, J. R. R. A. (2018). Coupled Aeropropulsive Design Optimization of a Boundary Layer Ingestion Propulsor. The Aeronautical Journal. https://openmdao.org/pubs/gray_bli_opt_2018.pdf
10. U.S. Energy Information Administration (EIA). (2024). Carbon dioxide emissions by fuel type. https://www.eia.gov/environment/emissions/co2_vol_mass.php
11. NASA Glenn Research Center. (2021). Thrust Specific fuel consumption values. https://www.grc.nasa.gov/www/k-12/airplane/sfc.html
12. Aviation Week. (2021). Airbus A320NEO wingspan values. https://aviationweek.com/special-topics/sustainability/airbus-x-plane-will-test-inflight-folding-wingtips
13. Airbus. (n.d.). A320neo: How many passengers can fly in the A320neo? https://aircraft.airbus.com/en/aircraft/a320-family/a320neo#:~:text=How%20many%20passengers%20can%20fly,Airbus%20A320neo%20is%20194%20passengers
14. PilotRise. (2025). Fuel efficiency of the Airbus A320. https://pilotrise.com/aircraft/fuel-efficiency-of-a320/
15. Shetty, S. (2012). ICAT report on transport aircraft. Massachusetts Institute of Technology. https://dspace.mit.edu/bitstream/handle/1721.1/72392/ICAT%20REPORT%20SHETTY.pdf?sequence=1&isAllowed=y
16. Transportation Research Board. (1989). Aircraft energy efficiency and design. Transportation Research Record, 1214. https://onlinepubs.trb.org/Onlinepubs/trr/1989/1214/1214.pdf#page=56
17. Gray, J. S., Mader, C. A., Yildirim, A., & Martins, J. R. R. A. (2021). Performance Analysis of Optimized STARC-ABL Designs Across the Entire Mission Profile. AIAA Scitech Forum.
https://doi.org/10.2514/6.2021-0891
18. Welstead, J., Felder, J., Guynn, M., Haller, B., *et al.* (2017). Overview of the NASA STARC-ABL (Rev. B) Advanced Concept. NASA Technical Report. https://ntrs.nasa.gov/api/citations/20170005612/downloads/20170005612.pdf
19. Simple Flying. (2022). Jet Engine price gauges. https://simpleflying.com/most-expensive-jet-engines/#:~:text=Similarly%2C%20the%20list%20price%20of,A320neo%20is%20approximately%20$12%20million
20. Airbus. (n.d.). The life cycle estimates of an aircraft. https://www.airbus.com/en/products-services/commercial-aircraft/the-life-cycle-of-an-aircraft/operating-life
21. Wei, W., & Hansen, M. (2003). Cost economics of aircraft size. Journal of Transport Economics and Policy (JTEP), 37(2), 279-296.AIAA. (2021). AIAA conference proceedings. http://www.jstor.org/stable/20053934
22. Ito, Y., Watanabe, T., Seki, N., Oyori, H., Himeno, T. (2022). Temperature and consumed energy predictions for air-cooled interior permanent magnet motors driving aviation fans–Part 1: Mathematical analytical solutions for incompressible air cases. SAE. https://doi.org/10.4271/14-12-01-0005
23. Campos, B. D. G., Tomita, T. J., Costa, P. F., Bringhenti, C., *et al.* (2018). Propulsive Efficiency of Boundary Layer Ingestion Propellers. https://www.icas.org/icas_archive/ICAS2018/data/papers/ICAS2018_0649_paper.pdf
24. Aerospace Technology Institute. (2021). The evolving aerospace R&D landscape. https://www.ati.org.uk/wp-content/uploads/2021/08/insight_10-the-evolving-aerospace-rd-landscape.pdf
25. Nolte, B., & Gollnick, V. (2014). Definition and selection of air transportation system requirements based on a posteriori knowledge. ResearchGate. https://www.researchgate.net/publication/259897270_Definition_and_Selection_of_Air_Transportation_System_Requirements_based_on_a_posteriori_knowledge
26. Pandya, S. A., & Uranga, A. (2014). Computational assessment of the benefits of boundary layer ingestion for the D8 aircraft. NASA Ames Research Center. https://ntrs.nasa.gov/api/citations/20140004910/downloads/20140004910.pdf
27. Hall, D. (2016). Boundary layer ingestion propulsion: A feasibility study. Massachusetts Institute of Technology. https://arrow.utias.utoronto.ca/crsa/iwacc/2016/mit-hall.david-boundarylayeringestionpropulsion.pdf

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REVIEW ARTICLE

Epigenetic Alterations in Gastric Cancer: Mechanisms, Classifications, and Therapeutic Implications

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ABSTRACT: The field of cancer epigenetics has shown that changes beyond genetic mutations play a critical role in tumor development. In gastric cancer, epigenetic alterations significantly affect gene expression, tumor behavior, and clinical outcomes. Modifications such as DNA methylation, histone changes, and non-coding RNAs are now seen as central to disease progression. Environmental factors like *Helicobacter pylori* infection can trigger these changes, leading to abnormal gene regulation and tumor growth. This study explores how epigenetic alterations contribute to the initiation and progression of gastric cancer. Recent research using genome-wide methylation mapping and RNA sequencing has identified key epigenetic changes in gastric tissues. These studies examine the relationship between *H. pylori* infection and DNA methylation, track long-term changes before and after eradication, and analyze how molecular profiles correspond to cancer stages. Many also proposed biomarkers for early detection and targets for therapy. Additionally, epigenetic changes, such as CpG island methylator phenotype and microRNA silencing, appear early and persist throughout progression. While some may be reversible with early intervention, later-stage changes are often permanent. These insights support improved treatment through epigenetic classification, earlier detection, and more personalized therapeutic approaches based on biomarker-driven strategies.

KEYWORDS: Biomedical and Health Sciences, Genetics and Molecular Biology of Disease, Epigenetics, Gastric Cancer, *Helicobacter pylori*, DNA Methylation Biomarkers.

Introduction

Gastric cancer is one of the most aggressive malignancies worldwide; with over one million cases diagnosed and 769,000 deaths every year, it is the fifth most common cancer diagnosed and the third most common cause of cancer death.[1,2] Although treatments like surgery, chemotherapy, and immunotherapy have improved, the survival rate for gastric cancer is low due to late diagnosis and high recurrence rates.

Gastric cancer is a complex disease influenced by genetic, environmental, and infectious factors. Among its most significant risk factors is *Helicobacter pylori*, a Gram-negative bacterium classified by the World Health Organization as a Group I carcinogen. *H. pylori* infections induce chronic gastritis, epithelial injury, and eventually precancerous changes.[3] Epigenetic alterations, such as DNA methylation, histone modifications, and non-coding RNA dysregulation, have been shown to link *H. pylori* infection and other environmental effects to gastric cancer.[4] These modifications influence gene expression without altering the DNA sequence, leading to tumor suppressor silencing, oncogene activation, and cellular pathway disruption. Recent studies have also shown that some epigenetic marks, specifically aberrant DNA methylation, continue even after eradication.[5]

Due to the high mortality rate of gastric cancer and the limitations of current diagnostic techniques, there is an urgent need to identify early, non-invasive biomarkers and develop targeted therapies. Thus, epigenetic modifications present a promising solution: they are detectable in body fluids, reversible under certain conditions, and tightly linked to disease mechanisms.[1] However, there are limitations in translating these findings into everyday medical use. While many epigenetic biomarkers have been identified, few are proven reliable for regular use, and resistance to epigenetic drugs is challenging.[6] This paper reviews recent research to explain how gastric cancer develops, improve how it is classified, and suggest future treatment options. Additionally, this paper argues that epigenetic alterations in gastric cancer, specifically DNA methylation, histone modification, and non-coding RNA problems, play a key role in how the disease starts and grows. These changes can also be categorized in ways that predict outcomes, help with treatment, and serve as targets for new biomarkers and therapies.

Results and Discussion

Foundations of Epigenetic Alterations:

Epigenetic mechanisms, such as DNA methylation, histone modification, and non-coding RNA regulation, play a central role in the development of gastric cancer. These alterations contribute to tumor progression by disrupting gene expression and are often triggered by environmental factors such as *Helicobacter pylori* infection. Due to the aggressiveness of gastric cancer, understanding its underlying mechanisms is key to improving early detection and treatment. While much research has focused on genetic mutations, recent studies have revealed that epigenetic changes also play a vital role in tumorigenesis. These changes can silence tumor suppressor genes, activate oncogenes, and reshape the chromatin without altering the DNA sequence. The primary mechanisms of epigenetic regulation include DNA methylation, histone modifications, and

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non-coding RNAs such as microRNAs and lncRNAs. These are often influenced by environmental and biological factors like *Helicobacter pylori* infection and chronic inflammation that weaken the gastric mucosa. This section investigates how these epigenetic modifications arise and function in gastric cancer.

DNA Methylation:

DNA methylation is one of the most studied epigenetic modifications in gastric cancer because of its link to tumor development. When methylation patterns are disrupted, they can silence important tumor suppressor genes that limit cell growth. A common example is CpG island hypermethylation, which targets the promoter regions of genes like *MLH1* and *CDH1* that are responsible for DNA repair and cell cycle control. When these genes are turned off, it can lead to microsatellite instability (MSI), which happens when the DNA repair system cannot fix mistakes in repeating DNA sections; not only does this increase genomic instability and mutation rate, but it also raises the risk of cancer development.[7,8]

Conversely, global hypomethylation, which occurs when methylation is removed from large regions of the genome, can activate genes that should remain silent. As a result, losing this control can reactivate repetitive DNA, which may lead to chromosome changes and mutations.[9,10] Additionally, oncogenes may become abnormally expressed, leading to even more tumor growth. Together, these effects disrupt normal gene activity, damage genome integrity, and increase mutation rates in gastric tissues.

Several studies also suggest *Helicobacter pylori* infection as a major environmental trigger for epigenetic changes. Chronic inflammation caused by the bacteria stresses the stomach lining and leads to increased activity of DNA methyltransferases (DNMTs), which are the enzymes responsible for adding methyl groups to DNA. Increased DNMT activity can result in abnormal methylation patterns and the silencing of tumor suppressor genes.[5,11] These epigenetic alterations often arise before any visible signs of cancer appear, making DNA methylation both an important early detection signal as well as a potential target for therapy.

Histone Modifications:

Histone proteins serve as structural supports that DNA wraps around, and they can be chemically modified, which influences how tightly the DNA is packaged and whether specific genes are turned on or off. Key types of histone modifications include acetylation (the addition of acetyl groups, usually to loosen the DNA and promote gene expression), methylation (the addition of methyl groups, which can either activate or repress genes depending on the site), phosphorylation (the addition of phosphate groups, often involved in DNA repair and cell cycle regulation), and ubiquitination (the addition of ubiquitin proteins that can signal gene activation or target proteins for degradation). In gastric cancer, abnormal patterns of these modifications can disrupt normal gene expression, promote uncontrolled cell growth, and contribute to resistance against therapies.

A key example is the loss of acetylation on histone proteins H3 and H4. Typically, acetylation makes genes more accessible by loosening the DNA structure. However, when acetylation decreases, the DNA becomes tightly packed, and critical tumor suppressor genes are silenced.[12,13] Thus, this creates conditions in the cell that allow cancer to develop and thrive.

Enzymes called histone deacetylases (HDACs) remove acetyl groups from histones. Many gastric cancer patients have higher levels of HDAC1 and HDAC2, which turn off many genes.[14] Due to their role in silencing tumor suppressor genes, HDACs have become promising targets for cancer drugs. Similarly, enzymes like EZH2, a type of histone methyltransferase, can add methyl groups to specific histones and silence key genes like E-cadherin, which is essential for keeping cells in place.[15,16] When the enzyme is silenced, cancer cells are more likely to undergo epithelial-mesenchymal transition (EMT), a process that allows them to detach, migrate, and invade surrounding tissues. Ultimately, understanding these changes in histone modifications reveals how cancer progresses and introduces new possible therapies to reactivate silenced genes and slow tumor growth.

Histone Modifications:

Non-coding RNAs (ncRNAs), especially microRNAs (miRNAs) and long non-coding RNAs (lncRNAs), are becoming key regulators of gene expression in gastric cancer. Although they do not code for proteins, these molecules influence how genes are expressed or silenced. One critical tumor-suppressive miRNA is miR-34a, which regulates cell cycle progression and apoptosis by targeting multiple genes involved in cell survival. In gastric cancer tissues, reducing the expression of miR-34a prevents apoptosis and increases cell proliferation.[17] Another tumor-suppressive miRNA, miR-200c, helps maintain epithelial cell characteristics by targeting EMT-related transcription factors such as ZEB1; when miR-200c levels are low, cells can easily detach and migrate, leading to metastasis.[18] On the other hand, miR-21 acts as an oncogene and is very common in gastric cancer; it promotes cancer cell invasion and spread by repressing the tumor suppressor PTEN. This then activates the PI3K/AKT signaling pathway that supports cell survival and growth.[17]

Additionally, long non-coding RNAs (lncRNAs) play an important role in shaping chromatin structure and epigenetic enzymes, helping to control which genes are turned on or off. For example, LINC00673 has been shown to promote gastric tumor development by leading EZH2 to the promoter regions of tumor suppressor genes; this results in H3K27 trimethylation, a chemical change that silences gene expression and contributes to cancer progression.[19] Another lncRNA, GAS5, has the opposite effect: it is often found at low levels in gastric cancer, helps suppress tumor growth by limiting cell proliferation, and promotes apoptosis through preventing oncogenic signaling pathways.[20] When GAS5 levels drop, growth signals are uncontrolled, which leads to tumor growth and worse patient outcomes.

Furthermore, lncRNAs influence critical pathways such as Wnt/β-catenin and PI3K/AKT. For instance, LINC00152

enhances Wnt/β-catenin signaling and increases the expression of downstream targets like c-MYC and Cyclin D1, which drive cell cycle and tumor progression.[21] These findings show that lncRNAs also contribute to chromatin regulation. Since their expression is often altered in early-stage gastric cancer, non-coding RNAs are promising biomarkers for early detection. Both miRNAs and lncRNAs can shape major pathways and interact with epigenetic enzymes, making them promising treatment options.

Environmental and Biological Triggers:

Environmental and biological factors frequently cause epigenetic changes in gastric cancer. One of the best examples is chronic infection with *Helicobacter pylori* (*H. pylori*) in the stomach lining, which leads to oxidative stress and the release of cytokines. Studies have shown that *H. pylori* infection is directly associated with the hypermethylation of tumor suppressor gene promoters, even in gastric tissues that are not yet cancerous.[5] This indicates that epigenetic changes start to take place in the early stages of disease development, long before any visible tumors are present. **Figure 1** illustrates this epigenetic progression of gastric cancer through stages of inflammation and increasing DNA methylation.

Aside from bacterial infection, the host's immune response plays a key role in epigenetic alterations. During *H. pylori* infection, inflammatory cytokines, such as IL-6 and TNF-α, increase and can heighten the expression of DNMT1, the enzyme responsible for maintaining DNA methylation. As DNMT1 activity rises, methylation of CpG islands occurs throughout the genome and silences genes that are essential for DNA repair and preventing apoptosis.[22] Genetic predisposition also contributes to a person's vulnerability to these epigenetic shifts. Specific single-nucleotide polymorphisms (SNPs) in DNMT1 and other epigenetic regulators have been linked to increased risk of gastric cancer in populations exposed to *H. pylori*. These inherited variants can make some individuals more likely to develop abnormal methylation patterns in response to environmental triggers.[23]

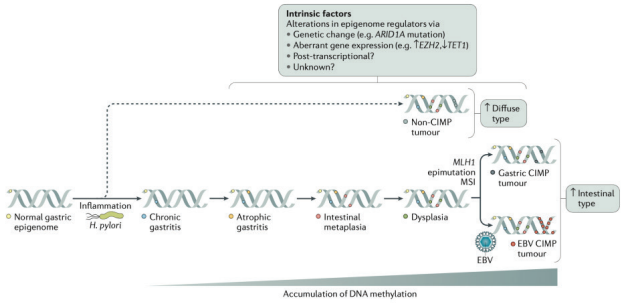

Figure 1: Epigenetic evolution of gastric cancer through inflammation and methylation. This figure shows how the gastric epigenome changes from normal tissue to *H. pylori*-induced inflammation, and then to chronic gastritis, atrophy, intestinal metaplasia, and dysplasia; it also shows a gradual accumulation of DNA methylation. The diagram illustrates how this process can split into non-CIMP tumors (often diffuse type) and CIMP-positive tumors (intestinal type). Adapted from Padmanabhan, N.; Ushijima, T.; Tan, P. How to Stomach an Epigenetic Insult: The Gastric Cancer Epigenome. Nature Reviews Gastroenterology & Hepatology 2017, 14 (8), 467–478. https://doi.org/10.1038/nrgastro.2017.53.

Together, these findings highlight that epigenetic changes in gastric cancer do not occur randomly: they are often affected by chronic infection, signaling, or inherited genetic makeup. Often driven by environmental stressors like *H. pylori*, these alterations alter gene expression without changing the DNA sequence. Thus, their role in silencing tumor suppressors and activating oncogenes makes them promising as biomarkers and therapeutic targets. A visual overview of these regulatory mechanisms is shown in **Figure 2**, highlighting how changes in DNA methylation and non-coding RNA expression contribute to abnormal gene regulation in gastric cancer. Future research should explore how these mechanisms interact and how early intervention might reverse or prevent permanent epigenetic damage.

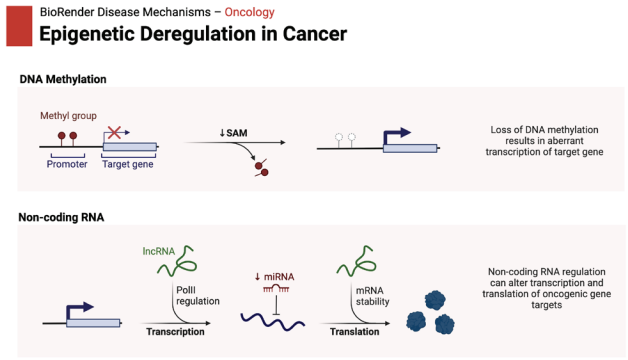

Figure 2: Epigenetic deregulation in cancer. This figure illustrates two key epigenetic mechanisms in cancer: (A) DNA methylation and (B) non-coding RNA regulation. Abnormal DNA methylation, such as promoter hypomethylation or hypermethylation, can lead to dysregulated gene expression. Meanwhile, non-coding RNAs, including lncRNAs and miRNAs, influence transcription and translation as well as impact oncogenic pathways. Created in BioRender. Chiu, J. (2025) https://BioRender.com/k6t23w3

Classifications of Epigenetic Alterations:

Epigenetic changes in gastric cancer can be grouped into specific molecular subtypes that influence how the disease develops and how patients respond to treatment. Unlike random mutations, these changes often follow recognizable patterns linked to certain cancer behaviors. Classification systems like the CpG Island Methylator Phenotype (CIMP) or EBV-related methylation profiles help researchers and doctors organize information, predict outcomes, and create more personalized therapies. Understanding and classifying these epigenetic patterns has become essential for improving diagnosis, prognosis, and precision treatment in gastric cancer.

CpG Island Methylator Phenotype (CIMP):

The CpG Island Methylator Phenotype (CIMP) is when many CpG islands, DNA regions near gene promoters, become abnormally methylated. This often silences tumor suppressor genes that control cell growth, DNA repair, or immune function. Recent studies show that CIMP-high gastric tumors are linked to Epstein–Barr virus (EBV) infection, which causes abnormal methylation across the genome. In EBV-positive tumors, PD-L1 is overexpressed because of epigenetic changes, not gene mutations. This suggests that these patients may respond well to immunotherapy.[24]

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In gastric cancer, hypermethylation of the MLH1 promoter is a key feature of the CIMP-high subtype and is closely associated with microsatellite instability (MSI). This silences the MLH1 gene, weakens DNA repair mechanisms, and allows mutations to build up. By damaging the DNA, these mutations may lead to abnormal proteins or functions that cause uncontrollable growth or cancer. As a result, MSI-high tumors tend to have a high number of neoantigens, making them more responsive to immunotherapy.[25] Furthermore, CIMP-high tumors frequently exhibit methylation of CDKN2A and SOCS1. Methylation of SOCS1 interferes with cytokine signaling regulation, which promotes tumor development due to inflammation. On the other hand, CDKN2A silencing eliminates a crucial stop during the cell cycle, allowing cancer cells to continue multiplying.[26] CIMP-high gastric tumors also have many immune cells around them; they often contain many cytotoxic T cells, possibly due to EBV infection or the high number of mutations caused by MSI.[27]

Environmental and Biological Triggers:

Instead of grouping epigenetic changes only by tumor type or patient outcome, some researchers organize them by their effect on the cell. To do this, they separate gene-silencing from gene-activating methylation. Gene-silencing methylation often shuts down important tumor suppressor genes. For example, when CDH1 is silenced, cancer cells lose their ability to stick together, making them spread more easily.[12] Additionally, the BRCA1 gene repairs DNA, but when it is silenced by methylation, the cell is unable to fix DNA damage properly, possibly leading to more mutations and cancer growth. Conversely, gene-activating changes can happen through hypomethylation, which makes it easier for certain genes to turn on when they should not be. For example, the oncogene c-MYC can become more active when its promoter region is demethylated, leading to uncontrolled cell growth.[28] Researchers also group methylation changes by the types of genes they affect. For instance, methylation of MLH1 is connected to microsatellite instability (MSI) and causes problems with DNA repair. Silencing DAPK1 (a gene involved in programmed cell death) lets cancer cells survive longer than they should, while methylation of CDKN2A removes an important checkpoint in the cell cycle, allowing cancer cells to divide too quickly.[29]

Clinical Utility of Epigenetic Classification:

Classifying gastric cancers by their epigenetic features, such as DNA methylation patterns, can help doctors predict how aggressive the cancer is and which treatments might work best. For example, tumors that are CIMP-high or infected with EBV often have high PD-L1 levels and a strong immune response.[26] Therefore, these patients could benefit from therapies that use the immune system to fight cancer. Another useful subtype is MSI-high, and these tumors often have methylation of the MLH1 gene, which impairs DNA repair. Since MSI-high cancers carry many mutations, they give more neoantigens to the immune system and may respond well to immunotherapy. Finally, knowing a patient's epigenetic subtype can also help determine the best drugs to use. For instance, demethylating agents or HDAC inhibitors may help in cancers with too much methylation or abnormal chromatin regulation. Classifying epigenetic changes in gastric cancer provides important insights into how tumors develop and progress in patients. CIMP, EBV-related methylation patterns, and other gene groupings prove how complex gastric cancer development is. These systems help group patients more accurately, predict outcomes, and guide treatment options. Improving and combining these classifications is the first step to achieving fully personalized therapeutic strategies.

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Therapeutic Implications and Clinical Applications:

As the role of epigenetic alterations in gastric cancer gets clearer, treatments that target them are becoming more common. Drugs that can reverse abnormal DNA methylation and histone changes are being tested in gastric cancer trials. New approaches, like RNA-based therapies, liquid biopsy biomarkers, and combination treatments, also show promise for improving diagnosis and prognosis. These developments underscore the growing potential of epigenetic medicine to transform clinical management and personalize care for gastric cancer patients.

Drugs and Epigenetic Therapies:

Epigenetic therapies are emerging as a new approach in gastric cancer, particularly for tumors marked by DNA methylation or histone modification abnormalities. DNMTs, such as azacitidine and decitabine, can reverse abnormal methylation and reactivate silenced tumor suppressor genes.[30] These treatments are especially useful for early gastric lesions and CIMP-high tumors, which often exhibit widespread promoter hypermethylation.

Histone deacetylase inhibitors (HDACis), such as vorinostat and belinostat, restore normal histone acetylation, which reactivates silenced tumor suppressor genes like PER1 and PER2 and promotes apoptosis in gastric cancer cells.[14] These genes are part of the circadian clock system, which regulates the body's 24-hour biological rhythms (i.e., cell growth, DNA repair, and metabolism). Recent studies using gastric cancer organoids also show that tumors with active RTK/MAPK signaling respond to HDACis, suggesting these drugs may work best in certain molecular subtypes.[31] This supports a more personalized approach to treatment, using pathway activity as a biomarker to guide therapy selection.

New therapeutic targets have also emerged. EZH2, a histone methyltransferase, is common in aggressive gastric cancers and is associated with E-cadherin loss and poor prognosis.[32] EZH2 inhibitors are being studied for their ability to slow tumor growth by changing chromatin structure. In addition, miRNAs and lncRNAs are increasingly recognized for their role in gastric cancer development. RNA-based therapeutics, such as antisense oligonucleotides and small interfering RNAs (siRNAs), target these epigenetic regulators and are being developed to suppress oncogenic RNA species.[33] These therapies are extremely specific, allowing them to directly silence non-coding RNAs that contribute to tumor growth and drug resistance. By adjusting the expression of these RNAs, therapies may reduce harmful traits and reshape cancer cells.

Finally, combining epigenetic treatments with immunotherapy is becoming more popular. For instance, epigenetic modulation can raise PD-L1 levels and attract immune cells, which may improve responses to checkpoint inhibitors in MSI-H and EBV-positive gastric cancers.[34] This effect occurs because epigenetic drugs can turn "cold" tumors (those that avoid detection by the immune system) into "hot" ones that are easier for immune cells to recognize and attack; they do this by exposing hidden tumor antigens, raising MHC levels to help the immune system spot cancer cells, and changing the surrounding areas. Consequently, these combination therapies may offer new treatment options for patients who initially show limited response to immunotherapy.

Biomarkers in Epigenetic Studies:

Epigenetic biomarkers are crucial for identifying gastric cancer patients who may benefit from targeted therapies. With the hypermethylation of genes (i.e., MLH1, CDKN2A, and PCDH10), abnormal DNA methylation remains a key marker and is linked to microsatellite instability and tumor progression.[35] Recently, PRKCB was also identified as a hypermethylated gene that could potentially be used for early detection.[15] The silencing of PRKCB is linked to decreased immune response and poorer outcomes, making it a strong possibility for non-invasive screening and risk assessment in early gastric cancer. Additionally, liquid biopsy technologies that assess circulating tumor DNA (ctDNA) or cell-free DNA (cfDNA) methylation offer a non-invasive approach for diagnosis and recurrence monitoring.[36] These approaches allow clinicians to monitor tumor evolution and treatment response in real time, reducing the need for invasive tissue biopsies and enabling faster clinical decision-making.

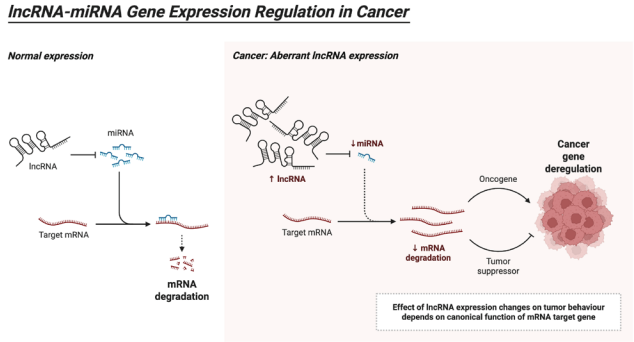

Figure 3: Regulation of gene expression by lncRNA and miRNA in cancer. Dysregulation of the interactions between lncRNA and miRNA alters mRNA degradation as well as contributes to oncogene activation and tumor suppressor silencing in cancer. Under normal conditions (left), lncRNAs regulate miRNA activity, which in turn promotes degradation of target mRNA. In cancer (right), too many lncRNAs or too few miRNAs reduce mRNA breakdown, which causes oncogenes to be overactive or tumor suppressors to be turned off, leading to cancer gene deregulation. Created in BioRender. Chiu, J. (2025) https://BioRender.com/exnv3l1

Aside from DNA methylation, non-coding RNAs and tRNA-derived fragments (tRFs) are recognized as predictive biomarkers. For instance, elevated expression of miR-21 and lncRNA HOTAIR corresponds to poor prognosis and resistance to HDAC and DNMT inhibitors.[37] A model of how altered lncRNA-miRNA interactions impair mRNA degradation and increase cancer gene dysregulation is shown in **Figure 3**. Likewise, measuring plasma tRFs can help detect early gastric cancer and predict outcomes.[38] Together, these biomarkers support precision medicine by improving early detection and treatment response.

Future Directions: Personalized Epigenetic Therapy:

New advances in epigenomics, transcriptomics, and proteomics are transforming gastric cancer treatment by making therapies more personalized. Integrating these multi-omics platforms, technologies that combine data from different biological layers (i.e., DNA, RNA, proteins, and epigenetic changes), helps identify key epigenetic drivers that can guide treatment selection and disease monitoring. Such approaches provide a full picture of the disease, allowing doctors to choose the best treatments based on each tumor's unique profile.[39] This strategy can help overcome barriers like chemoresistance and disease recurrence.

Moreover, a key innovation is the application of patient-derived organoids (PDOs), which retain the genetic and epigenetic characteristics of the patient's tumor. These 3D models are now being used for ex vivo testing of epigenetic therapies, such as DNMT and HDAC inhibitors.[40] In other words, they are practical tools for personalizing treatment and avoiding unnecessary side effects.

Stratification or grouping based on epigenetic risk scores is also proving useful. For instance, aberrant methylation patterns remain in tumors even after treatment, highlighting their potential as long-term markers.[41] After *H. pylori* is removed,

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patients with continued hypermethylation of tumor suppressor genes face a higher risk of the cancer returning.

Additionally, understanding the interaction between epigenetic changes and major oncogenic pathways is essential for advancing targeted therapies. Frequently altered in gastric cancer, this pathway is often influenced by epigenetic modifications, including promoter methylation and histone alterations.[42,43] Modifications can activate or silence genes involved in cell survival, proliferation, and resistance. Targeting both the PI3K/AKT/mTOR pathway and epigenetic regulators may simultaneously help slow tumor growth.

Finally, the role of AI and machine learning in epigenetics is also rapidly expanding. Computational tools using large methylome datasets are being trained to find patterns linked to drug resistance and disease progression.[44] Refining therapeutic decisions and improving patient outcomes, these models can help predict which patients are most likely to benefit from specific epigenetic agents or combination regimens.

Ultimately, these strategies reflect a growing shift toward personalized epigenetic therapy in gastric cancer. Clinicians can now better adjust treatments that work longer, respond better to changes, and are more effective overall. Epigenetic research has revealed powerful insights into the progression and treatment of gastric cancer, leading to the development of promising therapies that target DNA methylation, histone modifications, and non-coding RNAs. The identification of reliable biomarkers is key to optimizing treatment selection, monitoring progression, and guiding personalized care. As technology improves, integrating epigenetic profiles into clinical practice could transform gastric cancer diagnosis.

Conclusion

The concept of epigenetic alterations and their role in the onset and progression of gastric cancer is explained throughout this article, but leaves many unanswered questions. The review began by examining how these epigenetic changes begin, with DNA hypermethylation silencing tumor suppressors, histone-modifying enzymes, and ncRNAs. Environmental triggers, particularly *Helicobacter pylori*, were shown to leave lasting epigenetic damage, even after clearing the infection. Next, the paper discussed how classification systems like CIMP and EBV-related methylation profiles help sort patients by risk and guide treatment. Lastly, the review explored therapeutic and clinical applications, highlighting DNMT and HDAC inhibitors, RNA-based therapeutics, epigenetic–immunotherapy combinations, biomarkers for non- invasive monitoring, and AI-driven models.

Overall, these findings highlight how understanding the epigenetics of gastric cancer can create new precision medicine techniques and more individualized treatment strategies. These insights not only present earlier and more precise detection of the disease using epigenetic biomarkers but also open the door to targeted treatments capable of correcting abnormal patterns of gene silencing or activation.

However, despite recent progress, many questions remain. How can persistent methylation after *H. pylori* eradication be reversed? Can ncRNA-targeting drugs overcome resistance in solid tumors? Which epigenetic changes truly cause cancer, and which are simply linked to it? Future research should combine multi-omics integration and long-term patient monitoring to better track epigenetic changes over time.

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References

1. Canale, M.; Casadei-Gardini, A.; Ulivi, P.; Arechederra, M.; Berasain, C.; Lollini, P.-L.; Fernández-Barrena, M. G.; Avila, M. A. Epigenetic Mechanisms in Gastric Cancer: Potential New Therapeutic Opportunities. *International Journal of Molecular Science*s **2020**, *21* (15), 5500. https://doi.org/10.3390/ijms21155500.
2. Christodoulidis, G.; Koumarelas, K.-E.; Kouliou, M.-N.; Thodou, E.; Samara, M. Gastric Cancer in the Era of Epigenetics. *International Journal of Molecular Sciences* **2024**, *25* (6), 3381–3381. https://doi.org/10.3390/ijms25063381.
3. Salvatori, S.; Marafini, I.; Laudisi, F.; Monteleone, G.; Stolfi, C. *Helicobacter Pylori* and Gastric Cancer: Pathogenetic Mechanisms. *International Journal of Molecular Sciences* **2023**, *24* (3), 2895. https://doi.org/10.3390/ijms24032895.
4. Padmanabhan, N.; Ushijima, T.; Tan, P. How to Stomach an Epigenetic Insult: The Gastric Cancer Epigenome. *Nature Reviews Gastroenterology & Hepatology* **2017**, *14* (8), 467–478. https://doi.org/10.1038/nrgastro.2017.53.
5. Michigami, Y.; Watari, J.; Ito, C.; Nakai, K.; Yamasaki, T.; Kondo, T.; Kono, T.; Tozawa, K.; Tomita, T.; Oshima, T.; Fukui, H.; Morimoto, T.; Das, K. M.; Miwa, H. Long-Term Effects of *H. Pylori* Eradication on Epigenetic Alterations Related to Gastric Carcinogenesis. *Scientific Reports* **2018**, *8* (1), 14369. https://doi.org/10.1038/s41598-018-32717-3.
6. Dai, W.; Qiao, X.; Fang, Y.; Guo, R.; Bai, P.; Liu, S.; Li, T.; Jiang, Y.; Wei, S.; Na, Z.; Xiao, X.; Li, D. Epigenetics-Targeted Drugs: Current Paradigms and Future Challenges. *Signal Transduction and Targeted Therapy* **2024**, *9* (1). https://doi.org/10.1038/s41392-024-02039-0.
7. Kalra, A.; Meltzer, S. J. The Role of DNA Methylation in Gastrointestinal Disease: An Expanded Review of Malignant and Nonmalignant Gastrointestinal Diseases. *Gastroenterology* **2025**, *168* (2), 245–266. https://doi.org/10.1053/j.gastro.2024.07.001.
8. Weng, S.; Li, M.; Deng, J.; Xu, H.; Ren, Y.; Zhou, Z.; Wang, L.; Zhang, Y.; Xing, Z.; Li, L.; Liu, Z.; Han, X. Epigenetically Regulated Gene Expression Profiles Decipher Four Molecular Subtypes with Prognostic and Therapeutic Implications in Gastric Cancer. *Clinical Epigenetics* **2023**, *15* (1). https://doi.org/10.1186/s13148-023-01478-w.
9. Fu, D.-G. Epigenetic Alterations in Gastric Cancer (Review). *Molecular Medicine Reports* **2015**, *12* (3), 3223–3230. https://doi.org/10.3892/mmr.2015.3816.
10. Tang, S.-Y.; Zhou, P.-J.; Meng, Y.; Zeng, F.-R.; Deng, G.-T. Gastric Cancer: An Epigenetic View. *World journal of gastrointestinal oncology* **2022**, *14* (1), 90–109. https://doi.org/10.4251/wjgo.v14.i1.90.
11. Wang, X.; Dong, Y.; Zhang, H.; Zhao, Y.; Miao, T.; Mohseni, G.; Du, L.; Wang, C. DNA Methylation Drives a New Path in Gas-

tric Cancer Early Detection: Current Impact and Prospects. *Genes & Diseases* **2023**, *11* (2), 847–860. https://doi.org/10.1016/j.gendis.2023.02.038.

12. De Marco, K.; Sanese, P.; Simone, C.; Grossi, V. Histone and DNA Methylation as Epigenetic Regulators of DNA Damage Repair in Gastric Cancer and Emerging Therapeutic Opportunities. *Cancers* **2023**, *15* (20), 4976. https://doi.org/10.3390/cancers15204976.
13. Jenke, R.; Oliinyk, D.; Zenz, T.; Körfer, J.; Schäker-Hübner, L.; Hansen, F. K.; Lordick, F.; Meier-Rosar, F.; Aigner, A.; Büch, T. HDAC Inhibitors Activate Lipid Peroxidation and Ferroptosis in Gastric Cancer. *Biochemical Pharmacology* **2024**, *225*, 116257. https://doi.org/10.1016/j.bcp.2024.116257.
14. Hernández-Rosas, F.; Hernández-Oliveras, A.; Flores-Peredo, L.; Rodríguez, G.; Zarain-Herzberg, Á.; Caba, M.; Santiago-García, J. Histone Deacetylase Inhibitors Induce the Expression of Tumor Suppressor Genes Per1 and Per2 in Human Gastric Cancer Cells. *Oncology Letters* **2018**, *16* (2), 1981– 1990. https://doi.org/10.3892/ol.2018.8851.
15. Li, L.; Fei, X.; Wang, H.; Chen, S.; Xu, X.; Ke, H.; Zhou, Y.; Hu, Y.; He, C.; Xie, C.; Lu, N.; Liu, J.; Zhu, Y.; Li, N. Genome-Wide DNA Methylation Profiling Reveals a Novel Hypermethylated Biomarker PRKCB in Gastric Cancer. *Scientific Reports* **2024**, *14* (1). https://doi.org/10.1038/s41598-024-78135-6.
16. Zou, G.; Huang, Y.; Zhang, S.; Ko, K.-P.; Kim, B.; Zhang, J.; Venkatesan, V.; Pizzi, M. P.; Fan, Y.; Jun, S.; Niu, N.; Wang, H.; Song, S.; Ajani, J. A.; Park, J.-I. E-Cadherin Loss Drives Diffuse-Type Gastric Tumorigenesis via EZH2-Mediated Reprogramming. *Journal of Experimental Medicine* **2024**, *221* (4). https://doi.org/10.1084/jem.20230561.
17. Ghafouri-Fard, S.; Vafaee, R.; Shoorei, H.; Taheri, M. MicroRNAs in Gastric Cancer: Biomarkers and Therapeutic Targets. *Gene* **2020**, *757*, 144937. https://doi.org/10.1016/j.gene.2020.144937.
18. Elimam, H.; Hatawsh, S. A.; Moussa, R.; Radwan, A. F.; Elfar, N.; Abd- Elmawla, M. A.; Mohammed, O. A.; Zaki, M. B.; Doghish, A. S. Unraveling the Influence of LncRNA in Gastric Cancer Pathogenesis: A Comprehensive Review Focus on Signaling Pathways Interplay. *Medical Oncology* **2024**, *41* (9). https://doi.org/10.1007/s12032-024-02455-w.
19. Yousefi, L.; Osquee, H. O.; Ghotaslou, R.; Rezaee, M. A.; Pirzadeh, T.; Sadeghi, J.; Hemmati, F.; Yousefi, B.; Moaddab, S. Y.; Yousefi, M.; Shirmohammadi, M.; Somi, M. H.; Ganbarov, K.; Kafil, H. S. Dysregulation of LncRNA in *Helicobacter Pylori*-Infected Gastric Cancer Cells. *BioMed* 2021, **2021**, 6911734. https://doi.org/10.1155/2021/6911734.
20. Sun, M.; Nie, F.; Wang, Z.; De, W. Involvement of LncRNA Dysregulation in Gastric Cancer. *Histology and histopathology* **2016**, *31* (1), 33–39. https://doi.org/10.14670/HH-11-655.
21. Loe, A. K. H.; Zhu, L.; Kim, T.-H. Chromatin and Noncoding RNA-Mediated Mechanisms of Gastric Tumorigenesis. *Experimental & Molecular Medicine* **2023**, *55* (1), 22–31. https://doi.org/10.1038/s12276-023-00926-0.
22. Xi, Y.; Zhang, X.-L.; Luo, Q.-X.; Gan, H.-N.; Liu, Y.-S.; Shao, S.-H.; Mao, X.-H. *Helicobacter Pylori* Regulates Stomach Diseases by Activating Cell Pathways and DNA Methylation of Host Cells. *Frontiers in Cell and Developmental Biology* **2023**, *11*. https://doi.org/10.3389/fcell.2023.1187638.
23. Zhang, N.; Gao, X.; Yuan, Q.; Fu, X.; Wang, P.; Cai, F.; Liu, H.; Zhang, J.; Liang, H.; Nie, Y.; Deng, J. E3 Ubiquitin Ligase RNF180 Prevents Excessive PCDH10 Methylation to Suppress the Proliferation and Metastasis of Gastric Cancer Cells by Promoting Ubiquitination of DNMT1. *Clinical Epigenetics* **2023**, *15* (1). https://doi.org/10.1186/s13148-023-01492-y.
24. Nakano, H.; Saito, M.; Nakajima, S.; Saito, K.; Nakayama, Y.; Kase, K.; Yamada, L.; Kanke, Y.; Hiroyuki Hanayama; Hisashi Onozawa; Okayama, H.; Fujita, S.; Sakamoto, W.; Zenichiro Saze; Tomoyuki Momma; Mimura, K.; Shinji Ohki; Goto, A.; Kono, K. PD-L1 Overexpression in EBV-Positive Gastric Cancer Is Caused by Unique Genomic or Epigenomic Mechanisms. *Scientific Reports* **2021**, *11* (1). https://doi.org/10.1038/s41598-021-81667-w.
25. Yamamoto, H.; Watanabe, Y.; Arai, H.; Umemoto, K.; Tateishi, K.; Sunakawa, Y. Microsatellite Instability: A 2024 Update. *Cancer Science* **2024**, *115* (6), 1738–1748. https://doi.org/10.1111/cas.16160.
26. Padmanabhan, N.; Kyon, H. K.; Boot, A.; Lim, K.; Srivastava, S.; Chen, S.; Wu, Z.; Lee, H.-O.; Mukundan, V. T.; Chan, C.; Chan, Y. K.; Xuewen, O.; Pitt, J. J.; Isa, Z. F. A.; Xing, M.; Lee, M. H.; Tan, A.; L. K.; Ting, S. H. W.; Luftig, M. A.; Kappei, D. Highly Recurrent CBS Epimutations in Gastric Cancer CpG Island Methylator Phenotypes and Inflammation. *Genome Biology* **2021**, *22* (1). https://doi.org/10.1186/s13059- 021-02375-2.
27. Dash, M.; Mahajan, B.; Shah, S.; Dar, G. M.; Sahu, P.; Sharma, A. K.; Nimisha; Saluja, S. S. Distinct Methylome Profile of CfDNA in AMI Patients Reveals Significant Alteration in CAMP Signaling Pathway Genes Regulating Cardiac Muscle Contraction. *Clinical Epigenetics* **2024**, *16* (1). https://doi.org/10.1186/s13148-024-01755-2.
28. Lupan, I.; Bintintan, V.; Deleanu, D.; Samasca, G. Epigenetic Regulation of DNA Methylation and RNA Interference in Gastric Cancer: A 2024 Update. *Biomedicines* **2024**, *12* (9), 2001–2001. https://doi.org/10.3390/biomedicines12092001.
29. Tan, X.; Fang, Y.; Fan, X.; Deng, W.; Huang, J.; Cai, Y.; Zou, J.; Chen, Z.; Lin, H.; Xu, L.; Wang, G.; Zhan, H.; Huang, S.; Fu, X. Testing Region Selection and Prognostic Analysis of MLH1 Promoter Methylation in Colorectal Cancer in China. *Gastroenterology report* **2023**, *12*. https://doi.org/10.1093/gastro/goae011.
30. Ebrahimi, V.; Soleimanian, A.; Ebrahimi, T.; Azargun, R.; Yazdani, P.; Eyvazi, S.; Tarhriz, V. Epigenetic Modifications in Gastric Cancer: Focus on DNA Methylation. *Gene* **2020**, *742*, 144577. https://doi.org/10.1016/j.gene.2020.144577.
31. Seidlitz, T.; Schmäche, T.; García, F.; Lee, J. H.; Qin, N.; Kochall, S.; Fohgrub, J.; Pauck, D.; Rothe, A.; Koo, B.; Weitz, J.; Remke, M.; Muñoz, J.; Stange, D. E. Sensitivity towards HDAC Inhibition Is Associated with RTK / MAPK Pathway Activation in Gastric Cancer. *EMBO Molecular Medicine* **2022**, *14* (10). https://doi.org/10.15252/emmm.202215705.
32. Yu, W.; Liu, N.; Song, X.; Chen, L.; Wang, M.; Xiao, G.; Li, T.; Wang, Z.; Zhang, Y. EZH2: An Accomplice of Gastric Cancer. *Cancers* **2023**, *15* (2), 425. https://doi.org/10.3390/cancers15020425.
33. Saleh, R. O.; Al-Hawary, S. I. S.; Hammoud, A.; Hjazi, A.; Ayad Abdulrazzaq, S.; Rajput, P.; Alawsi, T.; Alnajar, M. J.; Alawadi, A. The Long Non-Coding RNAs (LncRNA) in the Pathogenesis of Gastric Cancer Cells: Molecular Mechanisms and Involvement. Mole. *Molecular Biology Reports* **2024**, *51* (1). https://doi.org/10.1007/s11033-024-09546-x.
34. Sun, K.; Jia, K.; Lv, H.; Wang, S.-Q.; Wu, Y.; Lei, H.; Chen, X. EBV-Positive Gastric Cancer: Current Knowledge and Future Perspectives. *Frontiers in Oncology* **2020**, *10*. https://doi.org/10.3389/fonc.2020.583463.
35. Usui, G.; Matsusaka, K.; Mano, Y.; Urabe, M.; Funata, S.; Fukayama, M.; Ushiku, T.; Kaneda, A. DNA Methylation and Genetic Aberrations in Gastric Cancer. *Digestion* **2021**, *102* (1), 25–32. https://doi.org/10.1159/000511243.
36. Qi, J.; Hong, B.; Wang, S.; Wang, J.; Fang, J.; Sun, R.; Nie, J.; Wang, H. Plasma Cell-Free DNA Methylome- Based Liquid Bi-

DOI: 10.36838/IJHSR811.110

opsy for Accurate Gastric Cancer Detection. *Cancer Science* **2024**, *115* (10), 3426–3438. https://doi.org/10.1111/cas.16284.
37. Yang, Q.; Yu, C.; Guo, R.; Dai, Y.; Tang, L.; Zhao, Y.; Wu, X.; Li, M.; Du, F.; Shen, J.; Yi, T.; Xiao, Z.; Wen, Q. Interaction of NcRNA and Epigenetic Modifications in Gastric Cancer: Focus on Histone Modification. *Frontiers in Oncology* **2022**, *11*. https://doi.org/10.3389/fonc.2021.822745.
38. Zhang, S.; Xie, Y.; Yu, X.; Ge, J.; Ye, G.; Guo, J. Absolute Quantification of a Plasma TRNA-Derived Fragment for the Diagnosis and Prognosis of Gastric Cancer. *Frontiers in Oncology* **2023**, *13*. https://doi.org/10.3389/fonc.2023.1106997.
39. Wang, Y.; Liu, H.; Zhang, M.; Xu, J.; Zheng, L.; Liu, P.; Chen, J.; Liu, H.; Chen, C. Epigenetic Reprogramming in Gastrointestinal Cancer: Biology and Translational Perspectives. *MedComm* **2024**, *5* (9). https://doi.org/10.1002/mco2.670.
40. Zhao, Y.; Li, S.; Zhu, L.; Huang, M.; Xie, Y.; Song, X.; Chen, Z.; Harry Cheuk-Hay Lau; Joseph Jao-Yiu Sung; Xu, L.; Yu, J.; Li, X. Personalized Drug Screening Using Patient-Derived Organoid and Its Clinical Relevance in Gastric Cancer. *Cell Reports Medicine* **2024**, *5* (7), 101627–101627. https://doi.org/10.1016/j.xcrm.2024.101627.
41. Choi, S. J.; Jung, S. W.; Huh, S.; Chung, Y.-S.; Cho, H.; Kang, H. Alteration of DNA Methylation in Gastric Cancer with Chemotherapy. *Journal of microbiology and biotechnology* **2017**, *27* (8), 1367–1378. https://doi.org/10.4014/jmb.1704.04035.
42. Fattahi, S.; Amjadi-Moheb, F.; Tabaripour, R.; Ashrafi, G. H.; Akhavan-Niaki, H. PI3K/AKT/MTOR Signaling in Gastric Cancer: Epigenetics and Beyond. *Life Sciences* **2020**, *262*, 118513. https://doi.org/10.1016/j.lfs.2020.118513.
43. Li, L.; Song, Q.; Zhou, J.; Ji, Q. Controllers of Histone Methylation-Modifying Enzymes in Gastrointestinal Cancers. *Biomedicine & pharmacotherapy = Biomedecine & pharmacotherapie* **2024**, *174*, 116488. https://doi.org/10.1016/j.biopha.2024.116488.
44. Song, J.; Yang, P.; Chen, C.; Ding, W.; Olivier Tillement; Bai, H.; Zhang, S. Targeting Epigenetic Regulators as a Promising Avenue to Overcome Cancer Therapy Resistance. *PubMed* **2025**, *10* (1), 219–219. https://doi.org/10.1038/s41392-025-02266-z.

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REVIEW ARTICLE

Bridging Oncology and Infectious Disease: AI-Driven Biotechnological Strategies Against Antimicrobial Resistance

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ABSTRACT: Antibiotic resistance is a pressing global health crisis, driven by multidrug-resistant pathogens such as *A. baumannii* that render last-resort antibiotics less effective. Despite advances in antibiotic discovery, drug development pipelines remain slow, costly, and vulnerable to the emergence of cross-resistance. This paper explores the integration of AI into antimicrobial drug research and delves into an interdisciplinary approach that leverages tools from other fields, especially oncology, to expedite antimicrobial research. Zosurabalpin is a novel drug with high specificity for *A. baumannii* that disrupts the lipopolysaccharide transport (LPT) system, thereby undermining the bacteria's structural integrity. Halicin was repurposed as an antibiotic after AI screening of existing compounds identified it as having promising antimicrobial properties. The parallel between oncology and antimicrobial resistance offers a rich collection of knowledge transferable into antimicrobial research. Using oncology tools, such as DNA microarrays, monoclonal antibodies, and predictive modeling, provides a broader scope, enabling an integrative and comparative approach to accelerate innovation while reducing costs and redundancy.

KEYWORDS: Antimicrobial and Antibiotics, Immunology, Zosurabalpin, Oncology, AI.

Introduction

Since the discovery of penicillin in 1928, bacteria have rapidly developed resistance to a wide range of antibiotics, including last-resort drugs such as carbapenems and polymyxins. Multidrug-resistant (MDR) bacteria are outpacing pharmaceutical innovation. In 2019, 1.27 million deaths were attributed to antibiotic resistance worldwide.[1] Even when new antibiotics are developed, they are slightly modifi ed versions of existing drugs, making them susceptible to cross-resistance. In this phenomenon, bacteria already resistant to one drug in a class are likely to be resistant to drugs with similar mechanisms of action. Medical professionals are discouraged from increasing antibiotic doses because resistant mutants survive the higher dose and replicate, contributing to greater resistance in that strain. These issues have slowed the development of eff ective drugs against highly resistant bacteria, as growing bacterial cultures can take days, which critical patients do not have, let alone the time it'll take to test the effi cacy of a new drug against the bacteria. AMR currently causes an estimated annual death of 700,000, projected to reach 10 million by 2050, with potential $100 trillion global economic losses. Patients with drug-resistant infections often remain hospitalized for over 13 days, costing $29,000 per case.[2] Beyond these economic costs, pharmaceutical companies face little incentive to invest in new antibiotics, which are used for short-term treatment compared to chronic disease treatments. These statistics underscore the need for antimicrobial stewardship and the growing use of AI to screen existing compounds for antimicrobial potential, accelerating drug discovery.

Classifi ed by the World Health Organization as "Priority 1: Critical Pathogen," *Acinetobacter baumannii* is resistant to carbapenem—a type of beta-lactam antibiotic that is a last-resort drug to treat multidrug-resistant bacteria—decreasing the effi cacy of current treatments while also contributing to antibiotic overuse, a driving factor of antibiotic resistance. Intensive Care Unit (ICU) patients are especially vulnerable to *A. baumannii* infections due to the bacterium's biofilm–complex bacterial microcolonies, which reduce cell membrane permeability, allowing it to adhere to and survive on catheters, surgical instruments, and ventilators for long periods. People in low-and middle-income countries are also vulnerable to antibiotic-resistant bacterial infections due to the misuse of antibiotics.[3] Thus, expediting the development and testing of novel drugs is an urgent priority. Cancer patients also suff er from a higher risk of bacterial infection, so exploring oncology data provides a vast perspective in fi ghting hospital-acquired infections. Bacteria and cancer cells share mechanisms to counteract treatment eff ects, such as drug effl ux and mutations, which we will explore in more detail later. Of course, infectious diseases diff er from cancers in their etiologies, responses, and environmental factors, but the shared complexity of biological resistance warrants a logical exploration of innovations. It should still be acknowledged that Zosurabalpin is in the nascent stages, so its performance in real-world settings remains to be determined.

Extensive cancer research has identifi ed antimicrobial properties in human monoclonal antibodies. Additionally, antimicrobial peptides (AMPs) have been used to treat a variety of infections, including cancer and fungal infections. Using an interdisciplinary approach to cancer research to combat antibiotic resistance is feasible and enables the development of faster, novel treatments for resistant bacterial infections. Given the growing issue of antibiotic resistance, driven by factors such as unnecessary antibiotic prescribing, poor infection control, and the fi nancial burden of pharmaceuticals, a multidisciplinary

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approach off ers a new perspective for combating this global health crisis.

Moreover, exploring alternative strategies to combat antibiotic resistance beyond traditional antimicrobial development is increasingly important. In fi elds such as oncology and HIV research, predictive AI and machine learning models have already been extensively developed to identify resistance mutations and guide treatment decisions. Leveraging substantial funding off ers a practical and effi cient pathway to repurpose treatments for AMR. This paper fi rst explores novel drugs and the application of AI tools from other fi elds to antibiotic drug discovery, offering deeper insights and providing a holistic overview of existing research as a preface to repurposing oncology tools for AMR. This paper argues that oncology-derived AI tools and therapeutic frameworks off er a scalable, underutilized pathway for accelerating AMR innovation. By drawing parallels between emerging antibiotics like Zosurabalpin and how other fi elds have integrated AI, bioinformatics, and predictive modeling into drug development, we can identify overlooked strategies and potential shortcuts. In the following subsections, we'll review the existing literature and innovations that use AI to combat antibiotic resistance. Then, we'll proceed to expand on the idea of repurposing drugs and resources from other medical fi elds in subsection two.

■ Overview of Novel Compounds and Existing Applications of AI in Antibiotic Resistance Research

This section will cover bacterial biofilms and the genetic mechanisms of transformation, conjugation, and transduction. Outlining key resistance strategies—drug modifi cation, target modifi cation, effl ux pumps, and altered membrane permeability—and highlighting parallels between bacterial resistance and cancer drug resistance. First, we'll delve into the physical properties of bacteria. More specifically, bacterial biofilms, formed by both Gram-positive and Gram-negative bacteria, are structured communities embedded in a self-produced polymer matrix composed of polysaccharides, DNA, and proteins. Then, we will cover how Zosurabalpin works through the mechanisms of action that degrade bacteria and other compounds, as well as the applications of AI tools in drug discovery. These similarities motivate the use of predictive models originally developed in oncology.

Along with biofilm-buff ered support, bacteria can acquire resistance through various mechanisms, including transformation, conjugation, and transduction. Transformation occurs when bacteria incorporate DNA fragments from the environment; conjugation is the active exchange of genetic material between two bacteria via plasmids; and transduction is the acquisition of resistance genes via phages that inject new DNA. Driving factors of antibiotic resistance include antibiotic misuse, which increases mutation rates and the likelihood of resistance, releases DNA from dead cells, and ensures the survival of the fi ttest bacteria. Bacterial resistance mechanisms include spatial exclusion, drug modifi cation, target modifi cation, bypass mechanisms, effl ux pumps, and alterations in membrane permeability. Spatial exclusion is the prevention of antibiotics from reaching their targets by barriers such as bacterial cell walls and biofilms. This is especially challenging for treating gram-negative bacteria, which form cell walls and biofilms, whereas gram-positive bacteria do not. Bacteria may acquire or naturally possess genes encoding enzymes that modify antibiotic molecules by adding functional groups, thereby hindering their binding to target sites or simply deactivating the drug. Such resistance strategies parallel how cancer cells alter therapeutic binding sites, underscoring why oncology models help predict patterns of resistance. Some bacteria may also produce enzymes such as β-lactamases, which break down β-lactam antibiotics like penicillin, and aminoglycoside-modifying enzymes that add chemical groups to aminoglycosides, inactivating them. Target modifi cation refers to the antibiotic's target protein in bacteria, whose structure or function can be altered by mutations in ribosomes, DNA gyrase, and other proteins. Even if the antibiotic reaches the target site, reduced binding affi nity prevents it from interacting properly with the substrate. Bacteria can also bypass antibiotic-disrupted processes, such as folic acid synthesis, by obtaining folic acid from the environment. Effl ux pumps are membrane proteins that actively transport antibiotics that enter the cell. For example, the AcrAB-TolC system, powered by the proton gradient, is integrated into the inner, periplasmic, and outer membranes of Gram-negative bacteria. Reduced membrane permeability, achieved by downregulating porins or other protein channels, prevents drugs from entering the cell effi ciently. The variety of resistance mechanisms, along with the improper use of antibiotics, underscores the urgency of exploring and rapidly developing eff ective treatments.

Antimicrobial Stewardship:

This subsection evaluates Antimicrobial Stewardship (AMS), a set of practices that ensure antibiotics are used only when necessary and appropriately, as a frontline strategy to mitigate antibiotic resistance through optimized antibiotic use. Issues such as prophylaxis and overreliance on broad-spectrum antibiotics constrain the use of AMS as a long-term solution. Thus, these gaps underscore the need for complementary innovation. A systematic meta-analysis of 26 studies found that hospital-based ASP implementation reduced overall antibiotic consumption by ~19.1%, restricted antibiotic use (e.g., carbapenems, glycopeptides) by ~26.6%, ICU use by ~39.5%, and antimicrobial spending by ~33.9%.[2] In hospitalized cancer patients with febrile neutropenia, adherence to stewardship-guided antibiotic protocols has been associated with significantly lower mortality, indicating that optimized antibiotic selection and duration can improve outcomes even in immunocompromised populations.[4]

However, since AMS focuses on optimizing existing drugs rather than developing new therapeutic options, its impact is inherently limited as resistance continues to evolve. Moreover, stewardship principles are already practiced in other fi elds such as oncology, where treatment decisions routinely balance effi cacy, toxicity, and long-term outcomes. The general appli-

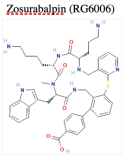
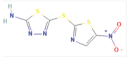
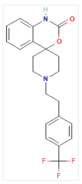
cations of AMS highlight its role as foundational rather than as a strategy that can be used alone. More importantly, what oncology stewardship that AMS currently lacks are adaptive protocols that adjust in real time to biomarker data, personalized dosing guided by pharmacokinetic/pharmacodynamic (PK/PD) modeling, and AI-assisted monitoring of treatment response. These well-established oncology tools represent a new frontier for AMS to incorporate.

The following section explores novel compounds to complement existing treatments and sustain eff ective antimicrobial therapy.

Novel Compounds:

One of the primary reasons AMR persists is the formation of biofilms by Gram-negative bacteria, which block antibiotic penetration and disrupt essential cellular processes. Addressing this structural defense has become a central focus of AI-driven drug discovery, leading to the identification of novel compounds such as Zosurabalpin. The biofilm creates a barrier to antibiotic penetration and disrupts biological processes. Zosurabalpin is a macrocyclic peptide that exhibits selective activity against carbapenem-resistant *A. baumannii*. It requires LPS to maintain the LptB2FGC complex in a substrate-bound conformation, thereby inhibiting LPS transport and damaging membrane integrity. The accumulation of LPS in the inner membrane becomes toxic to the cell, triggering cell death. Zosurabalpin, a macrocyclic peptide discovered through AI screening by Roche and Harvard, targets the outer membrane biogenesis of Gram-negative bacteria by inhibiting the LptB2FGC complex, blocking LPS transport to the outer membrane. It has shown potent activity against multidrug-resistant pathogens, especially *Acinetobacter baumannii* and *Klebsiella pneumoniae*.[5] Critically, it demonstrated no resistance emergence in *in vitro* testing, develops easily *in vitro*, and exhibits a mechanism of action not seen in previous antibiotics, making it especially promising and novel. Roche has announced plans to initiate Phase 3 trials, expected to enroll approximately 400 patients with carbapenem-resistant *A. baumannii* infections. While Zosurabalpin has been promising, it does not remain in the bloodstream for long and is cleared quickly from the body, so higher or more frequent dosages are necessary. It should still be acknowledged that Zosurabalpin is in the nascent stages, so its performance in real-world settings remains to be determined.[6] Such limitations emphasize the need for oncology-style optimization frameworks, such as PK/PD modeling from cancer trials, to adjust dosing and adapt to short half-life.

Table 1: Summary of Key AI-Discovered Antibiotic Candidates.

Compound	Drug Class	Mechanism	AI Method	Spectrum	Stage/Limitation
Zosurabalpin (RG6006) 	Tethered macrocyclic peptide	Inhibits LptB2FGC complex; blocks LPS transport to the outer membrane	AI compound screening (Roche/ Harvard)	Narrow: *A. baumannii*, *K. pneumoniae*	Phase 3 planned; short half-life requires dosing optimization
Halicin (SU3327) 	Thiadiazoles	Disrupts proton motive force; impairs ATP synthesis and iron regulation	Deep learning screen of ZINC15/Drug Repurposing Hub (MIT)	Broad: Gram-positive and Gram-negative	Preclinical; stability concern after storage; reduced efficacy vs *P. aeruginosa*
Abaucin (RS102895) 	Benzoxazine	Inhibits LolE (lipoprotein trafficking/ ABC transporter)	Deep learning trained on *A. baumannii* inhibition	Narrow: *A. baumannii* (MIC 2 μg/ mL, 41 strains)	Preclinical; narrow spectrum limits generalizability

Halicin was initially developed as an anti-diabetic drug. In 2020, MIT researchers built a deep learning model to screen the ZINC15 database for compounds with antimicrobial properties that were structurally distinct from current medications, enabling their repurposing as antibiotics. Unlike traditional antibiotics, Halicin disrupts the electrochemical gradient across bacterial membranes, interfering with their ability to produce energy (ATP synthesis), eff ectively killing them. Table 2 summarizes Halicin's novel mechanism of action and AI method of discovery.

Another promising strategy for using AI to synthesize and refi ne antimicrobial compounds is to leverage antimicrobial peptides (AMPs). AMPs are 2–50-amino-acid peptides produced by multicellular organisms as a defense mechanism against pathogenic microbes. AMPS have hydrophobic and hydrophilic regions and cationic properties, which allow them to disrupt bacterial membranes. They interact with the bacterial membrane, causing membrane perturbation and disrupting membrane-associated physiological processes, including cell wall synthesis, cell division, and translocation. AMPs also exhibit anti-biofilm activity while enhancing phagocytosis, wound healing, and angiogenesis. Platforms such as Deep-AmPEP30, IAMPE, and DeepACP have greatly facilitated the discovery and synthesis of novel peptides. There are well-maintained databases of AMPs derived from genetic sequences, and eff orts to design and synthesize protein epitope mimetics (PEMs) often lead to novel AMPs.

In parallel, bacteriophages—viruses that infect and replicate within bacteria—are being explored as promising AMR treatments because they share similarities with oncology viral vector-based therapies, in which engineered viruses are used to target and destroy malignant cells selectively. Bacteriophages have a tail-like structure that helps them attach to and inject their genetic material into bacterial cells. These viruses evolve rapidly to counter bacterial resistance and are highly specific, minimizing disturbances to the microbiota and preventing antibiotic-induced AMR. However, discovering novel bacteriophages can be tedious, and AI models can expedite the process. Two useful tools are PhageBoost and VirSorter2.

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PhageBoost is a novel ML method based on a feature space, designed for fast, generalizable prophage discovery and to significantly enhance bacteriophage identification. Another AI model, VirSorter2, substantially improves the accuracy and breadth of virus sequence detection in metagenomic datasets by leveraging multiple classifiers to identify a wide range of viruses with high precision.[7]

Collectively, these AI-enabled approaches encourage more targeted and adaptable treatments for antimicrobial resistance. Novel compounds such as Zosurabalpin and the repurposing of Halicin demonstrate how AI can uncover antibiotics with entirely new mechanisms of action that can bypass traditional resistance pathways and biofilm defenses. AI-driven design of AMPs and bacteriophages expands therapies, offering concrete, mechanism-diverse alternatives. Despite their promise, each approach faces practical limitations, such as narrow activity and dosing challenges, reinforcing the idea that no single solution is sufficient. Together, these advances highlight the value of combining AI-guided discovery with insights from complementary fi elds such as oncology. In the following subsection, the paper will delve further into the benefi ts of using AI tools in drug discovery and other therapeutic areas.

AI Tools: Expediting Connection from Oncology:

AI has substantially accelerated drug discovery to specific resistance problems, using support vector machines (SVMs), neural networks, and Hidden Markov Models (HMMs). SVMs classify novel genomic sequences as resistant or non-resistant by learning structural patterns from a curated database such as CARD. HMMs model the mutation pathway in a bacterial population under antibiotic pressure. Moreover, neural networks have been used to forecast cross-resistance. As these models are trained on large, comprehensive oncology datasets, they can be reused for antimicrobial resistance drug discovery.

Table 2: Summary of Key AI-Discovered Antibiotic Candidates.

Model Type	Core Functions	Oncology Example	AMR Applications
Predictive ***(SVMs, HMMs, Random Forest)***	Forecast resistance mutations from existing genomic data; classify susceptibility phenotypes.	Predicts which cancer patients will develop resistance to a targeted therapy (e.g., EGFR inhibitors in lung cancer) based on tumor genomic data	Deep-Arg (predicts ARGs); DASP (susceptibility phenotyping in 30 minutes)
Generative ***(GANs, VAEs, transformer-based)***	Synthesize novel molecular structures with desired biological properties	PETrans, ChemSpaceAL (de novo cancer drug design from cancer protein-ligand interaction data). ChemSpaceAL uses active learning, meaning it refines outputs based on experimental feedback.	Stanford's SyntheMol is a generative model trained on 13,000 *A. baumanii* compounds; 6/58 synthesized candidates showed potent activity against multiple resistant strains.
Screening/Classification ***(CNNs, deep learning)***	Screen large compound libraries for antimicrobial or anti-cancer activity, narrowing the database of chemical compounds to the most promising candidates for lab testing.	Oncology compound library screening (ZINC, ChEMBL to identify molecules that bind to cancer-relevant proteins)	MIT used deep learning to screen ~107 million compounds and identified Halicin (ZINC15); APRA-H TARGET project (107M molecule screen)

Abbreviations: AMR = antimicrobial resistance (when bacteria no longer respond to antibiotics); SVM = Support Vector Machine; HMM = Hidden Markov Model; GAN = Generative Adversarial Network; VAE = Variational Autoencoder; CNN = Convolutional Neural Network; ARG = antimicrobial resistance gene (a gene that allows bacteria to survive antibiotic treatment); MIC = minimum inhibitory concentration (the lowest drug dose that stops bacterial growth); PK/PD = pharmacokinetics/pharmacodynamics (how a drug moves through and acts on the body)

Models such as PETrans and ChemSpaceAL, originally trained on cancer proteome datasets, use transfer learning to generate de novo molecules for specific protein targets, making them well-suited to complex biological systems. These tools can be fine-tuned on bacterial genomic and structural datasets. The shared molecular properties—operating in protein-ligand binding interactions—enable knowledge transfer of generalized binding affi nities and structures between AMR and oncology.

Another transferable method from oncology is PK/PD optimization, a proven framework for individualized dosing that relies on real-time pharmacokinetic monitoring, biomarker-guided response assessment, and adaptive trials. This is especially applicable to Zosurabalpin, which has a short half-life and requires frequent redosing. Applying cancer-derived dosing optimization frameworks to antimicrobial agents with similar pharmacokinetic constraints would accelerate clinical translation.

In Table 2, you can see the various types of AI models and their diff erences, including ChemSpaceAL, Deep-ARG, and Synthemol. ChemSpaceAL is an AI model trained on four sources, combining SMILE strings from ChEMBL, GuacaMol, MOSES (~1.8 million molecules selected from ZINC15), and BindingDB. ChemSpaceAL uses active learning to create new molecules targeted to a particular protein, and part of its training data includes cancer-relevant compounds and general drug-like compounds. It fine-tunes a generative model to learn to produce compounds with desired biological properties.[8] This model has not been trained on bacterial proteins, which is where this tool can be transferable. The AMR application would require fine-tuning the model on bacterial protein-ligand datasets such as those for LptB2FGC or LolE.

AI-facilitated small-molecule antibiotic discovery can be used to identify biosynthetic gene clusters (BGCs), screen compound libraries, and repurpose drugs. For example, DeepARG, a DL-based model trained on a dissimilarity matrix derived from all known categories of antimicrobial resistance genes, achieves high precision and recall. DeepARG has two versions: SS and LS, tailored to handle short- and long-read sequences from metagenomic libraries. Another way AI has aided drug discovery is Synthemol, a generative AI model developed by Stanford Medicine to synthesize potential antibiotic compounds. It was trained explicitly on 13,000 compounds used to treat *A. baumannii*. Of the 58 synthesized candidates, six structurally novel molecules showed potent antibacterial activity against multiple strains, including resistant *A. baumannii*.[9]

A novel method, Deep Antimicrobial Susceptible Phenotyping (DASP), uses deep learning to analyze single-cell morphological phenotypes. It provides results in as little as 30 minutes, compared with antimicrobial susceptibility testing, which takes 18-24 hours. It examines individual bacterial cells and analyzes how their cell structures (DNA & membranes) change when treated with antibiotics. The method combines microscopy, which captures images of internal structures such as DNA and membranes, with the ability to observe individual cells in real time and track how they change when exposed to antibiotics.[10] Models, such as DASP, demonstrate how

phenotypic AI can reduce the time required to test bacterial responses to antibiotics delayed by biofi lms, thereby helping expedite antibiotic selection for critical care patients in ICUs.

Furthermore, AI models trained on datasets against specifi c bacteria, such as *A. baumannii*, have proven effective and efficient in discovering Abaucin and Zosurabalpin. Abaucin is a benzoxazine compound that kills cells by interfering with lipoprotein trafficking, the process cells use to transport proteins from the cell interior to the cell envelope. It inhibits LolE, a protein part of an ATP-binding cassette (ABC) transporter complex in Gram-negative microorganisms. While Zosurabalpin targets the membrane of Gram-negative bacteria by binding to the LptB2FGC complex in the periplasm, both drugs are specific for *A. baumannii*. They are most eff ective against *A. baumannii* and its close relatives compared to other bacterial classes.[11]

AI has played a crucial role in combating antibiotic resistance, from predicting ARGs to designing new compounds, but it faces limitations. Some AI-generated molecules cannot yet be synthesized, and many promising candidates remain in preclinical stages. Despite the urgent demand for new treatments eff ective against MDR pathogens, the pharmaceutical industry shows little inclination to support and invest in R&D&I in this area. The journey from discovery to commercialization averages between $161 million and $4.54 billion, not to mention the considerable time investment required.[12] Antimicrobial drug development receives substantially less funding and market priority than fields such as oncology, where higher commercial incentives and perceived urgency drive research investment. As a result, progress in AMR must be contextualized within this imbalance, requiring strategies that coexist with, rather than compete against, dominant cancer research pipelines.

While novel compounds, such as antimicrobial peptides (AMPs), show promise, they also pose challenges, including toxicity and proteolytic degradation. Because of AMPs' cationic nature, they interact with negatively charged human and bacterial cell membranes, increasing the risk of cytotoxicity. Both AMPs and bacteriophages face challenges with delivery and stability: bacteriophages, in particular, and agents like Zosurabalpin balance resistance avoidance with limited adaptability and a narrow therapeutic scope. Future research should focus on enhancing compound stability, delivery mechanisms, and the generalizability of promising AI-discovered drugs. Pairing AMPs and other particular drugs with oncology-derived delivery systems, such as nanoparticles, can improve stability and target accuracy. Consequently, repurposing cancer-derived tools and compounds offers a compelling interdisciplinary approach to overcoming persistent barriers in the fight against antimicrobial resistance. The following section explores how oncology strategies can be adapted to advance AMR therapeutics.

■ Insights on the Intersection of Oncology and AMR

Cancer Patient Vulnerability to AMR:

Cancer therapies like chemotherapy, radiation, and surgical procedures can weaken immune defenses. Chemotherapy is designed to target and eliminate rapidly replicating cells without much specificity, killing healthy body cells in the process. Specifically, bone marrow is reduced, where B cells mature and produce antibodies upon encountering antigens on pathogens, playing a critical role in human adaptive immune defenses.[13] Moreover, chemotherapy can directly affect immune cells, leading to cytotoxic effects, cell differentiation and function alterations, and disruptions in cell communication and signaling pathways. Such immune suppression can weaken the anti-tumor immune response and increase the risk of immune-related toxicities.[14] Chemotherapy disrupts the gut lining, allowing bacteria to enter the body more easily and compromising the immune system, which can lead to other health issues and increase susceptibility to infections. Antibiotic-resistant microbes are more likely to survive in hospital settings, including on equipment such as catheters and surgical tools, as well as on surfaces. Surgical procedures can create entry points for bacteria, leading to infections, and urinary catheters can introduce bacteria into the urinary tract. Therefore, cancer patients in weak conditions and those who must be hospitalized for long periods of time have a higher risk of severe infections compared to those without cancer. Drug-resistant bacteria can cause persistent infections, raising concerns among oncologists about the effectiveness of chemotherapy. Extended use of broad-spectrum antibiotics contributes to the emergence of resistance.

90% of cancer deaths when initial treatments fail, it is directly attributed to cancer drug resistance, not necessarily to early-stage or untreated cancers. Like bacteria, cancer exhibits resistance mechanisms, including mutating the drug target, pumping the drug out, repairing the damage it causes, and isolating in parts of the body where the drug cannot reach. Cancer and bacterial cells constantly mutate, creating diversity that may lead to the emergence of resistant genes. Drug efflux in both cancer and bacterial cells allows them to pump drugs out or break them down before they can work. Mutations in drug targets usually affect specific proteins, altering their shape or amount, so the drug no longer works. Cancer cell phenotypic plasticity means "shape-shifting" into more aggressive or drug-resistant forms, such as epithelial-to-mesenchymal transition (EMT), which enables cells to move more easily and better resist therapy.

Given the many commonalities between the two fi elds, existing oncology resources can be repurposed for AMR, reducing costs compared to developing new drugs and off ering a novel perspective on drug use. Potentially repurposing tools in AMR could also aff ect oncology, given the signifi cant impact of bacterial infections on cancer patients. To delve further into bacterial infections in oncology, prophylactic treatments are used to prevent them in cancer patients. Essentially, patients are treated with antibiotics before an infection occurs to lower the risk of serious Gram-negative infections in cancer

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patients, especially those undergoing chemotherapy. Patients with acute leukemia, neutropenia, or moderate-to-low infections are advised to use fluoroquinolones such as ciprofl oxacin or levofloxacin. Using this method also increases the risk of harmful side effects, such as *C.difficile* infection, which can cause dangerous diarrhea due to bacterial overgrowth from a gut microbial imbalance. Along with an increased risk of *C. difficile* infection, this method also promotes the growth of antibiotic-resistant bacteria, potentially hindering treatment of future infections.[15]

An example of a repurposed drug for its antimicrobial properties is human monoclonal antibodies, produced *in vitro* by B cells.[16] They have been used to treat cancer and autoimmune disease, with proven success in the treatment of COVID-19 of late. Subsequently, palivizumab, the first human monoclonal antibody, was approved in 1998 to prevent respiratory syncytial virus infection in high-risk infants, and obiltoxaximab was approved in 2016 to treat inhalational anthrax in combination with antibiotics. Monoclonal antibodies can block receptors or signaling pathways, such as anti-EGFR in cancer; tag cells for destruction by immune cells, such as through Antibody-Dependent Cell-Mediated Cytotoxicity; deliver toxic payloads, such as radioisotopes, toxins, or chemotherapy drugs; and neutralize viruses, such as anti-HIV or anti-COVID antibodies. Human monoclonal antibodies exert rapid and sustained antimicrobial activity through several mechanisms, including enhanced opsonization for phagocytosis, direct bactericidal activity, complement deposition, anti-virulence activity, and toxin neutralization. The high specificity of human monoclonal antibodies preserves the host's natural microbiota and minimizes the selective pressure for cross-resistance.

DNA Microarray Analysis:

In oncology, different gene expression patterns correlate with tumor aggressiveness, relapse likelihood, and treatment response. DNA microarrays are used to examine thousands of genes simultaneously in cancer cells, and have been a foundational oncology tool for predicting recurrence, guiding chemotherapy, and analyzing cancer gene expression. Despite early accuracy limitations—primarily due to small study sizes—microarray utility has improved through cross-validation and larger cohort designs. The benefit of DNA microarrays is that they offer a faster, cheaper alternative to whole-genome sequencing and are higher-throughput than PCR. PCR tests only a few genes at a time, whereas whole-genome sequencing (WGS) provides complete data but is more expensive and time-consuming. Given the overlapping resistance mechanisms—efflux pumps, mutations, and phenotypic plasticity—between cancer and AMR, DNA microarrays can detect known ARGs. Arrays can include probes for hundreds of known resistance genes, such as blaCTX-M, mecA, and vanA.[17]

Monoclonal Antibodies:

Extensive cancer research has led to the development of human monoclonal antibodies (mAbs) as precision therapeutics that can block receptors or signaling pathways (e.g., anti-EGFR in cancer), tag cells for immune destruction via antibody-dependent cell-mediated cytotoxicity, deliver toxic payloads, and neutralize viruses. Their high target specificity preserves the host microbiome and minimizes selective pressure for cross-resistance. Currently, 14 human mAb products are in development for ESKAPEE pathogens and *C. difficile* infections.[15]

Bispecific antibodies bind two targets to reduce the likelihood of resistance. Still, they have not yet been widely explored for antibiotic resistance. Bispecific antibodies are engineered to bind two distinct epitopes, such as two different antigens (e.g., CD3 and a tumor antigen) or two distinct sites on the same antigen, to block or cross-link. This dual binding enables unique therapeutic mechanisms that are not possible with standard antibodies. The involvement of additional target sites for bispecific monoclonal antibodies adds an extra layer of complexity and novelty, hindering the effi cacy of the various resistance mechanisms exhibited by MRSA bacteria or pan-resistant *A. baumannii*.[18] The overlap between oncology and AMR broadens the scope of research, advancing a deeper conceptual understanding and methodologies against these challenges. To apply monoclonal antibodies in AMR, they can be engineered to target bacterial virulence factors or toxins.

A Decision Framework for Cross-Domain Transfer:

Table 3: Oncology-to-AMR Transfer Mapping.

Resistance Mechanism	Example in Bacteria	Analog in Cancer	Oncology AI Tool	AMR Translation (Status)
Drug Efflux	AcrAB-TolC (Gram-negative efflux pump)	P-glycoprotein (MDR1) overexpression	ML models predicting MDR1 substrate binding	Predictive models for efflux pump inhibitor design (proposed)
Target Mutation	Ribosomal mutations (aminoglycoside resistance)	Kinase domain mutations (TKI resistance)	PeTrans / ChemSpaceAL (de novo inhibitor design)	Transfer learning for resistance mutation prediction (proposed)
Phenotypic Plasticity	Biofilm formation; persister switching	Epithelial-to-mesenchymal transition (EMT)	RNA-seq/ microarray gene expression profiling	Microarray-based AMR gene expression profiling (proposed)
Compound screen/ repurposing	Multi-drug resistance in ESKAPEE pathogens	Cancer polypharmacology/ combination screens	Deep learning (MIT Stokes et al.); ARPA-H TARGET	Halicin (validated); Abaucin (validated); ARPA-H 107M screen (in progress)
Immune evasion/ virulence	Toxin secretion; immune suppression	Immune checkpoint upregulation	Bispecific antibodies; mAb engineering	14 mAbs in development for ESKAPEE / C. difficile (active)
PK/PD Optimization	Short half-life (Zosurabalpin)	Narrow therapeutic window in targeted cancer therapy	Oncology PK/PD adaptive dosing models	CURATE.AI (validated in oncology; adapted for CRE/AMR in Singapore trials)

Furthermore, we can combine antibodies with antibiotics to neutralize bacterial defenses and design bispecific antibodies recognizing bacterial proteins and host immune receptors. The value of this perspective lies in acknowledging the alternative introduction and laying the groundwork for future research. Additionally, the Drug Repurposing Hub, ZINC15, and ChEMBL database contain millions of structurally characterized compounds screened in oncology contexts. Deep learning models trained on oncology activity data can be reused to screen the same libraries for antimicrobial agents against specific pathogens. This methodology was exactly how Halicin was discovered, and the synthesis of modifi ed monoclonal an-

tibodies can be advanced using models such as SyntheMol to treat hospital-acquired infections in cancer patients.

Ethical and Translational Constraints

Despite the promise of repurposing oncology-derived AI tools for antimicrobial resistance, this approach raises essential ethical and translational challenges that warrant careful consideration. AI-driven drug discovery models are susceptible to hallucinations—predicting compounds or interactions that cannot be synthesized or validated experimentally—posing risks of resource misallocation and delayed clinical translation. Moreover, while adaptive trial designs are well-established in oncology, their application to AMR is constrained by smaller patient cohorts, shorter infection durations, and ethical concerns regarding experimental therapies for acute infections. These concerns are real, as patients hospitalized with multi-organ failure or unconscious are often unable to provide informed consent, yet they're the most likely candidates for experimental antibiotic therapies.[20] These limitations underscore the need for rigorous human oversight, transparent model validation, and conservative deployment of AI predictions in clinical decision-making. Addressing these ethical challenges is essential to ensuring that oncology-inspired AI frameworks are not only innovative but also safe, equitable, and clinically responsible when applied to AMR.

Conclusion

This review establishes three strong arguments. First, oncology and AMR share fundamental resistance mechanisms—drug efflux, target mutation, phenotypic plasticity—which provide a basis for transferring existing tools for AMR drug discovery. To bridge the research between oncology and AMR, we can train oncology AI models on bacterial genomic datasets to predict emerging resistance mutations, or deploy AI screening systems such as AlphaFold or the DeepChem pipeline to discover new antibiotics or AMPs. Second, we already see this transfer being validated, with models screening antibiotic databases, leading to the discovery of Halicin and Abaucin. By adopting adaptive clinical trial designs for antibiotic testing, we can use real-time AI monitoring of patient responses to guide dosing and combination therapy and build AMR patient registries similar to oncology cohorts. Third, drug repurposing reduces time to approval by approximately 50% and can save more than $1 billion per compound compared to de novo discovery pipelines, averaging 10–12 years and $2+ billion per approved drug.[21]

According to the WHO, global statistics show that approximately 1 in 5 people develop cancer in their lifetime, and ~1 in 9 men and 1 in 12 women die from it.[22] Cancer is a universal and diverse disease, affecting populations across all demographics and geographies, which has positioned it as one of the most heavily researched biomedical fields. The intensity and breadth of cancer research have yielded cutting-edge techniques—from AI-driven predictive modeling to personalized therapeutic targeting—that remain underexplored in AMR contexts. The United States, in particular, stands at the forefront of cancer research and innovation, offering a rich repository of tools, data, and methodologies that can be adapted for AMR. The National Cancer Institute (NCI), a division of NIH, is the world's largest funder of cancer research, with an annual budget of approximately $6.9 billion.[23] By reimagining these assets for bacterial resistance, we stand to accelerate solutions for a problem that threatens to undermine decades of medical progress. Monoclonal antibodies, which have transformed oncology through targeted therapies and immune modulation, are now emerging as promising tools in AMR, and the adaptation against resistant bacteria represents a powerful comparative strategy. Their high specificity neutralizes bacterial toxins, blocks virulence factors, and precisely clears the pathogen without disturbing the human microbiome. To implement these actionable steps, we can establish interoperability between AMR genomic databases and oncology AI frameworks by funding interdisciplinary training programs through the Centers for Antimicrobial Precision Medicine that bridge microbiology, bioinformatics, and cancer biology.

This research primarily draws on existing literature and experimental data, but its value lies in providing a broader, clearer picture of current conditions and challenges related to antimicrobial resistance. This paper presents an interdisciplinary perspective on the use of existing oncology tools to explore AMR, opening new avenues for future research and inspiration within the scientific community. Although this paper primarily considers datasets from a Western setting and uses them to comment on a general geographical arc, it is still vital to acknowledge geographical variation. The datasets have transferable value and incorporate adaptations to local geographic factors, providing an overarching argument and supporting global AMR solutions. This offers a flexible foundation and data to use rather than a fixed framework that cannot be widely applied. The novelty of this approach lies in reframing established cancer research methodologies as tools for AMR innovation, thereby linking two high-impact global health challenges within a single research strategy. Furthermore, combination therapy is more promising given the added complexity of combating bacterial resistance.

Despite the promise of several novel antimicrobials, these agents face limitations in toxicity, stability, delivery, and specificity. AMPs can damage bacterial membranes, leading to cytotoxicity and proteolytic degradation. Similarly, both AMPs and bacteriophages provide delivery, but bacteriophages' high specifi city—while effective at preventing resistance—limits adaptability because bacterial targets rapidly mutate. Compounds like Zosurabalpin also pose this challenge, demonstrating strong efficacy against *A. baumannii* but restricted broader applicability. These constraints highlight the need for advanced delivery systems, stability enhancement, and target-expansion strategies, areas in which oncology has developed mature, clinically validated solutions that can be repurposed to advance antimicrobial resistance therapies.

Bridging insights from oncology into AMR accelerates drug discovery and underscores the value of leveraging well-developed cancer research platforms to tackle one of the most urgent infectious threats worldwide. Regarding future studies, the implications of this research are expansive. Future work could

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focus on developing AI-powered AMR predictive models, informed by cancer prognostic tools, to enable earlier detection and tailored interventions for infections resistant to antibiotics. The highlights of this research are the exploration and combat of AMR through the lens of cancer research, enabling future innovation.

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References

1. World Health Organization. *Antimicrobial resistance*. World Health Organization. https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance.
2. Majumder, M. A. A.; Rahman, S.; Cohall, D.; Bharatha, A.; Singh, K.; Haque, M.; Gittens-St Hilaire, M. Antimicrobial Stewardship: Fighting Antimicrobial Resistance and Protecting Global Public Health. *Infection and Drug Resistance* **2020**, *13* (1), 4713–4738. https://doi.org/10.2147/idr.s290835 (accessed 2025-08-27).
3. Gautron, J. M. C.; Tu Thanh, G.; Barasa, V.; Voltolina, G. Using Intersectionality to Study Gender and Antimicrobial Resistance in Low- and Middle-Income Countries. *Health Policy Plan*. **2023**, *38* (9), 1017–1032. https://doi.org/10.1093/heapol/czad054.
4. Rosa, R. G.; Goldani, L. Z.; dos Santos, R. P. Association between Adherence to an Antimicrobial Stewardship Program and Mortality among Hospitalized Cancer Patients with Febrile Neutropaenia: A Prospective Cohort Study. *BMC Infect. Dis*. **2014**, *14* (1), 286. https://doi.org/10.1186/1471-2334-14-286.
5. Manning, A. *Paving the Way for a New Class of Antibiotics | Harvard Medical School*. hms.harvard.edu. https://hms.harvard.edu/news/paving-way-new-class-antibiotics (accessed 2025-11-07).
6. Zampaloni, C.; Mattei, P.; Bleicher, K.; Winther, L.; Thäte, C.; Bucher, C.; Adam, J.-M.; Alanine, A.; Amrein, K. E.; Baidin, V.; Bieniossek, C.; Bissantz, C.; Boess, F.; Cantrill, C.; Clairfeuille, T.; Dey, F.; Di Giorgio, P.; du Castel, P.; Dylus, D.; Dzygiel, P.; Felici, A.; García-Alcalde, F.; Haldimann, A.; Leipner, M.; Leyn, S.; Louvel, S.; Misson, P.; Osterman, A.; Pahil, K.; Rigo, S.; Schäublin, A.; Scharf, S.; Schmitz, P.; Stoll, T.; Trauner, A.; Zoff mann, S.; Kahne, D.; Young, J. A. T.; Lobritz, M. A.; Bradley, K. A. A Novel Antibiotic Class Targeting the Lipopolysaccharide Transporter. *Nature* **2024**, *625* (7995), 566–571. https://doi.org/10.1038/s41586-023-06873-0.
7. Liu, G.-Y.; Yu, D.; Fan, M.-M.; Zhang, X.; Jin, Z.-Y.; Tang, C.; Liu, X.-F. Antimicrobial Resistance Crisis: Could Artifi cial Intelligence Be the Solution? *Mil. Med. Res*. **2024**, *11* (1), 7. https://doi.org/10.1186/s40779-024-00510-1.
8. Herráiz-Gil, S.; Nygren-Jiménez, E.; Acosta-Alonso, D. N.; León, C.; Guerrero-Aspizua, S. Artifi cial Intelligence-Based Methods for Drug Repurposing and Development in Cancer. *Appl. Sci.* **2025**, *15* (5). https://doi.org/10.3390/app15052798.
9. Swanson, K.; Liu, G.; Catacutan, D. B.; Arnold, A.; Zou, J.; Stokes, J. M. Generative AI for Designing and Validating Easily Synthesizable and Structurally Novel Antibiotics. *Nat. Mach. Intell*. **2024**, *6* (3), 338–353. https://doi.org/10.1038/s42256-024-00809-7.
10. Zagajewski, A.; Turner, P.; Feehily, C.; El Sayyed, H.; Andersson, M.; Barrett, L.; Oakley, S.; Stracy, M.; Crook, D.; Nellåker, C.; Stoesser, N.; Kapanidis, A. N. Deep Learning and Single-Cell Phenotyping for Rapid Antimicrobial Susceptibility Detection in Escherichia Coli. *Commun. Biol*. **2023**, *6* (1), 1164. https://doi.org/10.1038/s42003-023-05524-4.
11. Liu, G.; Catacutan, D. B.; Rathod, K.; Swanson, K.; Jin, W.; Mohammed, J. C.; Chiappino-Pepe, A.; Syed, S. A.; Fragis, M.; Rachwalski, K.; Magolan, J.; Surette, M. G.; Coombes, B. K.; Jaakkola, T.; Barzilay, R.; Collins, J. J.; Stokes, J. M. Deep Learning-Guided Discovery of an Antibiotic Targeting Acinetobacter Baumannii. *Nat. Chem. Biol*. **2023**, *19* (11), 1342–1350. https://doi.org/10.1038/s41589-023-01349-8.
12. Schlander, M.; Hernandez-Villafuerte, K.; Cheng, C.-Y.; Mestre-Ferrandiz, J.; Baumann, M. How Much Does It Cost to Research and Develop a New Drug? A Systematic Review and Assessment. *PharmacoEconomics* **2021**, *39* (11), 1243–1269. https://doi.org/10.1007/s40273-021-01065-y.
13. Safdar, A.; Bodey, G.; Armstrong, D. Infections in Patients with Cancer: Overview. *Princ. Pract. Cancer Infect. Dis*. **2011**, 3–15. https://doi.org/10.1007/978-1-60761-644-3_1.
14. Sharma, A.; Jasrotia, S.; Kumar, A. Eff ects of Chemotherapy on the Immune System: Implications for Cancer Treatment and Patient Outcomes. *Naunyn. Schmiedebergs Arch. Pharmacol*. **2024**, *397* (5), 2551–2566. https://doi.org/10.1007/s00210-023-02781-2.
15. Ho, C. S.; Wong, C. T. H.; Aung, T. T.; Lakshminarayanan, R.; Mehta, J. S.; Rauz, S.; McNally, A.; Kintses, B.; Peacock, S. J.; de la Fuente-Nunez, C.; Hancock, R. E. W.; Ting, D. S. J. Antimicrobial Resistance: A Concise Update. *Lancet Microbe* **2025**, *6* (1), 100947. https://doi.org/10.1016/j.lanmic.2024.07.010.
16. Kothari, M.; Wanjari, A.; Acharya, S.; Karwa, V.; Chavhan, R.; Kumar, S.; Kadu, A.; Patil, R. A Comprehensive Review of Monoclonal Antibodies in Modern Medicine: Tracing the Evolution of a Revolutionary Therapeutic Approach. *Cureus 16* (6), e61983. https://doi.org/10.7759/cureus.61983.
17. Ntzani, E. E.; Ioannidis, J. P. Predictive Ability of DNA Microarrays for Cancer Outcomes and Correlates: An Empirical Assessment. *The Lancet* **2003**, *362* (9394), 1439–1444. https://doi.org/10.1016/S0140-6736(03)14686-7.
18. Ingham, J.; Ruan, J.-L.; Coelho, M. A. Breaking Barriers: We Need a Multidisciplinary Approach to Tackle Cancer Drug Resistance. *BJC Reports* **2025**, *3* (1). https://doi.org/10.1038/s44276-025-00129-2.
19. Li, M.; You, K.; Wang, P.; Hooi, L.; Chen, Y.; Siah, A.; Tan, S.-B.; Teo, J.; Ng, O.-T.; Marimuthu, K.; Venkatachalam, I.; Blasiak, A.; Chow, E. K.-H.; Ho, D.; Gan, Y.-H. Discovery of Broad-Spectrum Repurposed Drug Combinations Against Carbapenem-Resistant Enterobacteriaceae (CRE) Through Artifi cial Intelligence (AI)-Driven Platform. *Adv. Ther*. **2024**, *7* (3), 2300332. https://doi.org/10.1002/adtp.202300332.
20. Boyd, N. K.; Teng, C.; Frei, C. R. Brief Overview of Approaches and Challenges in New Antibiotic Development: A Focus On Drug Repurposing. *Front. Cell. Infect. Microbiol*. **2021**, *11*. https://doi.org/10.3389/fcimb.2021.684515.
21. World Health Organization. *Global Cancer Burden growing, Amidst Mounting Need for Services*. WHO. https://www.who.int/news/item/01-02-2024-global-cancer-burden-growing--amidst-mounting-need-for-services. (accessed 2025-08-24).
22. *NCI's Role in Cancer Research - NCI*. https://www.cancer.gov/research/nci-role (accessed 2026-02-02).
23. Stokes JM, Yang K, Swanson K, *et al.* A deep learning approach to antibiotic discovery. *Cell*. 2020;180(4):688–702. https://doi.org/10.1016/j.cell.2020.01.021.

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Kayla Leung is a graduating senior at Monta Vista High School (Class of 2026) and an aspiring biomedical computation major. Her research was conducted under the mentorship of a current Cambridge PhD student, Dikshit Bhagabati. Her interest in antimicrobial resistance stems from her personal health journey, undergoing open-heart surgery to correct a ventricular septal defect. Witnessing fi rsthand the critical role of medical intervention inspired her commitment to advancing healthcare through research. She is passionate and inspired by research, exploring the intersection of AI and its applications to expedite drug discovery and address antimicrobial resistance. Kayla hopes to draw on her patient experience to integrate computational innovation with patient-centered care, with a greater focus on the humanistic impact her research can have on people's lives.

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REVIEW ARTICLE

Advancement in Fault Detection of Internal UAV Damage

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ABSTRACT: As UAVs become increasingly popular in both military and civilian applications, more sophisticated technologies related to UAVs are being developed to meet these demands. However, as technology becomes more complex, faults will become more common. This paper aims to examine the recent development of technology that enables companies to detect faults in UAVs before or during deployment, thereby avoiding potential problems in the future. Initially, more traditional methods were used to detect these problems early, such as model-based solutions that included internal sensors for sound, frequency, and signal response time between components. Due to recent developments in AI, more experimental data-driven models are emerging in response to the growing demand for AI; consequently, AI-driven solutions have become increasingly common. This review paper aims to connect different STEM fields to efficiently solve the problem of fault detection and suggest a more affordable method for detecting potential critical faults that may cause significant damage to the UAV.

KEYWORDS: Engineering, UAV, Drones, Fault detection, Artificial Intelligence.

Introduction

Unmanned Aerial Vehicles or (UAVs) have become popular in both military and civilian applications, from overseas reconnaissance, cargo delivery, to agriculture development and environmental monitoring, Novel technologies are being developed to meet the growing demands, which have not been effectively tested enough therefore having a higher risk of internal and external damage from preventable malfunctions which pose a threat to operation and budget to the users.[1]

Fault detection within UAVs is achieved by identifying anomalies or failures in the vehicle's components, usually vital functions such as propellers, sensors, actuators, and structural elements, before they escalate into potential problems. Early empirical papers heavily relied on a data-driven model, which compares real-time sensor data to the expected data set of a UAV.[2]

Although these methods allow for a basic framework to detect basic faults, they lack the adaptability to the dynamic situation or environmental disturbances that come with real-life usage. However, this problem has been identified and has been researched to find a solution. This solution is eventually referred to as Data-Driven or Machine Learning Methods.[3] This solution uses neural networks to use multiple different sensors and data sets on board the UAV to help capture and assess abnormalities and better detect faults, which include vibration, acoustic signals, flight trajectory, and motor data, to cross-reference different data sets of faults better and detect fault signatures with higher accuracy.[3]

The paper aims to report on the current technological advancements in UAV damage detection. Integrating data-driven AI models with traditional early detection methods can significantly reduce the likelihood of UAV crashes. Early fault detectors employ model-based methods to detect abnormalities in the critical components of a UAV.[2] Authors Altinors, Ayhan, and Ghazali, Mohamad, use vibration sensors and acoustic signatures to test the effectiveness of such sensors on abnormal/damaged motors.[4,5] However, due to the surge in AI's popularity, more data-driven AI diagnostics are being employed. For example, Yang utilizes flight trajectory data and motor speed data to detect faults as they arise onboard the UAV.[6] The methods and past research in the development of UAV damage detection focus on a solution that the technique provides, creating preventative measures that allow the controller to detect malfunctions of UAVs during pre-flight checks and early onboard time monitoring to prevent further costly damage to the UAVs.

Each solution provided is impressive in its paper, with its 85% detection of malfunctions.[5] They tend to only focus on how individually each method allows for accurate detection, with no comprehensive framework or interest in integrating multiple methods from acoustic, visual, vibration, and flight-data analytics to further capitalize on the strengths of different detection methods to allow quicker and more accurate fault detection. By gaining a deeper understanding of the interdisciplinary approach of each method together than in the problem of preventable malfunction, the risk of catastrophic failure will be mitigated, thereby improving UAV safety for both consumer and military uses. This paper argues that allowing multiple damage detection frameworks to work together, utilizing AI-based image and abnormality recognition, AI analysis of flight, motor speed, and acoustic signals, and real-time onboard sensor data, enables more accurate fault detection.

Discussion

2. Traditional Damage Detection:

Most existing research papers on UAV damage detection focus on technology that detects damage on wind turbines or architectural designs.[7] Focusing on using Acoustic and Vibration data in order to measure if the propeller of the wind turbine is faulty. This section will examine the primary meth-

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ods researchers in orderemploy to collect data for data model fault detection.

2.1. Vibration Sensors:

A prominent method being explored most extensively is the use of vibration sensors. Vibration sensors in engineering settings provide information about a structure's integrity without requiring a thorough examination of the structure to assess it. The function of this sensor is to identify damage by detecting changes in multiple properties of a structure, including density, connections between modules, and stiffness variations in the structure's geometric and material properties.[8] These functions of vibration sensors detect early stages or subtle damages that can lead to future problems in the structure.[5]

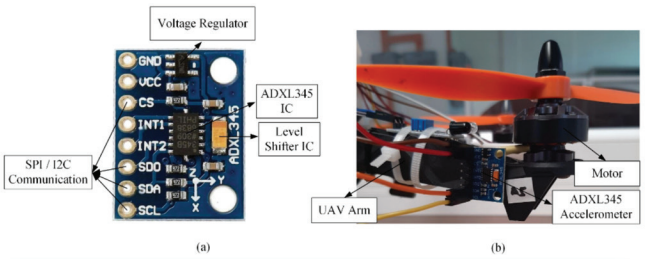

Figure 1: Annotated example of an accelerometer used to collect vibration data. Including the material used to create the ADXL345 accelerometer.[5]

In the context of UAVs, papers have been utilizing this technology to monitor dynamic changes in key components, including frames, motors, and rotors.[2] By analyzing the changes in vibration of these components, mechanics and operators of UAVs can detect shifts in frequencies within the UAV's body or an increase in motor frequency during operation, thereby inferring potential damage on board, as seen in (Figure 1).

Based on the paper written by Ghazali *et al.* on the effectiveness of vibration-based detection on a UAV, the vibration sensors were able to detect damage that commonly appeared. These common damages are propeller damage and wing damage.

Table 1: A data table of vibration data recorded using the ADXL335 accelerometer to prove the relationship between maximum amplitude and UAV damages.[5]

Configuration	Maximum Amplitude (g)	Average Absolute Amplitude (g)
Normal (Drone arm and propeller)	0.71	0.18
Minor crack (Drone arm)	0.89	0.22
Major crack (Drone arm)	1.82	0.46
10% Broken (Propeller)	0.83	0.22
25% Broken (Propeller)	1.65	0.55
50% Broken (Propeller)	3.46	1.5
Unbalanced (Propeller)	−1.72	0.41

To properly assess whether a vibration sensor can detect faults in a UAV, the best solution is to compare the data collected from a faulty UAV with a control dataset that represents a fully functional UAV without any faults. The data sets from the faulty drone arm dataset show a difference in amplitude when compared to the normal functional UAV dataset in Table 1. The minor crack in the drone arm has a maximum amplitude of 0.07, compared to a maximum amplitude of 0.03 from a normal drone arm configuration. The difference of 0.04 amplitude is a significant value in understanding the fault abnormalities that are occurring in the UAV. Since a difference can be found when comparing a minor fault to the arms of the UAV compared to a functional normal UAV, it's acceptable to believe this same conclusion would happen with a major fault. The same trend can also be seen when comparing vibration data from a faulty propeller UAV to that of a normal UAV propeller. The 10% broken propeller has a maximum amplitude of 0.05 compared to the 0.03 normal propeller maximum amplitude. This difference of 0.02, equivalent to the broken arm, is a significant value for detecting a fault with the UAV. Based on the data analysis, it's safe to assume that if the sensor can detect differences in the minor faulty UAV compared to the normal UAV, it can also detect faults within more catastrophic damage within a UAV.[5]

However, there are some drawbacks to using vibration sensors in assessing the faults of UAVs. Since the vibration sensors have not been implemented and adapted, the technology is not used within operational environments. Natural exterior variables that occur during the use of UAVs can affect the sensor's ability to detect faults during operations.[8] Another potential drawback of using vibration sensors is their offline nature.[8] The technology uses a recorded set of data from a pristine UAV to determine if the UAV is performing operations. Slight changes to the structure of the UAV will happen because of the prolonged use; the UAV may collect less or more amplitude data in the sensors. The increased amplitude from the data would create false detection when the UAV is safe to use.[8] Due to the nature of vibration sensors, which allow faults to be detected early before damage can occur, the technology falls short for either complex, non-standard damages or abrupt, catastrophic failures, such as sudden engine burnout or battery explosions. However, vibration sensors aren't the only technology being used to detect faults within UAVs; propellers and motors are also important components within a UAV. Sound-based detection is being explored to further enhance UAV fault detection.

2.2. Acoustic-Based Sensors:

Sound-based fault detection functions by collecting different types of auditory data from the moving parts of a UAV, from normal healthy motors, functional propeller, propeller failure, eccentric failure, and bearing failure, all of which are common faults seen in UAVs.[9]

Finally, the auditory data is then processed through various algorithms to properly differentiate between different malfunctions within the internal microphone of the UAV.[9]

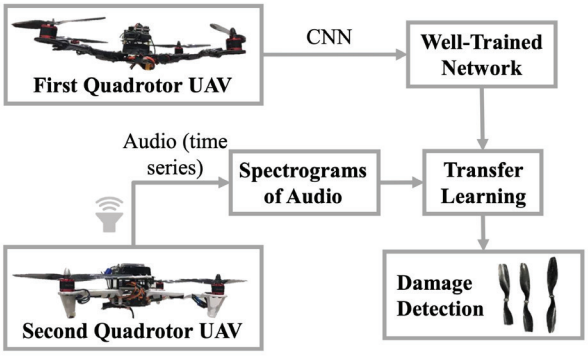

Figure 2: Flow chart showcasing the process for the collection of acoustic data of the UAV and how it's being used in Fault detection.[10]

Recent research demonstrates the potential future of technology for fault detection, while also sparking discussion on potential onboard usage and AI integration.[3-9,10] In the first paper, the author Ayhan explores the use of algorithms to assist in detecting common faults using sound data collected.[3] The microphone recorded four different sound data sets for the algorithm to learn from.[3] These sound data are processed through methods such as signal pre-processing and feature extraction, enabling algorithms to identify faults within different UAVs. This flow chart is observed in Figure 2.[10] The faults detected by the algorithms range from health Issues, propeller failure, motor failure, and bearing faults. The results concluded that regardless of the type of motor used, all algorithms trained on the datasets achieve 99% accuracy in detecting faults.

The paper notes that sound-based detection is fast and effective due to the use of algorithms that can pick up fluctuations in sounds that may signal faults.[3] Other papers, such as Steinhoff *et al.*'s paper, have replicated this experiment and found additional advantages to using sound-based detection, including the ability to isolate the fault's location within the UAV.[9] However, the drawback of using this method is the limitations of the data set. In the Ayhan paper, the motors of the UAV were placed within an empty room, ensuring that no major environmental sounds affected the collection of sound data during testing of the algorithms. Since the recorded data sets only recorded isolated UAV sounds, other environmental sounds may affect the algorithm's effectiveness in detecting faults within the UAV.

2.3. The Overall evaluation of traditional Damage detection and its effectiveness:

Overall, however, studies of vibration-based detection and sound-based fault detection strongly support the hypothesis that when AI is combined with more traditional, tangible methods, with advanced sensor data collection, it can provide accurate and effective breakthroughs for fault detection. As stated in the previous subsections, vibration sensors can detect minor changes in the physical body of UAV components by capturing shifts in amplitude, which can assist in identifying early stages of structural damage. However, it cannot adapt quickly.[11] The paper created by Ozkat mentions the offline nature of current vibration-based detection.[11] Based on the offline nature of the detection, slight changes resulting from wear and tear conditions of the UAV can cause false positives of faults in the UAV. The false positive occurs because the data is compared only with existing data from a perfectly manufactured UAV, which is unrealistic. With a sound-based system that accurately analyzes the auditory signatures of each UAV component.[12] Sound-based detection also has the added benefit of isolating fault locations within the UAV, which would enhance the utility of this direction.[13] The problem stems from its validated conclusion, which comes from controlled, low-noise environments, and is unrealistic for real-life usage.[13] However, these drawbacks can be alleviated by incorporating AI into traditional methods. AI can cross-reference data as well as make necessary judgments based on the environment to help assess better whenever a fault happens

3. AI Detection model:

With the rise of integrating AI into our technology, certain developments have been made to support AI usage in UAVs. The development of integrating AI has made reliable in-flight fault detection possible, while also improving existing fault detection methods.

The two primary studies that support this development are Yang *et al.*'s deep residual shrinkage network, used to enhance sound-based fault detection, but also uses flight path data to gather more accurate fault detection, and Pose *et al.*'s internal data-based detection, used to detect faults within propellers.[6–14]

3.1. Modal binning:

Within the paper proposed by Yang, a deep residual shrinkage network was developed and combined with wide convolutional layers to process motor speed and flight path data fully.[6] The network was created to minimize environmental sound data that may affect comparison, as well as to facilitate cross-referencing propeller status with existing healthy UAV data to identify faults.[6]

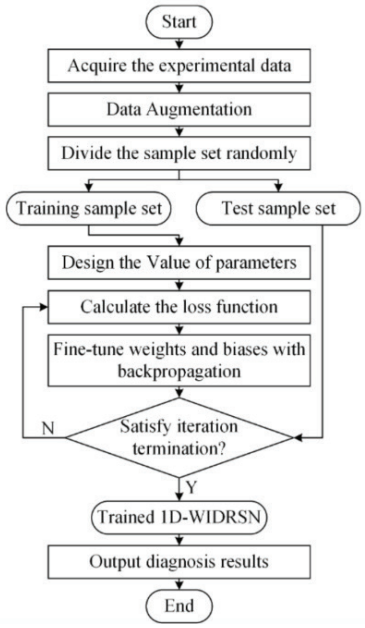

Figure 3: Flow chart describing the process of machine learning fault detection, as well as additional functions such as a loss function to reduce random error in data analysis. [6]

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To create this network, the authors gathered flight logs containing flight path data, mainly roll value, pitch value, roll rate, pitch rate, yaw rate, and the angular velocities of the four propellers on the UAV or quadcopter, of a normal operating UAV, and various flight path data where a major fault happened. To determine if a fault is detected within the AI, when collecting real-time data from the drone, meaningful data from the sensors implanted within the UAV was extracted while filtering out possible noises from sound sensors and other detectors that may cause false positives within the AI.[6] The fluctuations and major differences detected with the meaningful data are compared to the dataset of fault examples to determine if faults are happening and isolate where the damages are located. This is a simplification of the entirety of the process of machine learning for detecting faults, in which the whole process is viewed in Figure 3.[6]

Based on how the technology functions, using AI for fault detection has the same benefits as using traditional sensors, including the ability to detect minor faults within a fraction of a second. The AI also has the added benefit of filtering out possible irrelevant data, such as environmental noises outside the UAV, to yield high detection accuracy, potentially helping to mitigate one of the drawbacks of using only sound and vibration fault detection. Finally, due to how the AI was trained to detect faults, it lacks the universal adaptability of traditional means. When migrating this technology to different UAVs, new datasets need to be trained, as no two UAVs are identical, which may decrease detection accuracy if the same AI is used across multiple UAVs.

3.2. Autoencoders:

Another paper created by author Pose also trained the composite model using similar methods, such as classifiers and neural networks, to measure any abnormal data within the UAVS; however, instead of focusing on using different data sets to determine a specific component with faults.

Pose develops a damage classification and estimation of fault using inertial measurement data and control inputs from the UAV.[14] The AI uses this data to accurately categorize the damage type of each component in the UAV and employs a regression-type model to estimate the severity of the fault by comparing real-time data with the extent to which it deviates from example flight dynamics.[14] Similar to Yang *et al.*'s paper on using AI in fault detection, Pose utilizes inertial data collected from various scenarios that a UAV may encounter during operation (healthy, motor-damaged, etc.). The subtle changes in data can indicate a potential fault.[14] Although the paper focuses on using inertial data for the AI to determine faults, the author also expresses the potential adaptability of the AI.[14] The purpose of the AI was to provide a robust, scalable, and platform-agnostic solution for fault detection that utilizes only the basic data collected from UAVs, including Inertial data and control inputs, for in-flight fault detection.[14]

Based on how the paper describes the solution's functionality in addressing fault detection, the use of Autoencoders has several functions that mitigate sensor limitations. Since the AI is trained on a universal dataset available for all UAVs, this allows the AI to be implemented across multiple UAVs without any changes needed.[14] However, inaccuracy was expected due to the limited data provided to the AI—the autoencoders, however, average 98.8%.[14] One thing to note about the paper is that, by focusing only on inertial data and flight control data, it lacks the precision of sensors to monitor both structural health and propeller health effectively. Finally, since AI has a structure that allows it to analyze other data sets independently, if this method is applied to more traditional fault detectors, such as sound or vibration, the success rate of fault detection will increase.

4. Integrating Artif icial Intelligence and Existing Methods:

AI is an excellent tool for addressing fault detection in UAV development today; however, it sometimes lacks the necessary data and equipment to precisely detect faults in the integral parts of the UAV. This section aims to explore new and innovative papers that have delved deep into the exploration of combining AI and sensor-based detection.

Papers from NASA and Al Haddad featured how the UAV collects data within itself and how AI utilizes both the collected data and other unique data to detect faults. The IMU, or inertial measurement unit, is measured using the accelerometer. This data is then processed through various algorithms to effectively remove unnecessary data that could potentially lead to false detection within the UAV. The algorithms involve using low-pass filtering to remove high-frequency noise, aiming to strike a balance between temporal resolution and feature stability.[13] However, this isn't the only way the data gets processed, as there are currently two methods. PSD, or Power Spectral Density, measures the power used within a specific frequency range; this is used to determine if a component is not producing enough work despite the power being applied. The PSD method is especially great for detecting defect-related frequencies (bearing fault harmonics).[15] However, the discussion within the paper mentions that this method's inability to detect faults or health within components is mainly due to attenuation and mixed sources, which require more power.[15] Rather than manually analyzing the data processed by the PSD, both papers also employ AI or algorithms to analyze the data. Modal binning is a method used to detect faults. This method works by setting predefined data sets for different states of each UAV component, ranging from healthy to various types of malfunctions (bearing failure, signal failure, etc.).[15]

Comparing the data to either the pre-mandated data set or deviating from each data set could provide insight into whether a fault is occurring.[15] Another method used is Unsupervised Autoencoders, which are trained using flight data recorded from different normal, fault-free UAV operations with this methods also being used extensively outside of the 2 papers mentioned in which Chuanjiang Li *et al.*'s paper on integrating autencoder as a verification process of fault detection by using a generator consisting of two encoders and one decoder for the different classification of damage.[15,16]

These models learn to compress each UAV's healthy state data and then reconstruct the current UAV state using input features such as vibration signals, UAV attitude measurements,

and motor RPM data.[15,16] During operation and fault analysis, the difference between these features and the reconstruction is referred to as the reconstruction error by the paper, which is utilized as a possible fault detection signal.[15] Higher error scores indicate that the current UAV data do not resemble normal, healthy patterns; therefore, a potential fault may occur.[15]

To reduce false alarms caused by environmental noise and variations in flight dynamics, pre-processing techniques such as those described in Section 3 are employed.[15]

Conclusion

In this paper, fault detection methods are discussed and explored to further interest in this technology. Data collection methods of vibration sensors, acoustic sensors, flight path, and motor speed data were explored, and data processing techniques such as signal preprocessing and feature extraction helped AI analysis methods work better. Although both methods of detecting faults are effective within their own functions, they have limitations that the opposite methods can mitigate. Data collection methods effectively identify minor faults within the UAV; however, they face challenges such as environmental noise, a lack of adaptability in operational conditions, and a limited scope in detecting complex or sudden faults. AI, although effective in analyzing complex and unique datasets—such as IMU data, flight trajectories, and acoustic signatures — to find faults, suffers from a lack of precision that normal data collection methods have in identifying minor faults. The paper summarizes how studies reviewed hybrid frameworks where AI refines and supports vibration and sound-based diagnostics by adapting and analyzing non-linear data sets and contextualizing sensor inputs within the UAV data. The way AI architectures are trained on universal datasets enables transferable fault detection solutions that can be deployed across various UAV designs without requiring additional training. Looking further, creating a hybrid framework that combines AI analysis with precise data collection from sensors enables effective fault detection, paving the way for fault localization and damage severity analysis. The application of AI in existing fault detection allows UAVs to self-assess and communicate their operational status autonomously during operations.

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References

1. Sun, X.; Hu, Y.; Qin, Y.; Zhang, Y. Risk assessment of unmanned aerial vehicle accidents based on data-driven Bayesian networks. Reliability Engineering & System Safety 2024, 248, 110185. https://doi.org/10.1016/j.ress.2024.110185.
2. Roshanski, I.; Roshanski, M.; Kalech, M. Real-Time Sensor Fault Detection in Drones: A Correlation-Based Algorithmic Approach. drops.dagstuhl.de 2024. https://doi.org/10.4230/OASIcs.DX.2024.17
3. Tong, J. J.; Zhang, W.; Liao, F.; Li, C. F.; Zhang, Y. F. Machine Learning for UAV Propeller Fault Detection based on a Hybrid Data Generation Model. arXiv.org. https://arxiv.org/abs/2302.01556.
4. Altinors, A.; Yol, F.; Yaman, O. A sound-based method for fault detection with statistical feature extraction in UAV motors. Applied Acoustics 2021, 183, 108325. https://doi.org/10.1016/j.apacoust.2021.108325.
5. Ghazali, M. H. M.; Rahiman, W. An Investigation of the Reliability of Different Types of Sensors in the Real-Time Vibration-Based Anomaly Inspection in a Drone. Sensors 2022, 22 (16), 6015. https://doi.org/10.3390/s22166015.
6. Yang, P.; Geng, H.; Wen, C.; Liu, P. An Intelligent Quadrotor Fault Diagnosis Method Based on Novel Deep Residual Shrinkage Network. Drones 2021, 5 (4), 133. https://doi.org/10.3390/drones5040133.
7. Ma, Y.; Mustapha, F.; Ishak, M. R.; Rahim, S. A.; Mustapha, M. Machine learning methods for multi-rotor UAV structural damage detection based on MEMS sensor. International Journal of Aeroacoustics 2023, 22 (7–8), 656–674. https://doi.org/10.1177/1475472x231206495.
8. Limongelli, M. P.; Manoach, E.; Quqa, S.; Giordano, P. F.; Bhowmik, B.; Pakrashi, V.; Cigada, A. Vibration Response-Based Damage Detection. In Springer Aerospace Technology, 2021; pp 133–173. https://doi.org/10.1007/978-3-030-72192-3_6.
9. Steinhoff, L.; Koschlik, A.-K.; Arts, E.; Soria-Gomez, M.; Raddatz, F.; Kunz, V. D. Development of an acoustic fault diagnosis system for UAV propeller blades. CEAS Aeronautical Journal 2024, 15 (4), 881–893. https://doi.org/10.1007/s13272-024-00752-8.
10. Liu, W.; Chen, Z.; Zheng, M. An Audio-Based Fault Diagnosis Method for Quadrotors Using Convolutional Neural Network and Transfer Learning. 2020 American Control Conference (ACC) 2020, 1367–1372.
11. Ozkat, E. C. Vibration data-driven anomaly detection in UAVs: A deep learning approach. Engineering Science and Technology an International Journal 2024, 54, 101702. https://doi.org/10.1016/j.jestch.2024.101702.
12. Adaika, Z.; Al-Haddad, L. A.; Giernacki, W.; Jaber, A. A.; Boumehraz, M.; Hamzah, M. N.; Flayyih, M. A. Fault Detection and Diagnosis Methodologies for Unmanned Aerial Vehicles: State-of-the-Art. Journal of Intelligent & Robotic Systems 2025, 111 (2). https://doi.org/10.1007/s10846-025-02267-8.
13. Al-Haddad, L. A.; Jaber, A. A.; Mahdi, N. M.; Al-Haddad, S. A.; Al-Karkhi, M. I.; Al-Sharify, Z. T.; Ogaili, A. A. F. Protocol for UAV fault diagnosis using signal processing and machine learning. STAR Protocols 2024, 5 (4), 103351. https://doi.org/10.1016/j.xpro.2024.103351.
14. Pose, C.; Giribet, J.; Torre, G. Propeller Damage Detection, Classification, and Estimation in Multirotor Vehicles. IEEE Transactions on Robotics 2025, 41, 2213–2229. https://doi.org/10.1109/TRO.2025.3548536.
15. Banerjee, P.; Okolo, W. A.; Moore, A. J. In-Flight Detection of Vibration Anomalies in Unmanned Aerial Vehicles. Journal of Nondestructive Evaluation Diagnostics and Prognostics of Engineering Systems 2020, 3 (4). https://doi.org/10.1115/1.4047468.
16. Li, C.; Luo, K.; Yang, L.; Li, S.; Wang, H.; Zhang, X. A Zero-Shot fault detection method for UAV sensors based on a novel CVAE-GAN model. IEEE Sensors Journal 2024, 24 (14).
17. Zhou, S.; He, Z.; Chen, X.; Chang, W. An Anomaly Detection Method for UAV Based on Wavelet Decomposition and Stacked Denoising Autoencoder. Aerospace 2024, 11, 393. https://doi.org/10.3390/aerospace11050393

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REVIEW ARTICLE

Hydrogen-Powered Aircraft and Their Effectiveness in Reducing the Climate Impact of the Aviation Industry

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ABSTRACT: The aviation industry is a key part of the economy. Aerospace engineers have been looking for ways to reduce carbon emissions, and many have shown interest in hydrogen power. This paper evaluates long-haul hydrogen-powered aircraft and their effectiveness at reducing greenhouse gas emissions. Evaluation is based on different attributes of hydrogen and their interaction with both the environment and aircraft performance. This paper explores the production of hydrogen, its environmental impact, storage, and potential effects on efficiency and performance. Additionally, it explores the combustion of hydrogen, including the emissions and power generated. The three main types of emissions that will be evaluated are carbon dioxide, NO_x ($NO + NO_2$) emissions, and contrail formation. They impact the environment differently, and their impacts directly impact the effectiveness of hydrogen-powered aircraft at reducing emissions. There are major possible developments in the future that would be able to significantly reduce their emissions. Although many properties of the greenhouse gases are not certain, this paper has found that hydrogen-powered aircraft are very effective at reducing the impact of the aviation industry on the climate.

KEYWORDS: Engineering Mechanics, Aerospace and Aeronautical Engineering, Hydrogen-Powered Aircraft, Hydrogen Storage, Greenhouse Gases.

Introduction

The aviation industry undoubtedly has a large impact on the world. Aircraft ship both cargo and passengers all around the world daily. In 2011 alone, airliners transported 2.8 billion passengers and shipped 47.6 million metric tonnes of cargo.[1] They have also supplied tens of millions of jobs and contribute to a significant portion of global GDP.

However, the aviation industry has also had a significant impact on the climate. In 2019 alone, the air transport sector emitted upwards of 900 million tonnes of carbon dioxide.[2] Currently, the aviation industry accounts for 3.5% of total climate impact, and by 2050, the aviation industry is predicted to be responsible for 5% of total climate impact, illustrating how aviation emissions are bound to increase.[3] Because many of the emissions are released at high altitudes, the options of reversing the climate impact of the aviation industry are particularly challenging. The climate impact caused by the aviation industry presents new challenges, and its contributions need to be minimized.

Hydrogen-powered aircraft have the potential to lower aviation greenhouse gases on long-haul flights. When hydrogen is burned, no carbon dioxide, the most dominant greenhouse gas, is emitted.[4,5] This means that the climate impact caused by the aviation industry may be drastically reduced.

Hydrogen-powered aircraft have been considered by scientists and engineers as a viable solution to reduce climate impact in the future for years. However, many technical challenges stand in their way. Although the main concept of thrust production would largely remain the same, different engines that require new technologies would need to be developed to accommodate hydrogen as a fuel. Fuel tanks with new technology would also have to be developed, as the properties of hydrogen differ drastically from the properties of kerosene. These technical challenges make aircraft developers hesitant to shift toward hydrogen-powered aircraft.

There are two methods of hydrogen consumption: hydrogen combustion and fuel cells. This paper will only focus on hydrogen combustion. Fuel cells, although far more climate-friendly, are not the appropriate type of engine for long-haul flights, as they are used for smaller aircraft.[6] Therefore, fuel cells and their climate impact will not be analyzed in this paper. It will focus exclusively on hydrogen combustion engines.

In order to evaluate the effectiveness of hydrogen-powered aircraft at reducing the climate impact of the aviation industry, this paper will first examine the production of hydrogen, its efficiency, and its release of greenhouse gases. Next, this paper reviews hydrogen storage and its aerodynamic and weight effects, hydrogen's properties, technologies, and techniques that could be utilized, and future predictions on how efficient hydrogen storage systems may become. Then, this paper will explore combustion, the different ways in which hydrogen and kerosene are burned, and techniques that can be utilized to increase efficiency and decrease greenhouse gas emissions. Finally, this paper analyzes the amount of greenhouse gases that hydrogen-powered aircraft will produce, such as carbon dioxide, NOx emissions, and contrails, and the effect each of the gases will have on the atmosphere. These results will then be compared to current modern aircraft to determine the effectiveness of hydrogen-powered aircraft at reducing climate impact.

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Discussion

1. Hydrogen Production:

In order for hydrogen to be used as a fuel for aircraft, it must first be produced. There are various forms of production of hydrogen, including steam reforming, partial oxidation, and electrolysis. Steam reforming uses methane, partial oxidation uses coal and oil, and electrolysis uses electricity. Unfortunately, most hydrogen is created through the usage of fossil fuels, limiting hydrogen's friendliness toward the climate.[5] Although electrolysis can be achieved with no emissions through green energy production, such as nuclear and wind energy, hydrogen is rarely ever produced using this method, and its environmental benefits are therefore minuscule.

Approximately 99.5% of greenhouse gases throughout the lifecycle of kerosene are released during combustion.[7] This means that the amount of greenhouse gases produced during kerosene production is very small and insignificant.

1.1. Steam Reforming Method:

Steam reforming is the most popular method of producing hydrogen. In fact, more than 95% of hydrogen is created using this method.[8] This process reacts methane (CH_4) with steam (H_2O) to make carbon dioxide (CO_2) and hydrogen (H_2). The overall chemical reaction is:

$$CH_4 + 2H_2O \Rightarrow 4H_2+CO_2.^{9} \text{ (R1)}$$

The reaction can be broken down into two elementary steps.

$$CH_4 + H_2O \Rightarrow CO + 3H_2.^{9} \text{ (R2)}$$

$$CO + H_2O \Rightarrow CO_2 + H_2.^{9} \text{ (R3)}$$

For every four hydrogen molecules that are produced, a single carbon dioxide molecule is produced. This chemical reaction is endothermic, meaning that additional heat is required in order to make the methane and water vapor react. The change in enthalpy of the first elementary step is 206 kJ/mol, the second elementary reaction is -41 kJ/mol, and the reaction can only take place at temperatures over 700°C.[10] In fact, 30-35% of the methane used to produce hydrogen is used to create the heat necessary for the reaction.[10] Creating heat adds to the overall carbon dioxide production. For the production of 129 kg of hydrogen, 1275 kg of CO_2 is emitted.[4] The steam reforming method has an efficiency of about 85%, which is very efficient relative to other methods of energy production, such as burning coal.[10] Given that 90% of hydrogen is already created using the steam reforming method and the efficiency of this method is very high, this method of producing hydrogen will probably remain the most favorable for hydrogen producers. Therefore, the climate impact of the production of hydrogen is unlikely to decrease in the future.

2. Hydrogen Storage:

After hydrogen is produced, it must be shipped to airports. While an airplane flies, it must store fuel onboard. Only compressed and liquid hydrogen are viable for long-haul flights.[11] Hydrogen storage systems differ from modern kerosene storage systems, and the efficiency that hydrogen storage systems offer differs from the efficiency of modern kerosene storage systems. Therefore, using hydrogen as a fuel would change the amount of energy needed for consumption during the flight, which would expand its climate impact. The type of fuel that will be focused on will be liquid hydrogen.

2.1. Properties of Liquid Hydrogen:

Liquid hydrogen has a few properties that make storing it different from kerosene.

Firstly, hydrogen has a specific energy that is three times greater than kerosene.[5] If the same amount of grams of hydrogen and kerosene are combusted, hydrogen will release three times more energy. This decreases the weight of hydrogen that needs to be stored on a flight by roughly three.

Next, hydrogen has an energy density that is four times less than kerosene, with hydrogen having an energy that is 8 MJ/m^3 and kerosene having a volumetric energy density of 32 MJ/m^3.[12] For example, if a cubic meter of both hydrogen and kerosene is burned, the kerosene will produce four times more energy. This becomes problematic, as it would require the volume of fuel storage of modern aircraft to increase by four. This would increase the weight and size of the aircraft substantially and pose new sets of problems.

The extra fuel storage would take up more space and increase the size of the aircraft. Not only might this add to weight, but if the fuselage is bigger, the aircraft will have more aerodynamic drag. The extra fuel space would add 10% more aerodynamic drag compared to modern kerosene-powered aircraft.[5]

Then, liquid hydrogen has a boiling temperature of 20K.[13] This is -253°C, and although it is much colder higher in the atmosphere, it is not quite -253°C. Therefore, there needs to be systems to cool the fuel inside the aircraft as well as insulation to keep it cool. Furthermore, when liquid hydrogen is stored, it needs to be pressurized.[11] This will require the fuel tanks to be stronger to be capable of pressurizing the fuel.

The freezing temperatures of liquid hydrogen also require the storage system to be airtight.[14] The freezing temperature of oxygen and nitrogen is higher, and if oxygen or nitrogen enters the hydrogen storage tanks, it will freeze. Frozen pipes might block pipes and cause other disruptions with fuel flow.

These three properties of liquid hydrogen make the storage systems that would store the liquid hydrogen much more complex, high-tech, and heavier than current modern fuel storage systems. All of these attributes would decrease total aircraft efficiency.

2.2. Gravimetric Efficiency:

Gravimetric efficiency is defined as the ratio of the weight of the fuel to the weight of the fuel and the fuel tank combined.11 For example, if a fuel tank weighs 1 kilogram and can hold 99 kilograms of fuel, the gravimetric efficiency would be 99%. A heavier fuel tank would mean a lower gravimetric efficiency because the weight of the fuel and the fuel tank would increase as well.

Because a decrease in gravimetric efficiency generally means a heavier fuel tank and a heavier overall aircraft, gravimetric efficiency needs to be as high as possible. A high gravimetric efficiency would lead to higher overall efficiency, longer range, and lower climate impact.

Current modern airplanes have gravimetric efficiencies of nearly 100% (Table 1).[13] Although hydrogen-powered aircraft have not been developed yet, current technologies could support a gravimetric efficiency of about 30-45%, where 30% would represent a conservative estimate.[15] However, if hydrogen fuel tanks are developed, gravimetric efficiency could increase with an optimized and theoretical value of 65-70%.[13]

Gravimetric efficiency has a large impact on efficiency and range. It was found that increasing the gravimetric efficiency of an aircraft from 30% to 80% could increase the range from 4000 to 7000 nautical miles for long-range aircraft.[15] The same study also found that increasing gravimetric efficiency above 80% had a decaying impact on range.[15] This suggests that after years of development, the gravimetric efficiency of hydrogen-powered aircraft will contribute to a lack of efficiency and range slightly compared to conventional and modern kerosene-powered aircraft. However, first-generation hydrogen-powered aircraft will be significantly less efficient and will not even be able to complete long-haul flights. Therefore, hydrogen-powered aircraft may seem less efficient at first, and the efficiency penalty from a lower gravimetric efficiency would slowly disappear.

In total, a hydrogen-powered aircraft would be a little less efficient than a modern kerosene-powered jet (Table 1). A study was conducted where three aircraft flew a 7829 nautical-mile flight. The first aircraft was a conventional kerosene-powered aircraft, the second aircraft was a hydrogen-powered aircraft with a gravimetric efficiency of 45%, and the last aircraft was a hydrogen-powered aircraft with a gravimetric efficiency of 67%. The hydrogen-powered aircraft with a gravimetric efficiency of 45% consumed 20-40% more energy than the kerosene-powered aircraft, and the hydrogen-powered aircraft with a gravimetric efficiency of 65% consumed 10-20% more energy than the kerosene-powered aircraft. It is predicted that optimized hydrogen-powered aircraft will be able to use as little as 5% more energy than kerosene-powered aircraft.[16]

Table 1: Hydrogen and kerosene statistics.[12,13,15] Table 1 finds that the volumetric energy density of Kerosene is higher than that of hydrogen, allowing for a higher gravimetric efficiency.

Fuel type	Hydrogen	Kerosene
Volumetric energy density	8 MJ/m³	32 MJ/m³
Boiling temperature	-253°C	Not concerning
Gravimetric efficiency	Low	High

3. Combustion:

Combustion is the stage where the fuel is ignited in the engine and refers to the burning of the fuel. Hydrogen burns differently from kerosene and releases different gases. Although hydrogen burns very similarly to kerosene, entirely new engines will need to be developed to accommodate it.

For example, because of the lower volumetric energy density, 30% of the space in the combustion chamber must be hydrogen, while modern aircraft only require 5% of the combustion chamber to be fuel. As a result, only 70% of the combustion chamber will be filled with oxygen. This limits the amount of fuel that can be ignited at a single instant, also limiting thrust. Therefore, hydrogen-powered engines will be weaker than modern engines, and new and larger engines will probably have to be built in order to service long-haul flights with the same performance.

Since hydrogen's energy density is three times greater than kerosene, hydrogen engines generally operate at larger combustion temperatures.[17] It burns approximately 140K hotter than kerosene.[6] There are a few techniques that can be utilized to lower the temperature, leading to various benefits.

3.1. Hydrogen Combustion Properties:

Firstly, hydrogen has a higher ignition temperature than kerosene.[17] Part of this is because of the higher specific energy of hydrogen. This has effects on the amount of emissions that are released.

Next, despite requiring to fill up 30% of the combustion chamber to burn, hydrogen can be burned much leaner than kerosene. Hydrogen's stoichiometric fuel-to-air ratio is 1:34, which is less than half of kerosene's fuel-to-air ratio, which is 1:15.[11] This means that hydrogen has a lower lean stability limit. This leads to lower fuel flows and greater overall efficiency.

Finally, hydrogen has a lower residence time than kerosene.[16] This means that it burns faster. This impacts the formation of various greenhouse gases that may form inside the combustion chamber.

3.2. Hydrogen Combustion Emissions:

One of the major greenhouse gases that is produced by aircraft is nitrogen oxide (NO_x) emissions, which are nitrogen dioxide (NO_2) and nitric oxide (NO).[18] They are produced at high temperatures, such as in combustion chambers, when nitrogen (N_2) and oxygen (O_2) react with each other.

The temperature inside the engine directly impacts the amount of NO_x that forms. The low lean stability limit of hydrogen will allow a hydrogen-powered engine to burn at a leaner mix and burn at a lower temperature, even though hydrogen normally burns at much higher temperatures.[19] This will lead to the combustion chamber of a hydrogen-powered engine being 150-200K cooler than the combustion chamber of a kerosene-powered engine.[16] This will also lengthen the lifespan of the engines, leading to less maintenance, repairs, and replacements.[4]

Because of the low residence times, less NO_x will also be produced because NO_x has less time to form.[11] This means that hydrogen inherently produces less NO_x than kerosene with respect to residence times.

Finally, there is a special technique to reduce the NO_x emissions of an aircraft called rich-lean combustion. The inner nozzle supplies a rich mixture, and the outer nozzle supplies a lean mixture. A study finds this technique to be able to reduce NOx emissions by around 40% alone.[20] Advancements and developments within the field of hydrogen-powered aircraft will lead to greater abilities to further reduce emissions.

4. Emissions Comparison:

There are three main kinds of emissions that come from aircraft. They are carbon dioxide, nitrogen oxide (NO_x), and

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contrail formation. They each impact the environment in different ways. Although water vapor is a greenhouse gas, it has a short lifetime of only a few months and low radiative forcing, at 2 mW/m^2, which makes its climate impact minimal and insignificant compared to other greenhouse gases.[6,18]

4.1. Carbon Dioxide:

Carbon dioxide is widely known to be the gas most responsible for climate impact. It has a radiative forcing of 34.3 mW/m^2, which measures the amount of energy reflected per unit of carbon dioxide.[16] Its radiative forcing is slightly limited because carbon dioxide has a relatively high concentration compared to other greenhouse gases.[21]

Given that current modern aircraft burn kerosene, which is a fossil fuel, they emit a lot of carbon dioxide. However, when hydrogen is burned, it does not produce any carbon dioxide. Therefore, the carbon emissions are almost eliminated (Table 2). The only carbon dioxide that needs to be accounted for is the amount of carbon dioxide that is produced during the production of hydrogen. As a result, the total amount of carbon emissions could be reduced by approximately 88%.[14]

4.2. NO_x Emissions:

NO_x emissions are also problematic for the atmosphere. They are also considered greenhouse gases. Approximately 15-20% of the NO_x in the atmosphere 8-12 kilometers above the ground is produced by aircraft.[22]

NO_x emissions behave and impact the climate differently. NO_x emissions themselves have no impact on the atmosphere, but they produce ozone and reduce methane.[22] Both of these gases are greenhouse gases. Overall, NO_x emissions have a radiative forcing of 8.2 mW/m^2, which is lower than carbon dioxide because part of NO_x also helps reduce climate impact by eliminating methane.

Although when hydrogen burns it generally produces more heat, certain techniques can be implemented, such as feeding the engine a lean mix, that will be able to reduce the temperatures below those that burn kerosene. NO_x emissions will have the potential to be lowered by approximately 70%.[5]

4.3. Contrail Formation:

Contrails are the clouds created by engines as the hot exhaust from the engines mixes with the cold air high in the atmosphere. These clouds reflect heat back to the surface of the Earth. Although scientists are unsure of the exact radiative forcing of contrails, as there is substantial uncertainty about their climate effects, some have estimated it to be about 111.[4] mW/m^2.[18] This is about three times the radiative forcing of carbon dioxide, albeit very uncertain. However, their climate impact is undoubtedly strong. They account for 50% of the aviation industry's climate impact.[23]

Other factors influence how big an impact contrails have on the environment. Hydrogen-powered aircraft produce approximately 2.6 times more water vapor than kerosene-powered aircraft.[24] This does not necessarily mean that hydrogen-powered aircraft will produce 2.6 times more contrails than kerosene-powered aircraft.

The contrails that the aircraft produce also depend on weather conditions, such as temperature, pressure, and humidity.[23] The method to determine the probability of these factors creating a contrail is called the Schmidt-Appleman Criterion.[25] Contrails have the chance to become persistent, last a long time, grow, and expand into larger and more impactful contrail cirrus when aircraft fly through ice-supersaturated regions.[26] If aircraft do not fly through these regions, contrails can be eliminated for both kinds of aircraft. Short-lived and small contrails would have no climate impact.[27]

For example, research suggests that hydrogen-powered aircraft should cruise at an altitude of 2-3 km below modern kerosene-powered aircraft. This would help reduce the formation of contrails and cut climate impact.[24]

Furthermore, since contrails are clouds, this impacts how they impact the environment. Firstly, it means that they have a very limited lifespan. Even persistent contrails only last for a few hours.[26] This means that when contrails are produced, they only impact the atmosphere for a few hours, whereas carbon dioxide impacts the atmosphere until it is destroyed, meaning that over time, the contrails emitted by an aircraft are much less harmful than the carbon dioxide emitted by an aircraft. Next, it means that contrails can reflect energy away from Earth, meaning that during the day, contrails have much less of a warming effect than at night.[18] In fact, although only 25% of total flights occur at night, contrails at night account for 60-80% of the total radiative forcing of all contrails.[24]

Optical depth is how much light or radiation a medium scatters and absorbs. The optical depth of the contrail determines the magnitude of the radiative forcing of a contrail.[18] This means that thicker contrails will trap more heat. Therefore, the climate impact of the contrails that hydrogen-powered aircraft make is based on how thick their contrails are.

Finally, since clouds are made by ice and ice formation requires nucleation points, which soot helps to provide.[21] Only kerosene-powered aircraft produce soot. Hydrogen-powered aircraft, which don't burn hydrocarbons, do not produce soot. Therefore, the formation of contrails will be a little bit less intense with kerosene-powered aircraft compared to hydrogen-powered aircraft, suggesting that contrails produced by hydrogen-powered aircraft might reduce the radiative forcing of their contrails compared to the contrails of kerosene-powered aircraft by 30-50%.[18]

Taking all of this into consideration, it is difficult to generalize a consistent amount of impact that contrails have on the environment (Table 2). Even with one source suggesting that contrails produced by hydrogen-powered aircraft will have less climate impact than contrails produced by modern kerosene-powered aircraft, other sources predict the opposite, and there is still doubt in too many areas to determine whether hydrogen-powered aircraft produce bigger or smaller contrails. What can be said is that the amount of impact can be controlled. Depending on the size of the contrail, the contrail can have a very little impact to three times that of carbon dioxide for several hours. Although there is a lot of uncertainty in general concerning contrails, if the conditions that create the large, environmentally unfriendly contrails are known, aircraft can at

least avoid these areas to produce fewer contrails altogether by predicting their formation.

If contrail formation is closely monitored and flights actively look to avoid them, contrails could have very little impact on the environment. Therefore, the environmental impact of hydrogen-powered aircraft emitting more contrails than kerosene-powered aircraft can be largely limited.

Hydrogen-powered aircraft emit much less carbon dioxide and NO_x emissions, but produce more contrails. If the contrail formation of aircraft is limited, their impact will also be limited, and the total amount of emissions and climate impact of hydrogen-powered aircraft will be greatly reduced. Sources predict that hydrogen-powered aircraft might have the potential to reduce climate impact by approximately 71%.[11]

Table 2: The climate characteristics of the most prominent aviation-induced greenhouse gases.[5,14,16,18] Table 2 finds that kerosene-powered aircraft produce more CO_2 and NO_x emissions than hydrogen-powered aircraft.

Greenhouse gas	CO2	NOx	Contrails
Relative climate impact	Medium	Low	Very high
Certainty	High	Medium	Very low
Fuel that produces more of the respective greenhouse gas	Kerosene	Kerosene	Unsure

Conclusion

The life cycle of hydrogen includes its production, storage, and combustion.

Although burning hydrogen does not release any carbon dioxide, the most popular and cost-effective hydrogen production methods release carbon dioxide, which limits hydrogen-powered aircraft to reduce climate impact with respect to kerosene-powered aircraft.

The most appropriate type of hydrogen fuel for long-haul flights would be liquid hydrogen because it is more energy-dense than compressed hydrogen. Liquid hydrogen needs to be stored at extremely low temperatures, needs more space, and is therefore much more difficult to store than kerosene. New technology will need to be developed to store liquid hydrogen onboard aircraft, which increases complexity, weight, fuel consumption, and reduces efficiency. Furthermore, more aerodynamic drag is added due to the additional required space to store hydrogen. This magnifies hydrogen's impact on the climate because more fuel gets burned.

Hydrogen is used as a fuel similarly to kerosene, and hydrogen-powered engines will adapt the same functions and concepts used by kerosene-powered aircraft. However, it burns differently. Because of the nature of hydrogen, there are multiple techniques that can be implemented to reduce the temperature of the combustion, which in turn lowers NO_x emissions.

Finally, the total amount of emissions emitted by hydrogen-powered aircraft is much lower than that of kerosene-powered aircraft. The amount of contrails will not be controlled by the technology within the aircraft, but rather the routes that aircraft utilize.

To evaluate the efficiency of the aircraft increases the climate impact of hydrogen-powered aircraft, but not to the large extent that hydrogen-powered aircraft reduce overall greenhouse gas emissions. Overall, this paper concludes that although the effectiveness of hydrogen-powered aircraft will be weaker at first and their total impacts may vary widely, they would be able to reduce greenhouse gas emissions of the aviation industry by over 70%.

Further research would include exploring materials that would better suit hydrogen storage, hydrogen engine combustion and optimization, and developing methods to predict and mitigate contrail formation, all of which would enhance the performance and environmental benefits of hydrogen-powered aircraft.

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References

1. J. Blanke; T. Chiesa, Eds., *The travel & tourism competitiveness report 2013: reducing barriers to economic growth and job creation*, 2013, The World Economic Forum.
2. Aerospace Technology Institute (ATI), *Aviation Emissions: Modeling the Road to Net Zero 2050*, Jul. 2022, Aerospace Technology Institute.
3. D. S. Lee; D. W. Fahey; P. M. Forster; P. J. Newton *et al.*, *Aviation and global climate change in the 21st century*, July 2009, Atmos Environ (1994), vol. 43, no. 22, pp. 3520–3537, doi: 10.1016/j.atmosenv.2009.04.024.
4. R. Shoukat; R. Redondi, *GHG emissions evaluation of conventional, electric, hybrid, biofuel, and hydrogen aircraft*, June 2025, Journal of the Air Transport Research Society, vol. 4, p. 100067, doi: 10.1016/j.jatrs.2025.100067.
5. F. Li, *A Review of Hydrogen-powered Aircraft*, Dec. 2024, WSEAS TRANSACTIONS ON SYSTEMS, vol. 23, pp. 409–418, doi: 10.37394/23202.2024.23.43.
6. I. Dincer; C. Acar, *A review on potential use of hydrogen in aviation applications*, 2016, IJSA, vol. 2, no. 1, p. 74, doi: 10.1504/IJSA.2016.076077.
7. C. Koroneos, A. Dompros, G. Roumbas, and N. Moussiopoulos, *Life Cycle Assessment of Kerosene Used in Aviation* (8 pp), Nov. 2005, Int J Life Cycle Assessment, vol. 10, no. 6, pp. 417–424, doi: 10.1065/lca2004.12.191.
8. C. Koroneos, A. Dompros, G. Roumbas, and N. Moussiopoulos, *Advantages of the use of hydrogen fuel as compared to kerosene*, May 2005, Resources, Conservation and Recycling, vol. 44, no. 2, pp. 99–113, doi: 10.1016/j.resconrec.2004.09.004.
9. E. Meloni, M. Martino, V. Palma, *A Short Review on Ni-Based Catalysts and Related Engineering Issues for Methane Steam Reforming*, Mar. 2020, Catalysts, vol. 10, no. 3, p. 352, doi: 10.3390/catal10030352.
10. P. Nikolaidis; A. Poullikkas, *A comparative overview of hydrogen production processes, Jan. 2017, Renewable and Sustainable Energy Reviews*, vol. 67, pp. 597–611, doi: 10.1016/j.rser.2016.09.044.
11. E. J. Adler; J. R. R. A. Martins, *Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts*, Aug. 2023, Progress in Aerospace Sciences, vol. 141, p. 100922, doi: 10.1016/j.paerosci.2023.100922.
12. C. J. Butler, *Hydrogen storage for aerospace applications*, Nov. 2024.
13. J. Huete; P. Pilidis, *Parametric study on tank integration for hydrogen civil aviation propulsion*, Oct. 2021, International Journal of Hy-

DOI: 10.36838/IJHSR811.133

drogen Energy, vol. 46, no. 74, pp. 37049–37062, doi: 10.1016/j.ijhydene.2021.08.194.
14. A. J. Colozza; L. Kohout, *Hydrogen Storage for Aircraft Applications Overview*, Sep. 1, 2002, Contractor Report E-13540, NASA/CR-2002-211867, Glenn Research Center, Brook Park, OH.
15. J. Huete; D. Nalianda; P. Pilidis, *Impact of tank gravimetric efficiency on propulsion system integration for a first-generation hydrogen civil airliner*, Aug. 2022, Aeronaut. J., vol. 126, no. 1302, pp. 1324–1332, doi: 10.1017/aer.2022.60.
16. C. Mourouzidis; G. Singh; X. Sun; J. Huete *et al.*, *Abating CO_2 and non-CO2 emissions with hydrogen propulsion*, July 2024, Aeronaut. J., vol. 128, no. 1325, pp. 1576–1593, doi: 10.1017/aer.2024.20.
17. B. Shadidi; G. Najafi; Tall Yusaf, *A Review of Hydrogen as a Fuel in Internal Combustion Engines*, Jan. 2021, Energies, vol. 14, no. 19, p. 6209, doi: 10.3390/en14196209.
18. D. K. Singh; S. Sanyal; D. J. Wuebbles, *Understanding the role of contrails and contrail cirrus in climate change: a global perspective*, Aug. 2024, Atmospheric Chemistry and Physics, vol. 24, no. 16, pp. 9219–9262, doi: 10.5194/acp-24-9219-2024.
19. Z. Stępień, *A Comprehensive Overview of Hydrogen-Fueled Internal Combustion Engines: Achievements and Future Challenges*, Jan. 2021, Energies, vol. 14, no. 20, p. 6504, doi: 10.3390/en14206504.
20. T. Shudo; K. Omori; O Hiyama, *NO_x reduction and NO_2 emission characteristics in rich-lean combustion of hydrogen*, Sept. 2008, International Journal of Hydrogen Energy, vol. 33, no. 17, pp. 4689–4693, doi: 10.1016/j.ijhydene.2008.05.034.
21. W. A. van Wijngaarden; W. Happer, *Relative Potency of Greenhouse Molecules*, Mar. 30, 2021, arXiv: arXiv:2103.16465. doi: 10.48550/arXiv.2103.16465.
22. G. P. Brasseur; J. Müller; C. Granier, *Atmospheric impact of NO_x emissions by subsonic aircraft: A three-dimensional model study*, Jan. 1996, J. Geophys. Res., vol. 101, no. D1, pp. 1423–1428, doi: 10.1029/95JD02363.
23. D. I. Barton; C. A Hall; M. K. Oldfield, *Design of a Hydrogen Aircraft for Zero Persistent Contrails*, Aug. 2023, Aerospace, vol. 10, no. 8, p. 688, doi: 10.3390/aerospace10080688.
24. D. Scholz, *Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?*, Nov. 19, 2020, presented at the Hamburg Aerospace Lecture Series (DGLR, RAeS, VDI, ZAL, HAW Hamburg), doi: 10.5281/zenodo. 6233322.
25. H. Appleman, *The Formation of Exhaust Condensation Trails by Jet Aircraft*, Jan. 1953, Bulletin of the American Meteorological Society, vol. 34, no. 1, pp. 14–20, doi: 10.1175/1520-0477-34.1.14.
26. D. S. Lee; M. R. Allen; N. Cumpsty; B. Owen *et al.*, *Uncertainties in mitigating aviation non-CO_2 emissions for climate and air quality using hydrocarbon fuels*, 2023, Environ. Sci.: Atmos., vol. 3, no. 12, pp. 1693–1740, doi: 10.1039/D3EA00091E.
27. B. Kärcher, *Formation and radiative forcing of contrail cirrus*, May 2018, Nat Commun, vol. 9, no. 1, p. 1824, doi: 10.1038/s41467-018-04068-0.

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REVIEW ARTICLE

The Impacts of Government Policy on Electric Vehicle Adoption and Economic Development Across the U.S.

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ABSTRACT: In the past few years, many governments have pursued policies such as tax rebates/incentives and charging station infrastructure investment to promote electric vehicle (EV) adoption and curb emissions. While many studies have examined the impact of these measures on EV adoption and the economy, findings vary due to different markets and economic landscapes. There is also limited research on the effectiveness of EV policies on a state-by-state basis in terms of EVs per capita. This paper analyzes state and federal government EV policies to determine how they affect EV adoption and consumer behavior, EV production, private investment, manufacturing capacity, employment, and the automotive industry. It also focuses on the factors that influence government EV measures, and how EV adoption compares across different states in the U.S. This study uses data on EV sales over time, charging stations, and tax incentives across all 50 states, and references the number of EVs per capita per state as a baseline for comparison. This study's findings reveal correlations between state policies and EV growth, factors that influence state policies and consumer adoption, and the practical and economic implications of current and future federal EV policy.

KEYWORDS: Behavioral and Social Sciences, Other; Electric Vehicles, Tax Credits, Charging Infrastructure Expansion.

Introduction

Transportation is one of the leading causes of pollution in the world, accounting for nearly 30.9% of all carbon dioxide emissions.[1] In 2022, transportation made up 28% of all greenhouse gas emissions in the U.S., making it the largest contributor of any sector.[2] As a result, many efforts have been made to promote the transition to electric vehicles (EVs) as a sustainable alternative and to reduce emissions.

Two of the main factors that influence consumers' decisions regarding EV purchases are the price in relation to combustion counterparts and the number of charging stations. Thus, policies at the local, state, and national levels have focused on subsidization incentives and infrastructure investments. Since August 2022, there has been a federal tax credit of as much as $7,500, and the government has invested $50 million into expanding EV infrastructure.[1] Additionally, more than 400 incentives have been implemented at the state and local level to promote EV growth since 2008.[3] Many studies have examined the effectiveness of such policies, including the impact on consumer adoption and market development. For instance, Dabush *et al.*'s findings that subsidies lead to higher EV adoption rates correlate with the findings of Wang *et al.*, suggesting that incentives help lower the prices of EVs to be more on par with combustion cars. The study also found that direct subsidies for consumers are more effective than investment in charging infrastructure. More specifically, Narassimhan and Johnson found that among tax incentives, rebates tend to be more effective than credits. However, different markets and consumer demographics can lead to differing conclusions on the effectiveness of policies. For example, Dabush *et al.* recorded that the conclusion Wang *et al.* and Huang *et al.* both came to in their studies of China's EV market was opposite to theirs, finding that subsidies for charging infrastructure were more effective than consumer benefits. This indicates that due to market and socioeconomic variations across countries, EV adoption is influenced by different factors. While this has been examined across countries, there is a lack of research focusing specifically on states in the U.S. that analyzes varying policies and market trends. Furthermore, little has been found on how EV adoption and the market fluctuate under different federal policy measures in the U.S. As the federal incentive for EVs is repealed under provisions of Trump's One Big Beautiful Bill Act, the future of EVs is unclear, especially as the tax credits have not been eliminated since their implementation.

This study investigates the extent to which government subsidies, charging infrastructure investment, and federal policy impact EV market adoption and economic prospects in the transportation sector across the U.S., drawing upon empirical evidence from states and research regarding the impact of such incentives.

The findings in this study demonstrate that there is a strong correlation between EV adoption and tax incentives and infrastructure investment in many states. This positive relationship indicates that a lowering or absence of such policies, possibly due to shifting national political agendas, can lead to less EV adoption. Furthermore, without strict regulations such as emissions standards, automakers can be less inclined to manufacture EVs, and private investors may be less incentivized to expand charging infrastructure, leading to an even smaller supply and market. While there may be initial fiscal savings for the government not having to fund incentive policies, economic prospects will likely worsen over time due to decreases in manufacturing and innovation in the transportation sector. Granted, state-level incentives may remain to mitigate the effects of eliminating federal support.

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This paper includes secondary data analysis mixed with descriptive statistics, with comparative studies of monetary incentives and infrastructure investment regarding EV sales across all 50 states. Data on EVs, charging stations, and tax incentives/rebates will be used to determine the correlation between policies and EV sales. The number of EVs per capita per state will be used as a baseline for comparison. This study also documents the progression of EV sales in the U.S., with a longitudinal approach to monitor consumer preferences and purchase habits over time, potentially determining causal relationships or long-term effects of policies. Lastly, the federal government's influence will be explored through analyses of various federal policies on EV sales, private investment, manufacturing, and overall economic outlook.

Discussion

Tax Incentives and Rebates Across States:

States EV Incentives:

States with EV tax incentives/rebates tend to have higher rates of EV sales. Since 2008, more than 400 incentives have been issued by local and state governments in the U.S. to promote EVs.[3] The most common are tax credits and rebates. As of 2023, states with subsidy policies include California ($7,500), Connecticut ($7,500), Maine ($7,500), Oklahoma ($5,500), Colorado ($5,000), Oregon ($5,000), Vermont ($4,000), Illinois ($4,000), New Jersey ($4000), Massachusetts ($3,500), Pennsylvania ($3,000), Maryland ($3,000), Virginia ($2,500), Rhode Island ($2,500), Delaware ($2,500 rebate), Kansas ($2,400), New York ($2,000), and Alaska ($1,000).[4] Eligibility for such credits depends on factors like the vehicle's MSRP, final assembly location, battery components origins, and individual or household incomes.

Impact of Government Incentives on EVs:

Dabush *et al.* found that consumers are heavily influenced by government incentives, which lower the price of EVs to be more in line with combustion counterparts. It also found that incentives targeted towards consumers achieve higher rates of adoption in a short period of time, especially in areas with fewer EVs. More specifically, among tax incentives, rebates tend to be more advantageous than credits.[3] However, the efficacy of subsidies varies depending on the specific market. Compared to charging infrastructure investment, consumer subsidies have a greater effect on EV growth as fluctuations in their value more significantly alter EV rates. Doubling a consumer subsidy of $1,875 to $3,750 correlates with a substantial increase in EVs, while a doubling of a charging station subsidy of $50,000 to $100,000 does not. Conversely, a reduction in the consumer subsidy by half leads to a 8.8% decrease in sales, while the same reduction in charging station subsidies only yields a decrease of 0.87% in the first ten years.[1] The larger increase and decrease in EVs when consumer subsidies are doubled and reduced by half, respectively, compared to fluctuations for charging station subsidies, indicate that EV sales are more sensitive to changes in consumer subsidies than charging station subsidies. This suggests that incentives directly for consumers may boost EV sales more, but it doesn't mean those are more effective in the long-run and sufficient for EV policy.

State Incentives and EV per capita by State:

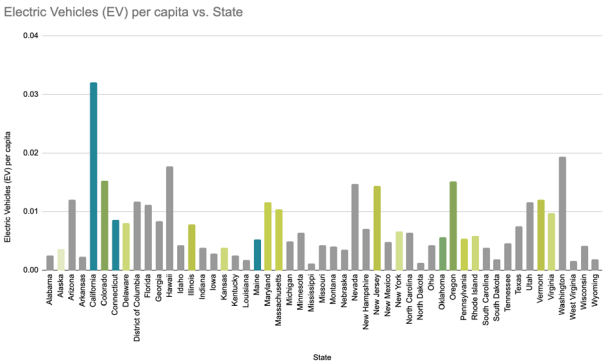

Figure 1: Graphical comparison of EV per capita and state. This graph depicts the number of EVs per capita in each state, with columns color-coded based on the incentive amount. It highlights the trend that states with EV incentives tend to have more EVs per capita.[6]

Table 1: States with the highest EV per capita. This table lists the states with the highest EV per capita from highest to lowest. It illustrates that states with EV incentives have more EVs per capita and that having a larger incentive tends to correlate with a higher ranking. [6]

Rank	State	EV per capita
1	California ($7,500)	0.0321
2	Washington	0.0194
3	Hawaii	0.0178
4	Colorado ($5,000)	0.0153
5	Oregon ($5,000 rebate)	0.0151
6	Nevada	0.0147
7	New Jersey ($4000 rebate)	0.0144
8	Vermont ($4,000)	0.012024
9	Arizona	0.012017
10	District of Columbia	0.0118
11	Utah	0.011617
12	Maryland ($3,000)	0.011597
13	Florida	0.0111
14	Massachusetts ($3,500)	0.0104
15	Virginia ($2,500)	0.0097
16	Connecticut ($7,500)	0.0087
17	Georgia	0.0084

From Figure 1, it appears that states with some form of EV tax incentive tend to have higher rates of EVs per capita, graphically. California has the highest EV per capita by far, and it also has the most generous EV incentive policy. States with the lowest EV per capita are overwhelmingly those without any EV incentive. From Table 1, 9 out of the 17 states with the highest EVs per capita have some form of EV tax incentive, which supports that monetary incentives lead to increased rates of EVs, but also indicates that there are other factors at play. Exceptions may exist because federal incentives apply even if states do not offer their own incentives. Additionally, states without separate tax incentives may still have high EVs per capita through other forms of incentives, such as charging rebates, reduced charging fees, free EV parking, HOV lane

access, and more. These factors show that EV rates are not dependent on just tax subsidies. Another trend is that states with more EVs per capita and/or that have EV tax incentives tend to be blue. In fact, 6 of the 8 states in Table 1 that do not have state-level tax incentives but still have high rates of EVs per capita are primarily Democratic-leaning. This backs up the research of Sintov *et al.*, which determines that Democrats buy EVs at higher rates than Republicans, thus areas with Democratic majorities will tend to have more EVs, meaning political ideology is also a factor.

From the secondary data analysis and descriptive data correlation statistics, it is clear that tax incentives/rebates promote EV adoption, but possibly to a limited extent, as the presence of outliers (8 of the 17 states not having such policies) implies there are other potential confounding variables.

Charging Infrastructure Across States:

Federal and State EV Infrastructure Policies:

States with more charging infrastructure tend to have higher rates of EVs, with many state and federal policies expanding EV charging station infrastructure. The Bipartisan Infrastructure Law, also known as the Infrastructure Investment and Jobs Act (IIJA), passed in November 2021, provides $7.5 billion for constructing a nationwide EV charging station network, with particular focus on developing infrastructure in rural and disadvantaged areas.[5] $5 billion will go to states as part of the National Electric Vehicle Infrastructure (NEVI) Formula Program for adding charging stations along corridors and highways from 2022-2026, which could help finance a minimum 33,000 charging ports.[6,7] At the end of 2024, 12 states used NEVI funds to implement 44 public charging stations.[8] $1.25 billion will go towards the Charging and Fueling Infrastructure Grants to build EV infrastructure on public roads, schools, parks, and parking in areas of highest need (i.e., rural, low-income, multi-family units).[6] In addition to helping the environment, this legislation creates jobs, improves infrastructure, and strengthens American competitiveness in the transportation and technological sectors.[9] Some states have implemented their own funding, such as California's $1.4 billion investment and New York's $60 million investment, while local governments fund and install charging stations on government-owned land and work with private interests to expand EV infrastructure investment.[10,11] The private sector also plays a large role, with companies like ChargePoint, Tesla, EVgo, Electrify America, and Blink Charging expanding their charging networks.

EV Charging Stations in the U.S.:

As of January 2025, all 50 states have EV charging stations, with a total of 69,679 public charging stations and 195,874 public charging ports. U.S. EV infrastructure has dramatically expanded in the past few years to address the surge in EVs, multiplying by more than 6 times since 2016. However, it continues to be more abundant in urban areas with more EVs. California takes the lead with 49,128 public EV chargers (triple that of any other state), followed by New York (15,890), Florida (11,100), Texas (10,629), Massachusetts (8,426), Washington (6,427), Georgia (5,867), Colorado (5,627), Pennsylvania (4,937), and Virginia (4,908). Though more charging stations are not indicative of more chargers for drivers. The density of EV chargers is highest in northeastern states. For the average number of public EV charging stations per 10 square miles, Massachusetts ranks first (8), followed by Connecticut (6), Rhode Island (5), New Jersey (5), Maryland (4), California (3), New York (3), Delaware (3), Florida (2), and Vermont (1).[12]

Types of Chargers:

There are also different types of chargers. Around 74% of EV chargers in the U.S. are Level 2 chargers, which typically charge at a rate of around 10-20 miles per hour, while 25% are DC (direct current) fast chargers that charge much quicker at around 180-240 miles per hour. DC fast chargers have increased rapidly since 2016, growing by 14 times, and are usually found along frequented U.S. highways.[12]

Charging Infrastructure and EV per capita By State:

Table 2: Top 15 states with the highest EV Charging Ports per capita. This table lists the states with the most EV Ports per capita from highest to lowest. States with more EV Ports per capita tend to have high rates of EVs per capita.[6]

State	EV Ports per capita
Vermont	0.00193
District of Columbia	0.00161
California	0.00148
Massachusetts	0.00135
Connecticut	0.0012
Colorado	0.0011
Maine	0.001
Oregon	0.0009128
Washington	0.00091276
New York	0.000895
Maryland	0.00084
Rhode Island	0.00076
Nevada	0.00075
Utah	0.00075
Delaware	0.00070

Table 3: Top 15 states with the highest EVs per capita. This table lists the states with the most EVs per capita from highest to lowest. States with more EVs per capita tend to be those with more EV Ports per capita.[6]

State	EV per capita
California	0.0321
Washington	0.0194
Hawaii	0.0178
Colorado	0.0153
Oregon	0.0151
Nevada	0.0147
New Jersey	0.0144
Vermont	0.012024
Arizona	0.012017
District of Columbia	0.0118
Utah	0.0116
Maryland	0.01159
Florida	0.0111
Massachusetts	0.0104
Virginia	0.0097

*Bolded are states that appear on both lists

According to Table 2 and Table 3, 10 of the 15 states with the most EV charging ports per capita are in the top 15 for the highest EVs per capita. This represents that there is a correlation between EV charging ports and the number of EVs, with more charging infrastructure potentially resulting in more EVs. However, this correlation is not perfectly linear, as the order is relatively random, suggesting other confounding factors may affect the link between charging ports and EV adoption.

Impact of Charging Infrastructure on EVs:

Some studies have found the availability of charging stations to be an indicator of EV sales.13 Fast chargers are especially influential in promoting EVs and make up the largest portion of infrastructure finances that are being used to bolster EV adoption.

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Government Subsidization of EV Charging Infrastructure:

Government incentives are important when it comes to charging infrastructure due to the discrepancy over whether increased charging stations lead to more EVs or if more EVs lead to more charging infrastructure. Additionally, EV chargers are not economically desirable due to high upfront costs and potential low returns (with revenue based on the number of kilowatts being charged). Thus, government subsidies for charging infrastructure are important to encourage investment that promotes EV growth. Charging station subsidization may also be more economically attractive than direct consumer subsidies when it comes to stimulating EV adoption, which could make it more strategic even if it is less effective than direct incentives.[13] Future research could focus specifically on how consumer incentives fare in comparison to charging station investment to see which leads to the most EV growth at the lowest cost.

It appears that even if charging infrastructure does not have as strong an effect on EV adoption, it still influences how likely a state is to have a high number of EVs. Additionally, states with more charging ports per capita tend to have more EVs per capita, suggesting that without charging infrastructure, EVs would not be as abundant.

Progression of EV Growth & Other Factors:

EV sales have greatly increased over time as a result of private investment and greater government support, though other factors also play into their growth in recent years.

Progression of State Subsidies:

From 1990 to 2009, before many new EVs hit the market, 9 states had EV sales subsidies. There was an increase of 14 states from 2010 to 2018. In 2015, the number of state subsidies reached a high of 17 before dipping to 13 in 2018 as states repealed such measures. From 2010 to 2018, more states adopted annual EV fees, with California, Colorado, and Oregon having both subsidies and fees in place.[14]

Timeline of Federal EV Policy:

Federal EV policy has changed throughout the years. In 2008, the Energy Improvement and Extension Act established the first consumer tax credits for EVs, which only applied to the first 250,000 battery and plug-in hybrid (PHEV) vehicles of specific battery sizes sold. In 2009, the American Recovery and Reinvestment Act changed the cap from 250,000 total to 200,000 per manufacturer. In 2022, the Inflation Reduction Act renamed the EV tax credit the Clean Vehicle Credit, removed the manufacturer sales cap, made Fuel Cell Electric Vehicles (FCEVs) eligible, stipulated requirements for final assembly in North America and mandates for minerals and battery part origins, and implemented limits on automakers' suggested retail price (MSRP) and consumers' modified adjusted gross income. In 2025, the One Big Beautiful Bill Act eliminated the Clean Vehicle Tax Credit for all EV sales after September 30, 2025.[15]

Other Factors:

Many other factors also affect EV adoption in terms of it being a type of new technology, such as time, awareness, knowledge, and the number of EV models. General barriers to new forms of technology include lack of knowledge, high upfront prices, and low risk tolerance, but these barriers can be alleviated through education, higher income, and environmental awareness. For the most part, more widespread knowledge about EVs has led to higher acceptance and use. Additional factors include electricity price, emission regulations, gasoline costs, and urban road use, though these vary significantly across states. For example, Vermont is most sensitive to electricity prices, while New Jersey is most sensitive to urban road use and incentives.[16] This alters states' focuses when attempting to increase EV adoption. Buckberg notes that dramatic increases in EV sales were brought on by high gas prices that made EVs the more financially sound option, and lower battery costs, which led to more affordable EV models with longer ranges. External factors can also affect EV adoption. For example, the minimal number of EVs in 2005 and 2006 was due to Hurricane Katrina, and a similar result in 2008 was because of the financial crisis. Still, time trend models indicate that time increases the number of EVs as consumers are more willing to buy into new technology that becomes further developed and researched.[13] These findings reveal that other factors contribute to shifting consumer preferences and increasing EVs over time, implying that surges in EVs should not be attributed to just tax incentives and EV infrastructure expansion.

Net Environmental Benefit:

As renewable energy sources and natural gas infrastructure expanded into the electricity grid while coal power plants decreased over time, the net environmental benefit of EVs (identified by Holland *et al.* as "the avoided pollution damages from a gasoline-powered vehicle minus the pollution damages from the power plant generating the electricity used to charge the EV") increased in all regions of the U.S. Specifically, Holland et al's study analyzing the average annual net environmental benefit of a Ford Focus EV compared to its gas version found that from 2010-2017, it increased from $75 to $107 in Texas, $233 to $258 in the West, and -$192 to $205 in the East.[14] This increase in net environmental benefit means EVs are increasingly more beneficial for the environment, which makes states more willing to incentivize them to reduce greenhouse gas emissions. Thus, another factor influencing EV sales is how much more environmentally friendly they are compared to gas counterparts.

While growth in EV sales was likely most influenced by consumer subsidies and expansion of charging infrastructure, there is evidence that other factors shape consumer decisions. This is crucial as it shows that tax and charging policies are not the only areas to focus on in attempting to increase EV sales.

Federal Policy Influences:

Federal policies have a large influence on private-sector investment, manufacturing, and the cost of purchase, thus affecting EV adoption and the rate of innovation. Government

tax incentives, subsidies, financing for research or development, and others can encourage EV adoption and stimulate the private sector to invest. In fact, Tesla's growth was largely supported by government policies like tax credits and subsidies. Government mandates (i.e., renewable energy baselines, EV quotas, EPA guidelines) can further prompt the private sector to act to comply with such standards. EV infrastructure relies on partnerships between the government and private companies.[17]

Inflation Reduction Act:

One such government policy that had a large impact on EVs was the Inflation Reduction Act (IRA), passed in August 2022. The following sections examine the impact of the IRA on EV growth and investment, employment, manufacturing, and clean energy projects.

EV Growth:

The IRA did not result in an immediate increase in EV adoption, partly due to stringent guidelines that originally disqualified 15 EV models from tax credits.[18] Overall, however, it does appear that the IRA is supporting a steady increase in EVs over time, as evident in Figure 2. In fact, compared to years prior, 2023 had the highest number of EV sales in the U.S. at 1.46 million—a 50% increase from 2022.[19] This is important as it shows that government policies are effective in increasing consumer demand for EVs.

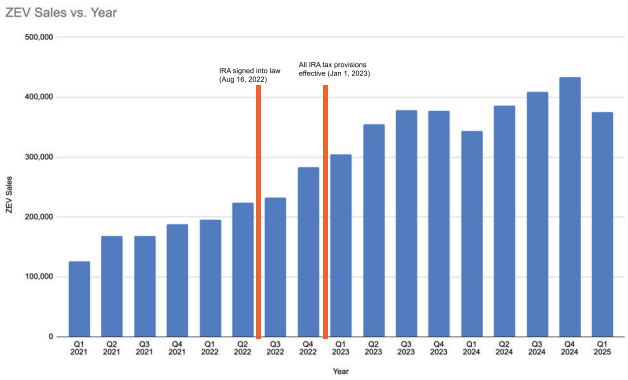

Figure 2: Growth of ZEVs from 2021 to 2025. This graph depicts the number of ZEV sales in each quarter of 2021, 2022, 2023, and 2024, and quarter 1 of 2025. It shows a steady rise in ZEVs and an increase following the IRA.[28]

EV and Clean Energy Investment:

Due to the IRA, many private companies invested extensively to produce EVs, batteries, and other clean energy elements, which has led to the creation of thousands of jobs, growth in local economies, and the U.S.'s lead in the sustainable energy transition. Despite the IRA being heavily opposed by Republicans, many of these major projects are located in Republican congressional districts, as indicated by Table 4. Before the IRA, EV investment was already higher in Republican-led areas, but the IRA enlarged the difference in EV investment between Republican-led districts and Democrat-led districts from $6.1 billion to $14.5 billion.[20] This trend may be primarily due to Republican districts representing more rural areas, which are particularly suitable for large-scale EV factories because of the availability and affordability of land, lower labor costs, and access to mineral resources. Regardless, this outcome suggests that federal EV policy especially boosts investment and economic prospects in Republican-majority areas.

Table 4: Republican congressional districts with major post-IRA clean energy manufacturing projects such as gigafactories, EV assembly facilities, battery recycling operations, and lithium extraction sites. This table indicates that many of these projects are located in Republican congressional districts, leading to increased investment and job creation.[20]

Congressional District	# Projects Underway	Planned jobs	Capital investment
Nevada, District 2	16	14,805	$14.3B
Missouri, District 1	1	2,000	$3.0B
South Carolina, District 1	4	4,660	$4.0B
Indiana, District 2	3	1,617	$3.5B
Ohio, District 15	3	3,550	$4.4B
Tennessee, District 7	4	944	$3.4B
Michigan, District 5	2	1,700	$2.6B
Georgia, District 1	4	12,640	$9.0B
South Carolina, District 4	7	1,440	$2.5B
Arkansas, District 4	3	100	$2.6B
Oklahoma, District 2	3	1,920	$2.2B

Employment:

The IRA is estimated to have generated ~109,026 jobs in the U.S. EV sector, and to result in a net job creation of 118,000+ jobs in the U.S. car, battery, and charging sectors from 2026 to 2030.[21, 22] This shows that federal EV policy further bolsters the economy by significantly increasing job creation.

Manufacturing:

The IRA also boosts domestic manufacturing and supply chains while limiting foreign influence through Section 30D New Clean Vehicle Tax Credit which requires that EVs be assembled in North America, comprise of battery parts mainly from North America, and use critical minerals that are made, handled, or recycled in North America or countries with free trade agreements (FTA) with the U.S. to be eligible for the federal tax credit. Cars are automatically ineligible if they use battery parts from a Foreign Entity of Concern (FEOC), which are any type of entity that is based in or owned by China, Iran, North Korea, or Russia. These provisions incentivize automakers to produce cars in the U.S. and use parts sourced domestically. Section 45X Advanced Manufacturing Production Tax Credit further promotes domestic production as it directly subsidizes the production of U.S. batteries and the mining, processing, and recycling of critical minerals.[18] According to Buckberg 2023, these two sections have backed over $85 billion in investment towards EV vehicle assembly and battery production facilities in the U.S., providing some 100,000 American jobs. This exemplifies how EV policy facilitates economic activity through increased domestic production.

Federal Policy Repeal Impact:

With President Trump back in office, the future of EV federal policy could be at stake. In addition to the Clean Ve-

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hicle Tax Credit being phased out after September 30, 2025, Trump has signaled doing away with federal regulations for vehicle emissions and government funding for EV charging infrastructure expansion. The following sections examine the potential impacts changes to government policies under the second Trump administration may have on the EV vehicle market and U.S. manufacturing.

EV Sales:

If EPA car emissions guidelines and the federal government's EV tax credits are repealed, EV sales could decrease 30% in 2027 and 40% in 2030 compared to if policies remained, as illustrated by Figure 3. Additionally, the projected percentage of new cars sold that are EVs could go from 18% to 13% in 2026 and 40% to 24% in 2030. In 2030, there could be 8.3 million fewer EVs or PHEVs in the U.S.[23] Another study estimates that Trump removing the EV tax credits will cut the portion of new cars in 2030 that are EVs from 48% to 42%, and save $168.5 billion from 2026-2035. However, it would decrease EV adoption and significantly increase emissions, with the 2030 baseline prediction going up 20.3 million metric tons.

Furthermore, ending the NEVI program would decrease the EV portion of new car sales by 3.2 percentage points, while removing all IRA and IIJA EV measures would lead to a decrease of 14 percentage points.[24] Elimination of clean air and vehicle emissions regulations, like Congress's recent repeal of California's vehicle emissions waiver that outlined the goal of all new car sales being zero-emission by 2035, will also drive down demand and manufacturing of EVs. Similarly, the removal of fines for car manufacturers that do not meet Corporate Average Fuel Economy (CAFE) standards will not only disincentivize automakers from producing more fuel-efficient vehicles, but ends an added revenue source for EV manufacturers who previously profited from selling zero-emission credits to manufacturers that did not meet guidelines.[25]

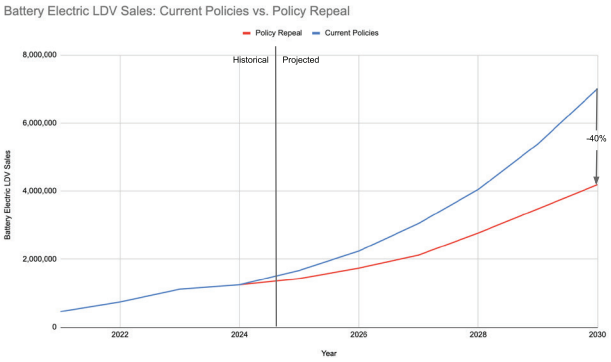

Figure 3: Projected EV Sales after Policy Repeal. This graph illustrates the number of battery electric LDV sales in a scenario with current policies in place and in a policy repeal scenario. By 2030, there are projected to be 40% less sales with a policy repeal scenario compared to current policies being in place.[23]

Tariffs:

Another policy that could impact EVs is tariffs. As of May 3, 2025, there is a 25% tariff on imported car parts, with possible future expansion of the tariff to cover other parts.[26] While parts coming from Canada and Mexico are exempt, these tariffs could impact prices of all cars in the U.S., though it is not clear if it would have unique repercussions for EVs specifically.[23] More research needs to be conducted, especially considering EVs' heavy reliance on components like batteries and critical minerals.

Manufacturing:

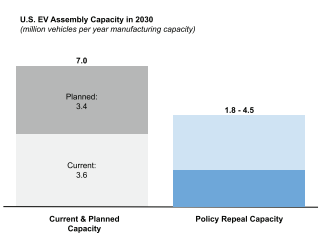

Figure 4: U.S. EV Assembly Capacity. This graph shows the amount of EV assembly capacity needed in 2030 if current policies remain in place and if policies are repealed. It illustrates that a policy repeal would lead to a significant reduction in the amount of EV assembly capacity needed.[23]

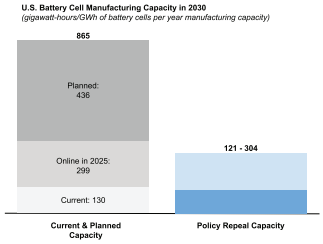

Figure 5: U.S. Battery Manufacturing Capacity. This graph shows battery cell manufacturing capacity needed in 2030 with current policies and a policy repeal. It illustrates that a policy repeal would lead to a significant reduction in the amount of battery cell manufacturing needed.[23]

U.S. EV manufacturing could significantly drop if EV tax credits are repealed. Figure 4 indicates that the scale of EV manufacturing needed with no EV tax credits is significantly less than the current and planned scale that accounts for EV tax credits being in place. In fact, the current capacity could even meet the capacity needed under a repeal scenario. This suggests that future expansion of manufacturing capacity currently being planned or constructed will be futile, and that some current manufacturing plants may close due to low demand. In fact, up to 100% of planned EV assembly facilities and 50% of current ones could be closed or called off. The repeal of EV tax credits would also lead to large excesses of battery cell manufacturing capacity, which would even render 2025 levels to be higher than needed, as is apparent from Figure 5. Of all battery cell manufacturing facilities currently or on track to be running by the end of 2025, an estimated 29% to 72% would not be needed and could shut down. All planned projects would likely be scrapped. This endangers the U.S.'s battery manufacturing boom, potentially halting it completely. Domestic production would be affected, including EV and battery component producers in the U.S. and critical minerals suppliers, processors, and recyclers, as there becomes a significant dip in demand for EVs and battery cells made in the U.S. It is clear that a repeal of federal EV credits and other changes in government policy would have large repercussions for the EV market and manufacturing in the U.S.

Private Sector Investment:

The government also significantly influences private investment in EV infrastructure. If it were to adopt an unfavorable EV policy, the future EV market could be unpredictable, which steers investors away for fear of not turning a profit. This uncertainty, along with the irreversible and flexible nature of investment, leads to the opportunity cost of the timing of in-

vestment, creating optionality for investors.[13] This could delay or even eliminate private sector investment. Thus, not only does the federal government impact whether or not incentives are repealed, but it can also create an unfavorable EV market that deters private investors. This phenomenon is especially true in rural areas with low competition and demand, resulting in inequality as areas with less EV demand continue to lag with no federal government help.

State Policies:

State policies may remain in place, which can partially alleviate the negative impacts of limited federal measures. In addition to tax rebates/incentives and charging infrastructure investment, there are several other policies that states have implemented. These include New Jersey's law for EVs to make up 85% of all light-duty vehicle (LDV) sales by 2040; Massachusetts', New York's, and California's mandates for zero-emissions vehicles (ZEVs) to make up 100% of all passenger LDV sales by 2035; and Washington's requirement for 100% of LDV sales to be ZEVs by 2030.[27] However, there are also several factors that affect state EV policies. The first is state politics, and which party is in power. Between 2010 and 2016, the Republican Party gained many seats in state elections. In 2010, 24 governors were Republican, and 14 states had Republican majorities in state legislatures, while in 2018, there were 33 Republican governors and 32 Republican-majority state legislatures. A political party can determine environmental ideology, which can affect the implementation and ratification of EV policies. Specifically, the Republican takeover of the House of Representatives in 2010, the Senate in 2014, and the presidency in 2017 led to more opposition surrounding environmental policies as the average League of Conservation Voters (LCV) score for the Senate and House dropped from 52 to 45 from 2010 to 2018.[14] (LCV scores are yearly gauges of how a state's congressional members vote on legislation relating to the environment.) Republican majorities can hinder the passage of EV policy, which impacts demand. Another factor is how environmentally friendly EVs are, measured by their net environmental benefit. A higher net environmental benefit means that EVs are more beneficial to the environment, which makes them more appealing, both for consumers and states. One factor that could turn states away from implementing beneficial policies or even start instituting disadvantageous measures is the economic impact of EVs. Fuel taxes are one such economic factor, as states rely on revenues generated from the tax to fund road infrastructure and other projects relating to transportation. EVs are predicted to lower fuel tax revenues by $200-$900 million by 2025.[14] This reduction may make states less inclined to incentivize EVs or even start charging annual EV fees to make up for losses.

Overall, the federal government has a large sway over EV sales due to its impact on private sector investment and financial support for subsidies and expansion. It can significantly boost manufacturing, employment, and investment into clean energy through its policies, as seen by the IRA. But a removal of such measures could be devastating for EV sales and manufacturing and would result in major environmental and economic consequences. However, states are affected by many other factors that make their decisions to implement EV policies less dependent on the federal political landscape, which could mean that states can take the lead in promoting EV adoption when the federal incentives are not there. Nonetheless, more research needs to be done on how EV sales can fluctuate due to different presidencies and federal political landscapes, and how this affects economic outlooks as the U.S. sees less manufacturing and job growth, and clean energy project investments dwindle. The U.S. could also be more behind on EV research and innovation when there is less incentive and demand for manufacturers to produce EVs. This is especially pertinent as many countries around the world, particularly China, are attempting to lead the EV sector with technological innovation and investment into research.

Conclusion

Tax incentives and rebates are the most common form of EV subsidies, and many studies have found them effective in increasing EVs, and to a larger extent than charging infrastructure investment. Tax incentives generally indicate higher EV per capita, with 9 of the top 17 states with the highest EVs per capita having some form of incentive. There have been many policies expanding EV charging infrastructure, most notably the NEVI program under the IIJA. States and private companies have also contributed. In addition to increasing charge ports, these measures also help create jobs and strengthen American competitiveness in the transportation and technological sectors. While all 50 states have charging stations, they are still primarily clustered in urban areas or places with more EVs. Most states that have high EV charging ports per capita also have high EVs per capita. However, the correlation is not as strong as it is not a linear relationship. Due to the charging infrastructure being more economically sustainable and uncertainties for investors, government funding for charging expansion is especially important. In addition to government subsidies, EVs are also impacted by time, awareness, knowledge, the number of models, electricity price, emission regulations, gas costs, and urban road use, and face barriers such as a lack of knowledge, high upfront prices, and low risk tolerance. Over time, as EVs' net environmental benefits increased and became more environmentally friendly, states became more inclined to support EV policies. Government subsidies encourage EVs and promote private sector investment, while mandates like renewable energy baselines, EV quotas, and EPA guidelines compel companies to prioritize sustainable efforts. As with the IRA, government policies can stimulate EV growth, create jobs, promote domestic manufacturing, and boost investment in Republican congressional districts. However, changes in government measures, such as tax credits and emission regulations repeals, can drastically decrease EV sales and manufacturing. Though state policies, which are dependent on state politics and the environmental and economic impact of EVs, can support EV adoption in the absence of federal policies.

This paper sets the foundation for further research regarding EV growth and policies. With correlations established between tax incentives and charging infrastructure with EVs per capita,

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future analysis can focus on the specifics behind each option to predict which is more effective and economically strategic in the long run. For example, studies can test how much incentives and charging infrastructure investment increase EVs per dollar spent to determine which yields the most significant outcomes at the lowest cost, or if a combination of both is needed. Further research can help to better understand the optimal balance between these strategies and develop predictions on the impact of various policy scenarios on EV adoption across different market conditions, levels of infrastructure, charging costs, and demographics. This paper can also guide government EV efforts. By pointing out the clear correlations, future policy can focus on increasing incentives and infrastructure in places where there is lower EV per capita. The in-depth analysis of the IRA can also guide future legislation and predictions on its impact in different sectors. This study's examination of the factors that influence state policies demonstrates how policies and EV adoption can fluctuate over time. The findings also contextualize the growth of EVs as a new form of technology. Some limitations of this paper are that the data and correlations do not account for states that do not have their own tax incentives but have other forms of incentives, such as charging rebates, reduced charging fees, free EV parking, and HOV lane access. These factors could be confounding variables, as they may result in those states having higher EVs per capita despite not having tax incentives. This can make the relationship appear not as strong because such data is not included.

While the future repeal of federal EV measures will almost certainly affect EV adoption, the exact quantifiable scale of its impact is yet to be known. What is certain is that through policies like the IRA, tax incentives/rebates, and charging infrastructure investment, the government has helped boost EV adoption over the years. In addition to driving consumer demand for EVs, it has expanded domestic manufacturing for batteries, EV assembly, and other components needed for EV production; created thousands of American jobs; boosted the economies of many regions in the U.S.; and heavily incentivized innovation, research, and development in the transportation sector. Advances in these areas will be at risk when federal EV policy is rolled back. To alleviate some of the impact, states with EV policies should keep them in place, and those without EV policies should adopt them. States might even consider increasing measures to fill in the gap, such as creating grant programs co-funded by private investors that will encourage companies to scale up infrastructure. Only time will reveal how accurate researchers' predictions are and how influential an absence of government policies can be.

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References

1. Dabush, Itay; Battat, Idan; Cohen, Chen; Lavee, Doron. "Navigating the Electric Vehicle Revolution: Optimal Subsidy Allocation for Electric Vehicles and Charging Infrastructure." *Journal of Cleaner Production*, vol. 486, Jan. 2025, p. 144586. *ScienceDirect*, https://doi.org/10.1016/j.jclepro.2024.144586.
2. US EPA, OAR. *Fast Facts on Transportation Greenhouse Gas Emissions*. 25 Aug. 2015, https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions.
3. Narassimhan, Easwaran; Johnson, Caley. "The Role of Demand-Side Incentives and Charging Infrastructure on Plug-in Electric Vehicle Adoption: Analysis of US States." *Environmental Research Letters*, vol. 13, no. 7, July 2018, p. 074032. Institute of Physics, https://doi.org/10.1088/1748-9326/aad0f8.
4. Aviles, Steven. "Tracking the Adoption of Electric Vehicles in the U.S." *ArcGIS Blog*, 15 Mar. 2024, https://www.esri.com/arcgis-blog/products/arcgis-living-atlas/decision-support/tracking-the-adoption-of-electric-vehicles-in-the-u-s.
5. U.S. Senate Committee on Environment and Public Works. *Bipartisan Infrastructure Law*. 2025, https://www.epw.senate.gov/public/index.cfm/bipartisan-infrastructure-law.
6. U.S. Department of Energy. *State Planning and Funding for Electric Vehicle Charging Infrastructure*. 2025, https://afdc.energy.gov/fuels/electricity-infrastructure-state-planning.
7. Pierce, Logan; Slowik, Peter. *Assessment of U.S. Electric Vehicle Charging Needs and Announced Deployments through 2032*. Mar. 2024.
8. U.S. Congress. *EV Charging Infrastructure: Frequently Asked Questions*. https://www.congress.gov/crs-product/R48351. Accessed 24 Aug. 2025.
9. BlueGreen Alliance. *How New and Expanded Federal Programs Can Deliver Good Jobs and Environmental Benefits*. 27 Jan. 2023, https://www.bluegreenalliance.org/site/a-user-guide-to-the-bipartisan-infrastructure-law-bil/.
10. Spiller, Beia; Russo, Suzanne. "Leveraging Investments in Electric Vehicle Charging Stations to Maximize Public Benefits." *Resources for the Future*, 7 Apr. 2025, https://www.resources.org/common-resources/leveraging-investments-in-electric-vehicle-charging-stations-to-maximize-public-benefits/.
11. Cain, Bruce E.; Gerber, Elisabeth R.; Lee, Nathan; Miller, Susan. "Investing in the Future of Mobility: The Role of US Local Governments in Building EV Infrastructure." *Energy Policy*, vol. 195, Dec. 2024, p. 114372. *ScienceDirect*, https://doi.org/10.1016/j.enpol.2024.114372.
12. Climate Central. *Electric Vehicle Charge Up*. 23 Apr. 2025, https://www.climatecentral.org/climate-matters/electric-vehicle-charge-up.
13. Dimanchev, Emil; Fleten, Stein-Erik; MacKenzie, Don; Korpås, Magnus. "Accelerating Electric Vehicle Charging Investments: A Real Options Approach to Policy Design." *Energy Policy*, vol. 181, Oct. 2023, p. 113703. *ScienceDirect*, https://doi.org/10.1016/j.enpol.2023.113703.
14. Hayashida, Sherilyn; La Croix, Sumner; Coffman, Makena. "Understanding Changes in Electric Vehicle Policies in the U.S. States, 2010–2018." *Transport Policy*, vol. 103, Mar. 2021, pp. 211–23. *ScienceDirect*, https://doi.org/10.1016/j.tranpol.2021.01.001.
15. Plug in America. "Federal EV Policy Timeline & Tracker." *Plug In America*, 2025, https://pluginamerica.org/policy/federal-ev-policy-timeline/.
16. Soltani-Sobh, Ali; Heaslip, Kevin; Stevanovic, Aleksandar; Bosworth, Ryan; Radivojevic, Danilo. "Analysis of the Electric Vehicles Adoption over the United States." *Transportation Research*

Procedia, vol. 22, Jan. 2017, pp. 203–12. *ScienceDirect*, https://doi.org/10.1016/j.trpro.2017.03.027.
17. Nwokolo, Samuel. "From Policy to Practice: Evaluating the Role of Private-Sector Champions Like Elon Musk in Shaping Trump's 2.0 Climate Agenda." *Trends in Renewable Energy*, vol. 11, no. 1, Jan. 2025, pp. 122–54. *Crossref*, https://doi.org/10.17737/tre.2025.11.1.00190.
18. Buckberg, Elaine. *Clean Vehicle Tax Credit: The New Industrial Policy and Its Impact | Stanford Institute for Economic Policy Research (SIEPR)*. Aug. 2023, https://siepr.stanford.edu/publications/policy-brief/clean-vehicle-tax-credit-new-industrial-policy-and-its-impact.
19. Bassett, Luke; Sun, Chris. "After Just Three Months, the Inflation Reduction Act (IRA) Has Saved Americans an Estimated $600 Million on Clean Vehicle Purchases at the Time of Sale." *U.S. Department of the Treasury*, 3 May 2024, https://home.treasury.gov/news/featured-stories/after-just-three-months-the-inflation-reduction-act-ira-has-saved-americans-an-estimated-600-million-on-clean-vehicle-purchases-at-the-time-of-sale.
20. Shivdasani, Janina; Zablotska, Yelyzaveta. "The Clean Energy Manufacturing Landscape in Republican-Led Congressional Districts: Investment, Jobs, and Industrial Growth." *The Big Green Machine*, 20 Apr. 2025, https://drive.google.com/file/u/0/d/1I4QlNFzGGiUcOafrnICTrPxjwZO0bUtt/view?usp=embed_facebook.
21. Bui, Anh; Pierce, Logan; Slowik, Peter; Searle, Stephanie; Orvis, Robbie. *How the Inflation Reduction Act Is Driving U.S. Job Growth across the Electric Vehicle Industry*. Apr. 2025, https://theicct.org/wp-content/uploads/2025/04/ID-344-%E2%80%93-IRA-jobs_report_final.pdf
22. *Environmental Defense Fund. U.S. Electric Vehicle Manufacturing Investments and Jobs: Characterizing the Impacts of the Inflation Reduction Act after 2 Years*. 20 Aug. 2024, https://library.edf.org/AssetLink/07l26xtk0xv2bw713c64na3g5g1kmbb7.pdf?_gl=1*1s5mecw*_gcl_au*MTQwNDk5NjI0Ni4xNzU1MTgzMjIz*_ga*NDYzMjU1MTkuMTc1NTE4MzIyMw..*_ga_2B3856Y9QW*czE3NTUxODMyMjMkbzEkZzEkdDE3NTUxODUyOTckajM4JGwwJGgw.
23. Jenkins, Jesse. *Potential Impacts of Electric Vehicle Tax Credit Repeal on the US Vehicle Market and Manufacturing*. REPEAT Project, 18 Mar. 2025. *Zenodo*, https://doi.org/10.5281/zenodo.15047921.
24. Buckberg, Elaine; Cole, Cassandra. "Quantifying Trump's Impacts on EV Adoption." *The Salata Institute*, 18 Mar. 2025, https://salatainstitute.harvard.edu/quantifying-trumps-impacts-on-ev-adoption/.
25. Turner, Jay; Zablotska, Yelyzaveta; Yang, Emily. "Post-Trump Changes | US Clean Energy Manufacturing Investment Update: Trump + 6 Months." *The Big Green Machine*, 29 July 2025, https://www.the-big-green-machine.com/post-trump-shifts.
26. U.S. Congress. *Section 232 Automotive Tariffs: Issues for Congress*. https://www.congress.gov/crs-product/IN12545. Accessed 24 Aug. 2025.
27. International Energy Agency. "Global EV Policy Explorer." *IEA*, 14 May 2025, https://www.iea.org/data-and-statistics/data-tools/global-ev-policy-explorer.
28. Alliance for Automotive Information. "Electric-Vehicle-Sales-Dashboard." *Www.autosinnovate.org*, 2025, www.autosinnovate.org/EVDashboard.
29. Conte, Niccolò. "Interactive: EV Charging Stations Across the U.S. Mapped." *Elements by Visual Capitalist*, 22 Oct. 2022, https://elements.visualcapitalist.com/interactive-ev-charging-stations-across-the-u-s-mapped/.
30. Holland, Stephen P.; Mansur, Erin T; Muller, Nicholas Z; Yates, Andrew J. "Are There Environmental Benefits from Driving Electric Vehicles? The Importance of Local Factors." *American Economic Review*, vol. 106, no. 12, Dec. 2016, pp. 3700–29. *DOI.org (Crossref)*, https://doi.org/10.1257/aer.20150897.
31. Holland, Stephen P.; Mansur, Erin T.; Muller, Nicholas Z.; Yates, Andrew J. "Decompositions and Policy Consequences of an Extraordinary Decline in Air Pollution from Electricity Generation." *American Economic Journal: Economic Policy*, vol. 12, no. 4, Nov. 2020, pp. 244–74. www.aeaweb.org, https://doi.org/10.1257/pol.20190390.
32. Huang, Xingjun; Lin, Yun; Zhou, Fuli; Lim, Ming K.; Chen, Simin. "Agent-Based Modelling for Market Acceptance of Electric Vehicles: Evidence from China." *Sustainable Production and Consumption*, vol. 28, Oct. 2021, pp. 206–17. ScienceDirect, https://doi.org/10.1016/j.spc.2021.04.007.
33. Ledna, Catherine; Muratori, Matteo; Brooker, Aaron; Wood, Eric; Greene, David. "How to Support EV Adoption: Tradeoffs between Charging Infrastructure Investments and Vehicle Subsidies in California." *Energy Policy*, vol. 165, June 2022, p. 112931. *ScienceDirect*, https://doi.org/10.1016/j.enpol.2022.112931.
34. Sinton, Jonathon; Cervini, Gaia; Gkritza, Konstantina; Labi, Samuel; Song, Ziqi. "Examining Electric Vehicle Adoption at the Postal Code Level in US States." *Transportation Research Part D: Transport and Environment*, vol. 127, Feb. 2024, p. 104068. *ScienceDirect*, https://doi.org/10.1016/j.trd.2024.104068.
35. Sintov, Nicole D.; Abou-Ghalioum; Victoria; White, Lee V. "The Partisan Politics of Low-Carbon Transport: Why Democrats Are More Likely to Adopt Electric Vehicles than Republicans in the United States." *Energy Research & Social Science*, vol. 68, Oct. 2020, p. 101576. *ScienceDirect*, https://doi.org/10.1016/j.erss.2020.101576.
36. Wang, Ning; Tang, Linhao; Zhang, Wenjian; Guo, Jiahui. "How to Face the Challenges Caused by the Abolishment of Subsidies for Electric Vehicles in China?" *Energy*, vol. 166, Jan. 2019, pp. 359–72. *ScienceDirect*, https://doi.org/10.1016/j.energy.2018.10.006.

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RESEARCH ARTICLE

From Vague Claims to Transparency: Confronting Stealth Marketing Practices on Social Media in Japan

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ABSTRACT: With the rapid development of technology and the widespread use of social media, the line between paid promotions and genuine reviews has become exceedingly vague. Stealth marketing is a market strategy that promotes a product to consumers without them realizing that they are being targeted. This research paper discusses the issue and current regulations of stealth marketing, specifically for beauty and health-related products, highlighting the importance of proposing a potential solution for consumers to perceive deception within misleading advertisements on social media such as TikTok and Instagram. It is hypothesized that most consumers are unaware of the existence of stealth marketing and are unable to distinguish between authentic reviews and illegally paid promotions without proper disclosure. Data collection was carried out from an interview on: 1) samples with histories of purchasing a product online through misleading promotion, and 2) TikTok influencers that explicitly oppose stealth marketing products. In addition, prior research reveals that authenticity and accountability in online promotion are demanded by consumers; hence, this research proposes a solution: a dedicated platform where products are promoted with verified transparency.

KEYWORDS: Social and Behavioral Science, Sociology and Social Psychology, Social Media, Stealth Marketing, Consumer Trust.

Introduction

In this digital era, social media has significantly impacted the marketing style in businesses. Studies highlight the crucial role of social media, including trendiness, customization, and electronic word-of-mouth (eWOM) in shaping online buying decisions. It is indicated that comments or reviews shared on social media or e-commerce sites are effective on consumer actions, accounting for 59.1% of the variation in online purchase intention.[1]

Correspondingly, technological advancement has been contributing significantly to the prevalence of false advertisements, particularly on social media platforms favored by teenagers. AI-generated advertisements demonstrate flexibility and customization for personalized content, features that contribute to the potential customer deception through undisclosed promotions. Vogue recently astonished the public with new Guess commercials showcasing AI-generated image models, among the over 1,000 AI-generated advertisements accessible online. "Ads" labelling is implemented barely fifty percent of the time to deliberately engage consumers favorably, thus attracting them without their awareness.[2] On a global scale, the Japanese market has been significantly impacted by "*stealth marketing*" practices, a marketing strategy that promotes a product to consumers with deceptive promotions and fraudulent advertisements.

Kobayashi's research examines the recent rise of stealth marketing on social media, highlighting the controversial practice of "Sakura," where company employees pose as consumers and post favorable reviews to attract potential customers.[3] The issue of stealth marketing presents significant risks in online information dissemination, given the widespread adoption of technology and the decreasing age at which individuals engage with social media platforms. This underscores the necessity of developing critical skills and knowledge to perceive accurate information. Without such competencies, many youths may remain vulnerable to misinformation and unable to develop independent judgment. However, many adolescents remain unaware of the persuasive intent behind influencer content and therefore often fail to recognize sponsored videos as advertising.[4] It is especially relevant in Japan, where social media use among teenagers has expanded considerably, despite limited educational exposure to advertising risks. Okayama's research indicates that explanatory manuals show advertising-related content to account for approximately 25% of instructional material in elementary school, but only 1.8% in junior high school and 2.9% at the high school level. This pattern suggests that formal exposure to advertising education decreases during adolescence, precisely when students become more exposed to social media.[5]

With respect to products, premium-priced goods are generally less affected by inauthentic advertising, as such companies maintain strict online branding policies that safeguard their reputations. In contrast, less differentiated or lower-priced products are more correlated to consumers' income levels, as individuals with limited purchasing power may be unable to afford high-end alternatives and instead resort to products with lower reputations. Moreover, luxury brands are generally less inclined to rely on stealth marketing because their reputation and perceived authenticity are central to consumer trust, whereas mass market brands, facing lower product dif-

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ferentiation, often resort to such tactics more frequently.[6] This highlights that ethical lapse damage in luxury brands is more severe, incentivizing them to maintain transparent practices.

Based on a survey incorporating twelve distinct scenarios, Yamaguchi clarified that sponsorship disclosure can enhance consumer favorability, contrary to the conclusions of many previous studies. This finding indicates that consumers have developed heightened awareness and reduced tolerance for stealth marketing, perceiving it as an unacceptable practice.[7] For instance, some posts embed links that direct consumers to external websites, a strategy known as "affiliation." This is commonly accompanied by comment sections containing exclusively positive feedback, suggesting that employees may be impersonating consumers.

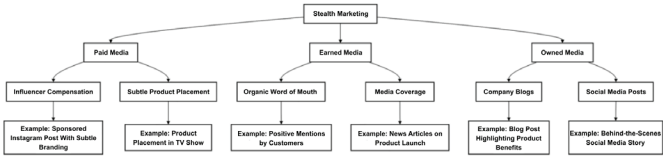

Figure 1: Subsegments within stealth marketing. The figure highlights the increasing complexity of common stealth marketing strategies used on digital platforms. "Stealth Marketing on Social Media." Springer Texts in Business and Economics, https://doi.org/10.1007/978-3-031-69518-6_16. 2024.

Figure 1 presents various examples of stealth marketing across three media types: paid, earned, and owned.[8] Each tactic ultimately aims to generate buzz subtly without consumers recognizing it, while utilizing resources and time efficiently. In general, stealth marketing refers to promoting products in ways that conceal persuasive intent.[9] However, in this study, the focus is limited to online marketing where product promotions are undisclosed.

Therefore, stealth marketing misleads consumers, particularly the younger demographic, who struggle to differentiate between truthful and false claims, resulting in their purchase of overpriced products. To address this issue, it is hypothesized that a dedicated platform offering authentic feedback on health and beauty products would enable informed purchasing decisions by incorporating verification methods such as receipt submission, proof of product use, and expert medical advice. Consequently, this may increase trust in product reviews, reduce post-purchase dissatisfaction, and diminish the influence of stealth marketing on social media.

Methods

Primary Research:

This primary qualitative research aims to explore how stealth marketing practices on social media platforms affect perceptions of trust and ethical responsibility among the key stakeholders: consumers and influencers. The sample techniques employed were judgmental sampling, which targeted seeking people who have either purchased the product that was advertised by the stealth marketing method or influencers on TikTok who have created certain content addressing stealth marketing to raise awareness and avoid deception. Emails and direct messages were sent via TikTok and Instagram to 19 individuals, 7 consumers, and 12 influencers; among those, interviews were conducted with 3 consumers and 5 influencers.

The demographic consists of Japanese residents, with a broad age range from teenagers to mid-30s, where influencers are predominantly adults and customers are primarily teenagers. Four out of five influencers obtained a Cosmetic Ingredient Licensing, a certification conferred by the Seibun Kentei Association in Japan, which signifies their expertise in the beauty industry.

Table 1 shows two different collections of interview questions, each of seven questions, were presented to consumers and influencers, in addition to extra follow-up questions when responses required clarity:

Table 1: Interview questions. These questions were used to obtain detailed qualitative insights aligned with the research topic.

For consumers	For influencers
1. We think that stealth marketing and misleading promotions on social media are a frustration for consumers like yourself. Is this true, and what are your pain points?	1. With stealth marketing becoming more common on TikTok, how do you feel this is affecting the relationship between creators like you and your audiences?
2. What are your biggest challenges when trying to purchase products online?	2. In your view, what contributes to the widespread use of stealth marketing in the health and beauty industry?
3. How do you determine that the product is high quality and the seller is legitimate?	3. How did you first encounter stealth marketing and what influenced you to speak out against it, even though it could be financially rewarding?
4. Were there any shortcomings of the solution that you used?	4. Have you ever received an offer that emphasized you not to disclose sponsorship clearly? If so, how did you respond?
5. When buying a product based on online content, what matters the most to you? (Price, trust, influencer credibility, results etc.)	5. Is there anything you are doing to maintain trust with your audience? If so, what do you focus on?
6. Have you ever been a victim of stealth marketing? If so, what did you buy?	6. Are there specific red flags when evaluating a brand's credibility before accepting a promotion?
7. On a scale of 0 to 5, how likely would you be to use an app that helps you verify whether a post was paid to create untruthful content or not?	7. On a scale of 0 to 5, how likely would you be using an app that allows influencers like yourself to prove the honesty and trustworthiness of your promotions to your followers?

Secondary Research:

Secondary data were obtained from academic journals addressing the themes of "stealth marketing," "social media," and "cosmetics," in addition to the associated ethical and legal considerations. Some of the sources were derived from Japanese journal articles to specifically address the research question, to assess the prevalence and awareness of stealth marketing, and to synthesize findings from prior scholarly studies. Through large-scale research and specific quantitative data, which are not attainable through primary research, this approach facilitates a comprehensive understanding of the current situation, underlying causes, and representative examples of stealth marketing on social media in Japan, as well as its consequent influence on individual consumers' consumption intentions.

The majority of relevant sources were restricted to publications from the past five to six years in order to mitigate the use of outdated information. However, obtaining detailed case studies specifically addressing online deception within the Japanese context proved to be challenging; consequently, the data may not be directly applicable to the precise objectives of this research.

Results

Primary Data:

[Consumers]

In general, consumers demonstrated similar trends in their responses, albeit there were only a small number, with three participants, and their wants and needs were anticipated, alongside the expectation to provide online guidance, distinguishing between truthful content and paid promotions intended to deceive customers.

Figure 2: Consumer satisfaction with online advertisements. Indicates varying levels of consumer satisfaction, highlighting differences in perceived satisfaction among consumers.

Figure 2 illustrates consumer satisfaction with online advertisements based on survey responses to question one, analyzed based on consumers' tone and answers; a smiley face represents high satisfaction, while a frowning face indicates high dissatisfaction. This sentiment analysis shows that consumers generally view online advertisements negatively, largely due to brands intentionally implementing deceptive practices to increase sales. The feedback highly emphasized their dissatisfaction, with one responding that "Frustration is an understatement. The main pain points are the time and resources spent trying to determine what is real and what is not."

Participants consistently relied on multiple sources to identify trustworthy brands, including WOM recommendations, product reviews, and company profiles. This suggests that consumers actively seek verification when making purchasing decisions. However, several shortcomings of the methods were the prevalence of fake reviews generated by bots or paid influencers, and the shortage of peer recommendations that limit the effectiveness of WOM verification.

Overall, despite participants actively attempting to assess product reliability, they are still exposed to deceptive content. Therefore, this highlights the demand for a platform that could enhance informed decision-making, improve consumer trust, and mitigate the impact of stealth marketing within the health and beauty industry.

[Influencers]:

With a participant group of five, the responses demonstrated consistent patterns. Participants emphasized that, despite the fact that content is neither promotional nor sponsored, users frequently show skepticism about whether their videos are stealth marketing or not. Consequently, the increasing caution among teenagers presents both advantages and disadvantages, as they continue to have difficulties in effectively distinguishing authentic from counterfeit content, given that social media is a primary information source and provides a wide range of advice for reference.

Figure 3 illustrates several underlying factors that lead to the prevalent cases of stealth marketing in the beauty industry. Notable responses are "it is a tactic that exploits everyday concerns and insecurities", "Promoted products are often categorized as necessities, thereby increasing their perceived indispensability and enabling them to reach a broader target audience." Others additionally responded that: (1) such products are easily accessible to a wide age range of consumers; (2) outcomes are difficult to visualize as results vary between individuals, encouraging the creation of buzz to attract broad audience attention; (3) WOM and reviews spread rapidly, making it challenging to determine whether a message constitutes advertising; and (4) from a firm's perspective, stealth marketing can be more cost-effective and efficient than conventional advertising. In fact, recent marketing strategies indicate a shift from paying influencers a fixed rate per post toward performance-based (pay-per-sale) arrangements, which incentivize influencers to frequently use exaggerated expressions to maximize views and sales.

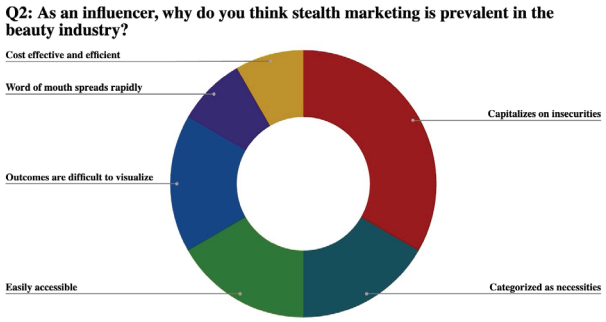

Figure 3: Interview responses from influencers to question two, 'In your view, what contributes to the widespread use of stealth marketing in the beauty and health industry?' Responses indicate several perceived causes of stealth marketing issues, highlighting concerns raised by consumers.

The primary motivator for their opposition to stealth marketing was their personal experience as victims of misleading promotions, which led to the purchase of products advertised through stealth marketing strategies. After acquiring knowledge regarding such illegal practices and the information on ingredients in certain cosmetic products, they recognized that numerous videos contain fabricated information designed to attract customers and increase financial gain. Their personal principles are such that "money cannot buy trust," "money earned through deceiving customers cannot be used without regret," and "having once been a victim of stealth marketing, I do not wish other consumers to repeat my experience; I want to convey messages that would have protected my past self."

Most participants reported having been approached by businesses that requested they refrain from disclosing promotional content or from including a #PR (Public Relations) tag. All participants stated that they either rejected such offers or ignored the messages entirely. Before declining, they informed the companies that failure to provide clear disclosure, or providing ambiguous disclosure, is illegal to prevent further cases of stealth marketing promotion. However, in cases where the companies were foreign, which are mostly based in Korea, they often insisted that such laws did not apply within their jurisdiction.

Moreover, they clarified that maintaining sincerity and honesty in reviewing content has become essential for their identity as influencers. Demonstrating credibility by acquiring certifi-

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cation in Cosmetic Ingredient Licensing and testing products for a specific period before introducing them publicly suggests that authenticity is to respond to audiences with transparency. Furthermore, by limiting the frequency of promotional posts, participants attempt to make sponsorship more visible, implying: "I am being paid to introduce these products, but I have thoroughly verified them beforehand."

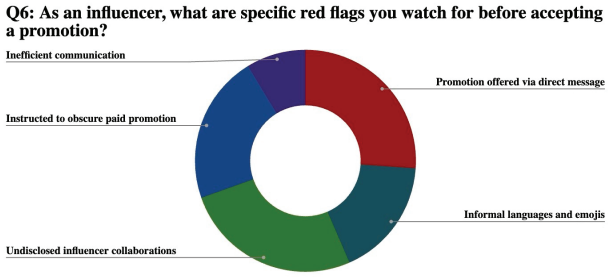

Figure 4: Interview responses from influencers to question six, 'Are there specific red flags you watch for when evaluating a brand's trustworthiness before accepting a promotion?' Results indicate that specific common features are representative of firms engaged in stealth marketing.

Figure 4 indicates that companies initiating offers via TikTok direct messages, despite explicit instructions on their profiles stating, "For work inquiries, contact via email," are most perceived as red flags. Thus, their responses included investigating the company's prior promotional activities with other influencers and examining whether the content or images are identical in order to determine whether the company is engaging in stealth marketing or employing a performance-based compensation model.

However, there was an outlier who promoted a product well known within the industry for employing stealth marketing strategies. His purpose was to examine the societal impact if a product widely associated with stealth marketing was instead promoted with honesty and sincerity. To mitigate the risk of producing a misleading advertisement, honest reviews and accurate product ingredient information were included. Although the positive effects of products were introduced, as there was a disclosure with #PR, consumer purchases declined. Thus, this act concluded that companies employing stealth marketing methods primarily focus on financial gain and attracting customers with appealing promotional lines rather than fostering genuine relationships with consumers.

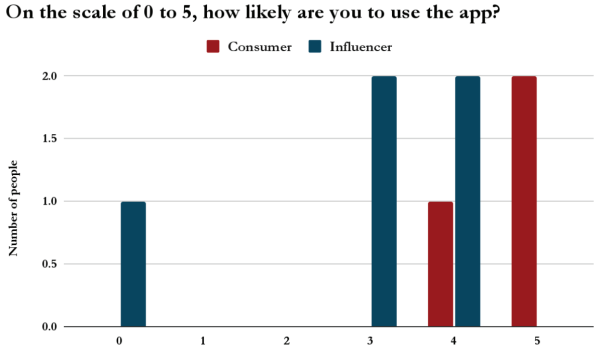

Figure 5: Interview answers to question seven from consumers and influencers. Participants' feedback reflected a moderately favorable impression of the app.

Figure 5 illustrates the responses to question seven on the possibility of consumers and influencers adopting the potential app developed to tackle stealth marketing on social media. Despite most responses being favorable to neutral, one outlier claimed that such an app may not be feasible due to possible deficiencies in trust and accuracy.

Therefore, the convergence of primary data emphasized the significance of the ongoing stealth marketing issue on social media from both consumer and influencer perspectives, while the divergence of opinions concerning the app's potential adoption prompted discussion on several possible solutions to address it.

Secondary Data:

The analysis of prior research and case studies indicated an insufficient focus on stealth marketing within the beauty and health industry and demonstrated the limitations of existing solutions in effectively addressing the issue.

The regulations across different countries are that developed economies, such as the United States, the United Kingdom, and Germany, possess robust advertising transparency laws despite certain enforcement gaps. In contrast, emerging economies such as India, Brazil, and South Africa experience regulatory delays, largely attributable to weaker enforcement mechanisms and limited consumer awareness.[10] In addition, the study proposed a solution aimed at empowering consumer initiatives with media platforms and awareness campaigns, thereby facilitating more effective communication between consumers and regulatory authorities.

On 1 October 2023, the Japanese Cabinet Office issued Notification No. 19 of 2023 pursuant to Article 5, Item 3 of the Act. This stipulates that "representations made by an entrepreneur regarding transactions for its goods and services which would be difficult for ordinary consumers to recognize as such representations" are subject to regulation as stealth marketing.[11] In addition, the Consumer Affairs Agency establishes guidelines under Article 5, Item 3 of the Act against Unjustifiable Premiums and Misleading Representations, to protect consumers and prohibit business operators from engaging in transactions that do not clearly disclose their origin, thereby misleading consumers for financial gain.[12]

Regardless of these regulations, stealth marketing in the cosmetics industry poses urgent challenges that extend beyond simple consumer dissatisfaction. Alnazzawi *et al.*'s research examined the FakeAds corpus, which was annotated using AMT and manual inspection according to guidelines incorporating both account-related and lexical or syntactic features.[13] Annotation was conducted at two levels: first, at the tweet level, where each post was classified as real or fake; and second, at the word level, where tweets were categorized by market segment. Analysis of the dataset revealed that cosmetics accounted for 83% of all annotated product mentions within the 5,000 tweets, in which merely 55.7% were associated with real information.

Nonetheless, over 80% of Japanese consumers occasionally experience difficulty in making rational purchasing decisions within digital environments. It is identified that age is the most significant factor contributing to their sense of vulnerability in

commercial transactions, followed by economic conditions and social experience.[14] This issue is especially common in the cosmetics industry, where social media advertisements are frequently aimed at younger audiences and designed to promote products relevant to their daily lives and interests. Moreover, research indicates that societal pressures to preserve a youthful appearance contribute to increased demand for anti-aging products, potentially incentivizing companies to adopt exaggerated or misleading marketing strategies to appeal to consumers.[15]

In contrast, Natsir *et al.*'s research proved that stealth marketing in cosmetics successfully increases buying interest; buying interest scores dropped after viewers learned the video was a promotion.[16] However, according to the hypothesis, such behavior is regarded as a natural human tendency; when a communication is explicitly identified as promotional, the content is often perceived as a biased opinion, thereby diminishing consumers' willingness to purchase the product.

Consequently, stealth marketing raises three primary ethical concerns: deception, intrusion, and the exploitation of social relationships.[17] The ethical analysis presented that misleading audiences into perceiving a message as unbiased when it is commercial, interfering in consumers' personal digital spaces without informed consent, and exploiting the personal trust between influencers and followers for commercial advantage without transparency result in adverse social consequences, despite potential short-term advantages for brands.

■ Findings

Various measures have been implemented to address this issue, one of which is the use of filtered review systems employed by platforms such as Google and Yelp. These systems combine automated algorithms with human moderation to identify and suppress fraudulent reviews, thus promoting the visibility of more trustworthy, content-based feedback. Google's guidelines explicitly prohibit misinformation or the misleading of consumers through false representations regarding the quality or characteristics of goods and services.[18] Therefore, these services are regarded as indirect competitors, offering different features but fulfilling the same needs for the same target customer base.

Al-Ramahi's research sought to establish a systematic, automated technique for identifying insincere content on social media, thereby enhancing the quality and reliability of user-generated content. It suggested that a combination of automated filtering with a highly advanced model and human moderation is optimal for performance.[19] Likewise, eBay has implemented a "Verified Purchase" tag on buyer feedback to enhance transparency for customers by clearly indicating authentic reviews, thereby encouraging the platform's reliability.[20] Figure 6 illustrates an example of the "Verified Purchase" tag as it appears alongside buyer feedback.[21]

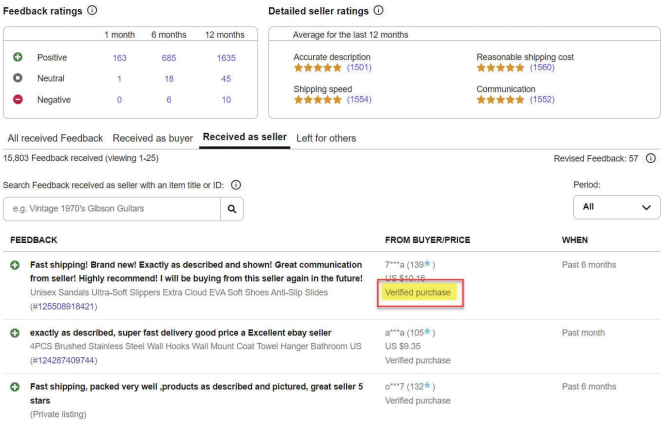

Figure 6: Feedback page on eBay website with the "Verified purchase" tag. This provides an immediate distinction between verified and unverified purchases. "eBay Feedback Shows Verified Purchases - But What Does Verified Mean?" Morton, 2024. https://www.valueaddedresource.net/ebay-feedback-verified-purchase/.

Alternatively, Japan has the largest cosmetic review website named '@cosme', which is highly recognized by users who seek honest and reliable reviews.[22] It provides a space where products are evaluated based on real-world use by a community of beauty enthusiasts.

Figure 7 shows the official website for @cosme, the largest and most trusted beauty product review platform in Japan, which features over 22 million user reviews.[23] Nevertheless, it may be subjected to popularity bias, whereby established or trending brands dominate rankings and limit visibility for smaller brand products. In addition, partnerships with the platform may involve sponsored placements or advertising that influence ranking outcomes. Although @cosme contains extensive user reviews, limited expert verification of product claims or ingredients raises questions regarding the overall reliability of the information provided.

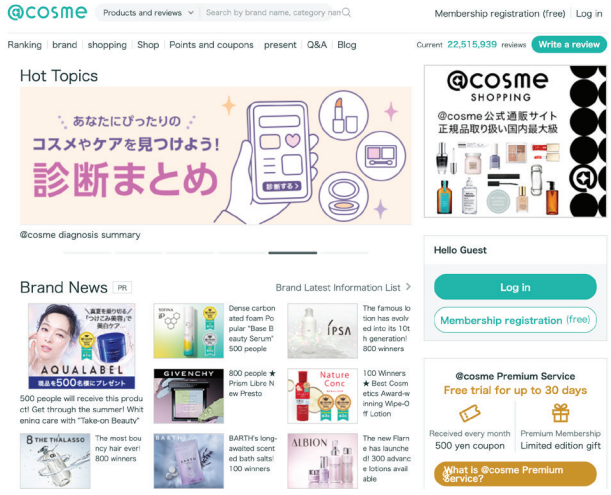

Figure 7: Official @cosme Website, https://www.cosme.net/. The platform provides cosmetic information and user reviews to support genuine evaluations.

■ Discussion

Limitations:

This research aimed to address the growing trend of stealth marketing on social media platforms, specifically on TikTok, and proposed strategies for its improvement. It was hypoth-

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esized that the development of a transparent and precise application would enhance the trust and interaction among consumers, influencers, and brands.

However, interviews were conducted with parties opposing stealth marketing, which leads to confirmation bias that only produces responses aligned with the research focus. To eliminate any biases, future research could have diversified samples of groups who have employed stealth marketing strategies, as well as groups who are not aware of such practices. In addition, the primary data were derived from a small set of three consumers and five influencers, which weakens the generalizability of the results obtained. Finally, this research is limited to the Japanese context; thus, literature reviews and proposed solutions are primarily applicable only within Japan. Consequently, future studies should employ larger samples to enable more robust testing of populations relevant to stealth marketing and examine how these findings may be adapted in cross-cultural comparisons, with advanced quantitative testing of consumer awareness.

Implications:

The interviews with potential users suggest that the proposed service is likely to benefit, thereby offering substantial support for the underlying hypothesis. The findings reveal that consumers remain particularly vulnerable in digital purchasing environments, where rapid developments in AI technologies, the widespread circulation of ambiguous content, and the growing use of financial incentives create additional barriers to making rational and informed decisions.

Survey data further indicate that consumer skepticism toward online product information is strongly associated with concerns over deceptive promotional practices.[24] As illustrated in Figure 8, one of the prominent factors contributing to diminished trust in online reviews is the suspicion that employees are posing as customers to produce positive evaluations; an activity that constitutes a form of stealth marketing. Reducing these sources of doubt, therefore, represents a key objective of the proposed platform and aligns with further efforts to improve transparency and accountability within the beauty and health industry.

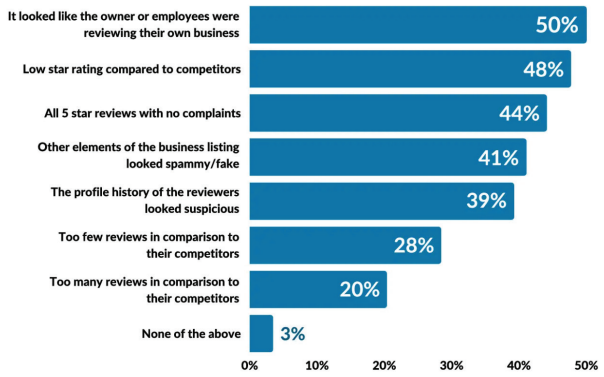

Figure 8: Survey Answers Moz, "What makes you lose trust in a business's reviews?" This highlights the attributable characteristics that may undermine consumer trust in a brand. https://moz.com/local-business-review-survey-report/habits-of-review-readers.

Solutions:

The findings from primary and secondary data indicate that stealth marketing in Japan's beauty and health sector predominantly impacts Generation Z consumers who experience difficulties in distinguishing authentic from deceptive information. Particularly, consumers with moderate or unstable incomes are more inclined towards buying affordable products marketed through stealth practices, thus falling into such deceptive practices. Correspondingly, participants consistently emphasized that it is crucial to explicitly demonstrate transparency, sincerity, and credibility in influencer reviews on social media: therefore, manipulated or exaggerated content breaks trust and misleads consumers utterly.

Although the study explored technological interventions as a potential outcome, participants' responses revealed mixed opinions regarding their feasibility of implementation, such as potential resistance from industry and effectiveness. Some influencers suggested that, along with transparency, efforts should focus on establishing consumers' critical judgment with the long-term goal of reducing the prevalence of marketing strategies that exploit vulnerable youths. While technological solutions offer structured guidance, they are unable to fully replace consumer education, as overreliance on technology may undermine the development of critical thinking and independent decision-making skills.

To apply these findings, the platform may offer verified product information, expert advice, and monitored influencer content. This could improve transparency in review and provide accessible educational resources, which help consumers make informed purchasing decisions and gradually establish their critical judgment. However, this proposed application is a solution design rather than direct testing; hence, future research could explore the feasibility and adoption of such a platform, as well as its effectiveness in combination with educational support, which strengthens consumer literacy and resilience against stealth marketing practices.

■ Conclusion

This study highlights the potential solution that assists consumers in distinguishing authentic and misleading reviews of health and beauty products, fostering long-term trust among brands, influencers, and consumers. Incorporating an educational component would further enhance consumers' critical judgment, helping them recognize paid or deceptive content and make informed decisions, while also encouraging more sustainable consumption patterns. The service could feature a model similar to ChatGPT, allowing users to ask through a chatbot-style Q&A system, which would provide essential product reviews and relevant influencer feedback.

Along with this, Japanese regulators could collaborate with such social media to establish strict advertising standards, monitor compliance, and maintain transparency in online advertising. This could further strengthen consumer protection, support ethical influencer practices, and mitigate the risk of stealth marketing.

To protect consumers in the beauty industry with reliable information, it is essential to combat deceptive practices such as stealth marketing and strengthen ethical standards among influencers on social media. Nevertheless, the issue may also be relevant to other countries, and its implications could extend beyond the Japanese context, but to further cross-cultural research.

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■ References

1. Chuah, S.-C. (PDF) Impact of Social Media Marketing Activities on Online Purchase Intention for the Cosmetic Industry in Malaysia. https://www.researchgate.net/publication/370768511_Impact_of_Social_Media_Marketing_Activities_on_Online_Purchase_Intention_for_the_Cosmetic_Industry_in_Malaysia .
2. Krings, M. Ai in Your Ads. https://news.ku.edu/news/article/2023/02/14/study-finds-only-about-half-ai-generated-ads-labeled-unknowingly-driving-consumer.
3. Kobayashi, J.; Ikeda, K. Yearly Archive: 2023, A Study on Stealth Marketing in Japan. https://ijrm.humanjournals.com/2023/.
4. Dam, S. van; Reijmersdal, E. van. Cyberpsychology: Journal of Psychosocial Research on Cyberspace, Insights in Adolescents' Advertising Literacy, Perceptions and Responses Regarding Sponsored Influencer Videos and Disclosures. https://cyberpsychology.eu/article/view/11976.
5. 学校広告教育についての研究ー小・中・高校生の意識分析を中心にー. https://www.jstage.jst.go.jp/article/jjace/17/0/17_17-14/_article/-char/ja/.
6. Vock, M. Luxurious and Responsible? Consumer Perceptions of Corporate Social Responsibility Efforts by Luxury versus Mass-Market Brands. https://pmc.ncbi.nlm.nih.gov/articles/PMC9651106/.
7. Yamaguchi, H. Consumer Perceptions of Stealth Marketing: What Makes Consumers Disgusted? By Hiroshi Yamaguchi :: SSRN. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4067569. 8. Söilen K. Stealth Marketing on Social Media_Digital Marketing: 10.1007/978-3-031-69518-6_16.
9. Stealth Marketing. https://dictionary.cambridge.org/dictionary/english/stealth-marketing.
10. Rasool K, Mahmood H, Rauf A, Yen Y. (PDF) Consumer Rights and Stealth Marketing: A Comparative Socio-Legal Exploration across Developed and Emerging Economies. https://www.researchgate.net/publication/392525426_Consumer_rights_and_stealth_marketing_A_comparative_socio-legal_exploration_across_developed_and_emerging_economies .
11. Kato S, Fujimoto Y, Suzuki S. December 2023 No.43 This Issue Covers the Following Topics: Entertainment and Sport. https://www.noandt.com/wp-content/uploads/2023/11/japan_no43.pdf.
12. Gov 法令検索. https://laws.e-gov.go.jp/law/337AC0000000134.
13. Alnazzawi *et al.*, "Using Social Media to Detect Fake News Information Related to Product Marketing." 2022. 10.3390/data7040044
14. White Paper on Consumer Affairs 2024 https://www.caa.go.jp/en/publication/annual_report/2024/assets/consumer_research_cms201_241224_01.pdf.
15. "Too Good to Be True – Misleading Advertising of Cosmetics Products." 2019. https://www.theseus.fi/bitstream/handle/10024/266420/Vaisanen_Heli.pdf?sequence=2&isAllowed=y
16. Natsir, A. D. S. R.; Riskawati, R.; Lestari, R. I.; Junianti, F.; Wardana, A. The Impact of Viral Stealth Marketing on Consumers' Buying Interest in Cosmetic Products. https://cot.unhas.ac.id/journals/index.php/epiije/article/view/1754.
17. Commercializing Social Interaction: The Ethics of Stealth Marketing by Kelly D. Martin, N. Craig Smith : SSRN. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1111976.
18. "Prohibited & Restricted Content - Maps User Generated Content Policy Help."
19. Al-Ramahi and Alsmadi, "Using Data Analytics to Filter Insincere Posts from Online Social Networks: A Case Study." 2020. http://hdl.handle.net/10125/64046.
20. "eBay Introduces 'Verified Purchase' Label to Boost Feedback Authenticity."
21. "eBay Feedback Shows Verified Purchases - But What Does Verified Mean?"
22. "Japan's largest cosmetics review & ranking service "@cosme" has launched its global app starting with Malaysia. PDF." 2019. https://www.grandviewresearch.com/horizon/outlook/beauty-and-personal-care-products-market/japan.
23. "@cosme | Japan's Largest Cosmetics Review and Ranking Site." https://www.cosme.net/.
24. Moz. "The Habits of Local Business Review Readers | SEO Industry Report." https://moz.com/local-business-review-survey-report/habits-of-review-readers.

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REVIEW ARTICLE

Constant Dark Energy Density in the Universe on a Large Scale: A Challenge to Energy Conservation

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ABSTRACT: A mysterious force termed dark energy is believed to accelerate the expansion rate of the universe. Dark energy is assumed to have a constant density, which appears to violate the energy conservation principle, a universal law of physics, on large scales. While Noether's Theorem may explain the constant density of dark energy as the universe expands, many other frameworks, including the backreaction hypothesis, are still under investigation. Researchers have tried to understand dark energy through the application of several aspects of physics, including quantum field theory and general relativity. In this review, we suggest that Noether's theorem may provide a plausible explanation to resolve this by connecting energy conservation to space-time symmetry. This challenges the notion that regular energy conservation is a universal law that can be applied to all scales, irrespective of other factors. This research is important as it helps to deepen our understanding of dark energy, ultimately helping us to figure out the mystery of cosmic evolution. In this review paper, we explore the quantum approach to explain this density, followed by an alternative to dark energy through backreaction in the universe, concluding with Noether's Theorem, which is the most plausible explanation given to date.

KEYWORDS: Physics and Astronomy, Astronomy and Cosmology, Dark Energy, Energy Conservation, Noether's Theorem.

Introduction

The universe expands in a puzzling manner, as galaxies seem to drift away, pushed by an unknown force. In the late 1990s, it was discovered that the expansion rate of the universe is increasing. When the luminosity distances of Type Ia supernovae were measured, and the data from the cosmic microwave background and baryon acoustic oscillations were analysed, it was confirmed that the acceleration was being driven by a mysterious component that was termed 'dark energy'.[1] Dark energy was a new form of energy that showed an effect similar to repulsive gravity. Although it was initially discovered from observations of distant supernovae, dark energy is now supported by observations from various cosmological structures, such as cluster abundance[2] and weak gravitational lensing.[3] It has also been measured that the universe is composed of 68% dark energy, 27% dark matter, and only about 5% ordinary matter.[4]

Although the cosmological constant was initially introduced in Einstein's theory of General Relativity to allow for a static universe, it was later abandoned after it was discovered that the universe was expanding. It was later reintroduced in the ΛCDM model to explain the accelerating expansion of the universe.[5] But this has led to inherent theoretical problems, such as the large difference between the value of dark energy that was observed and the predictions from Quantum Field Theory.[6] Such problems may suggest that there are some interactions of dark energy that have not been discovered.

The most widely accepted theory in cosmology is the ΛCDM model. In this framework, dark energy serves as a cosmological constant Λ, which has a fixed density that does not change as the universe expands. However, this behaviour of dark energy conflicts with the notion that all forms of energy must be conserved in the universe. This paradox comes into existence when conventional energy conservation principles are applied across cosmological scales, when other theories of physics, such as general relativity and quantum field theory, began to diverge.

The notion that dark energy density remains constant when the universe expands raises several fundamental questions about the applicability of the traditional principle of energy conservation. This could be an indication of the possibility that classical conservation laws break down at cosmological scales. This could also mean that our current models and principles are lacking. Several theories and principles based on symmetry have now been suggested to solve this paradox. Among them, Noether's Theorem has emerged as a key candidate for rethinking our current principle of energy conservation.[7] Noether's Theorem connects conservation principles to the symmetries of spacetime. The observed constant density of dark energy is not a paradox if Noether's symmetries can be applied to an expanding universe. Rather, it could be simply an outcome of space-time geometry and symmetry. Solving this paradox could help us further understand our universe.

This review paper suggests that the application of Noether's Theorem could explain the constancy of dark energy in the expanding universe based on symmetry. The explanation based on Noether's Theorem is simpler and more plausible than other explanations given to solve this problem. This paper is organized into five sections. It begins with a section on the discovery and background of dark energy. It also talks about the relation between dark energy and the conservation laws. The second section discusses the role of dark energy as the cosmological constant in the ΛCDM model. This is followed by a section talking about the quantum and relativistic approach-

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es to explain the constant density of dark energy. We talk about the process of backreaction, which explains acceleration without dark energy in the fourth section. The fifth and final section talks about Noether's Theorem and how it attempts to solve this paradox in a very logical manner.

In this paper, we will discuss solutions to the question: How can the constant density of dark energy be explained by the energy conservation principle in an expanding universe?

Discussion

Section 1 - Background of Dark Energy and Conservation Laws:

This section reviews the discovery and behaviour of dark energy. It talks about the conflict of constant dark energy density and traditional conservation of energy, as well as the mismatch between theory and observation.

The analysis of observations of distant Type Ia supernovae in the late 1990s revealed something that was unexpected. It indicated that the expansion of the universe is accelerating.[8] Considered as "standard candles" because of their predictable luminosity, these supernovae helped astronomers to measure distances between bodies in the universe. It was observed that galaxies were moving away from each other at a rate that was speeding up. This was surprising to astrophysicists as gravity, which attracts matter together, was expected to slow down the rate of expansion. This was the exact opposite of what was observed. The acceleration of the expansion rate alluded to the presence of a repulsive force or energy throughout the empty universe.

The idea of this repulsive force was also supported by observations from various other data sources. Complementary data from the cosmic microwave background (CMB) and large-scale structures confirmed the presence of a repulsive force that has negative pressure.[4] The CMB is the oldest light in the universe. It is the remnant microwave radiation after the Big Bang. Detailed information about the geometry and composition of the universe can be obtained from tiny fluctuations in the CMB. Satellites like Planck and WMAP provided data that showed us that although the universe is spatially flat on average, its rate of expansion is increasing. This gave us an indication of the presence of an energy form that exerted negative pressure. The large-scale surveys of the distribution of galaxies also supported this. These observations hence confirmed the presence of a mysterious force or energy now termed as dark energy. Dark energy is estimated to contribute to about 70% of the total energy composition of the universe.[4]

These conclusions proved to be a challenge to some of the integral properties of physics, such as the law of conservation of energy. To further comprehend this, we must further examine the conservation of energy in the context of general relativity. In general relativity, a globally conserved energy is not always defined, as our cosmological models lack global time-translation symmetry.[9] As a result, general relativity does not have a universal law of energy conservation, unlike in Newtonian mechanics.[10] This is because gravity is described as the curvature of spacetime, which evolves with the energy and matter the universe contains. This results in a fundamental mismatch regarding a basic principle in the two major theories of physics.

In general relativity, energy conservation is expressed as the disappearance of the covariant divergence of the energy-momentum tensor in a local context:[11]

$$\nabla_\mu T^{\mu\nu} = 0 \quad (1)$$

In this equation, ∇_μ represents the covariant derivative, which accounts for the curvature of spacetime. $T^{\mu\nu}$ is the energy-momentum tensor, which is responsible for describing the density and flow of energy and momentum. This equation tells us that although energy and momentum are conserved in the universe locally, that is, in any small region of spacetime, it does not suggest that the total energy in the entire universe is globally conserved. Therefore, it becomes essential to formulate a global energy conservation law that applies to an expanding universe.[12]

Dark energy is included in the ΛCDM model as the cosmological constant Λ.[6] In classical physics, the energy of baryonic matter and radiation spreads out as the universe expands. But dark energy, instead of spreading out, increases in amount to fill the infinitely growing volume of the universe due to expansion.[13] This violates the conventional law of conservation of energy as it suggests that the total amount of energy is not fixed, which conflicts with the Newtonian notion that energy cannot be created or destroyed.[14]

The paradox of the constant dark energy density with respect to the energy conservation law is a large problem in theoretical physics, as it suggests that the conventional energy conservation principle may not be global and may not work in an expanding, curved universe. This may suggest a breakdown of classical physics at all scales, especially quantum scales. It also highlights the need for modifying our understanding of the laws of physics so that they are applicable on a universal scale.

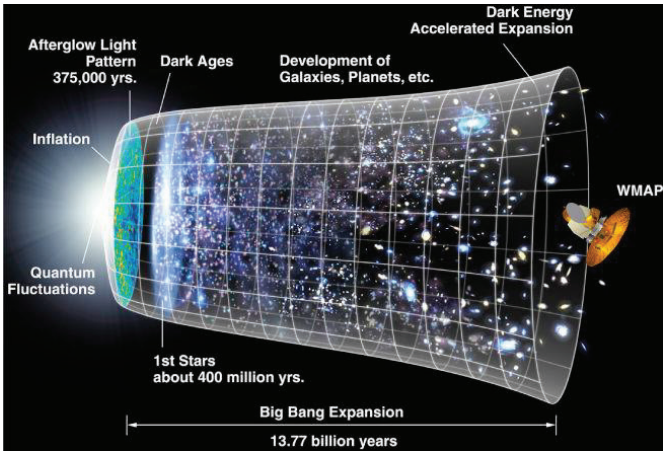

Figure 1: The figure shows the evolution of the universe from early inflation and structure formation to a late-time, dark energy-dominated phase characterized by accelerated expansion. Credits - Wilkinson Microwave Anisotropy Probe (WMAP) and National Aeronautics and Space Administration (NASA).

Section 2 - Dark Energy as the Cosmological Constant in the ΛCDM Model:

The ΛCDM model, which is the most widely accepted theory, provides the simplest explanation for the acceleration of

the cosmic expansion. ΛCDM stands for Lambda Cold Dark Matter. It combines dark energy with cold dark matter and general relativity.[4] It explains several observations in cosmology, like baryon acoustic oscillations (BAO), observations from Type Ia supernovae, and anisotropies of the Cosmic Microwave Background (CMB). The regular periodic fluctuations in the density of ordinary matter that are visible in the universe are defined as baryon acoustic oscillations. They often help in determining distances on a cosmic scale.[15] Observations from Type Ia supernovae are analysed for measuring the acceleration of the expansion rate of the universe. The small difference in the temperature of various regions of the CMB is referred to as the anisotropies of the CMB. These differences were measured by missions such as Planck and WMAP.[4] The ΛCDM model has achieved a high degree of accuracy with respect to the observations from large-scale structures by integrating all these observations simultaneously. Dark energy serves as the cosmological constant Λ in this model. Although this theory agrees with observational data, it has major theoretical issues like the cosmological constant problem, Hubble Tension, and the energy conservation paradox.

The cosmological constant Λ was introduced in 1917 by Albert Einstein in his equations of general relativity. During his time, it was believed that the universe was static and was not expanding. In contrast, his equations initially implied that the universe was either expanding or contracting. For the equations to predict a stationary universe, he included Λ as a repulsive force that balanced gravity.[6] However, this term was theoretical and had no observational evidence to prove its existence.

In 1929, Edwin Hubble discovered that the universe was indeed expanding. Consequently, Einstein said that including Λ in his equations was his "greatest blunder". Λ was considered unnecessary in cosmology for several decades. But this changed in the late 1990s. Two independent teams analysing observations from Type Ia supernovae found that the expansion rate of the universe was accelerating.[8] This discovery made Λ relevant again, and it was now considered a constant form of energy that pushes the universe apart.

It was predicted in the Quantum Field Theory that the vacuum energy in space should have an enormous energy density. This value is 10^120 times greater than the value that has been obtained from observations. This is known as the cosmological constant problem. A large amount of fine-tuning helps to reduce the magnitude of this discrepancy, which is considered to be unsatisfactory.[16]

In classical Newtonian physics, the energy of a closed system is always conserved. But the energy density of dark energy in the universe is a constant and does not dilute with expansion. This is not because energy is physically created, but because dark energy remains uniform as it is an inherent property and is hence not affected by the expansion of the universe. This raises questions about the applicability of the traditional energy conservation principle. Energy conservation in a global context is still not well defined in general relativity. This is a major roadblock to scientists who wish to formulate a perfect theory of everything.[14]

The difference between the value of the expansion rate of the universe (H_0) measured using Cepheid variables and Type Ia supernovae and the value obtained from the CMB is referred to as the Hubble Tension.[17] The value of H0 obtained from the distance ladder methods is 73 km/s/Mpc, while the value of H_0 obtained from CMB observations is 67 km/s/Mpc. Currently, the error bar in the value obtained from the distance ladder method is ±1.04, while the error bar in the value obtained from CMB observations is ±0.80. As the error in measurement is decreased, the difference between the two values also increases. This indicates a need to revise our current cosmological model.[17]

The ΛCDM model is still the most widely accepted because of its simple framework and its accuracy in regard to observational data. According to the ΛCDM model, dark energy is constant, dark matter is cold and non-relativistic, while the rest is ordinary matter and radiation. It is often used as a baseline against which theories that are more complex and speculative can be compared because of its clarity. The ΛCDM model is also very successful in explaining the expansion of the universe. As a result, it is still used for large-scale surveys and simulations in cosmology. It is the closest approximation to the universe's history of events that we currently have. However, in the future, it should be replaced by a model that solves all of these flaws while still being accurate in regard to observational data.[4] Therefore, by modifying the ΛCDM model by utilizing other theories such as Noether's Theorem, we can get one step closer to solving a paradox that has been confusing scientists for years.

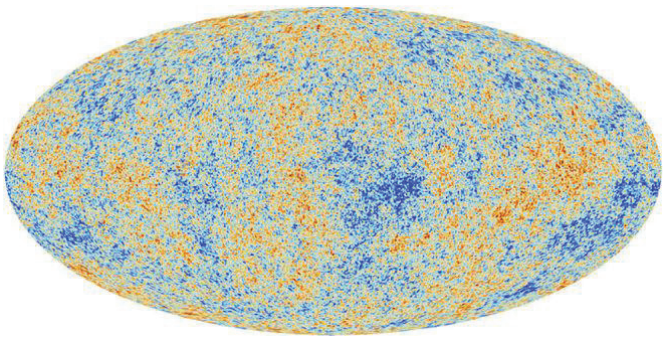

Figure 2: The figure shows the 2013 Planck all-sky map of the Cosmic Microwave Background temperature is shown. The small difference in the temperature of various regions of the CMB, referred to as anisotropies, provides strong observational evidence that the universe is spatially flat and supports the ΛCDM model, in which dark energy dominates the universe's late-time expansion. Credits - European Space Agency (ESA) and the Planck Collaboration.

Section 3 - Quantum and relativistic approaches:

This section examines quantum and relativistic approaches to explain dark energy and its constant density.

3.1. - Quantum Field Theory:

Quantum Field Theory has been used to try to explain this paradox. Vacuum energy is another term used instead of dark energy. The vacuum of space is filled with fluctuating energy in quantum field theory. The vacuum (dark) energy density predicted by quantum field theory is 10^120 times greater than the observed values. This gives rise to the cosmological

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constant problem.[16] This is one of the most famous inconsistencies between theory and observations in astrophysics. This is considered the cosmological constant problem since this huge mismatch highlights the discrepancy between QFT and our observations. The magnitude of the difference in the values can be decreased by using renormalisation techniques. However, it cannot be completely removed. This is still a major problem that hinders our understanding of dark energy in the expanding universe.

3.2. - Semiclassical Gravity:

Semiclassical gravity is one method that can be used to connect quantum mechanics and gravity. In semiclassical gravity, quantum fields propagate on a classical spacetime background.[18] Vacuum expectation values can be calculated using the framework. But it fails to consistently include backreaction, which becomes a problem when we consider an evolving universe. The phenomenon of backreaction is explained further in the next section. Also, when the quantum fluctuations become too large or when non-classical states are involved, this method can no longer be applied.

3.3. - Modified Gravity Theory:

Modified gravity theories can also be used, which adjust Einstein's equations without adding dark energy as Λ. f(R) gravity and scale-tensor models attempt to explain accelerating expansion without using the cosmological constant Λ (dark energy).[19] Corrections based on curvature are introduced to the action of gravity in these theories, which can result in an acceleration in the expansion rate of the universe. However, for f(R) gravity models to be viable, they need to satisfy several conditions, such as avoiding instability and passing local gravity tests. Hence, building models utilising these theories becomes complicated.

3.4. - Other Mathematical Frameworks and Limitations:

Mathematical frameworks such as Lagrangian and Hamiltonian mechanics can define conserved quantities in stationary (static) spacetimes. However, they cannot clearly define these quantities in an expanding universe.[20] The absence of time translational symmetry in an expanding universe in a global context means that energy conservation cannot be directly applied.[21]

There is no quantum or relativistic approach that currently clearly explains the reason for the creation of energy as the universe expands without violating conventional energy conservation. Each theory has its respective flaws. The estimated values from Quantum Field Theory are much greater than the values obtained from observations, while semiclassical gravity models are inconsistent. Modified gravity theories have several flaws that require fine-tuning, while theories using mathematical frameworks such as Hamiltonian mechanics are not applicable in evolving spacetimes. None of these frameworks perfectly solves this paradox; however, they bring us closer to finding this solution. The models obtained from quantum and relativistic approaches have several flaws and also require excessive assumptions. What if we just discard the cosmological constant?

Section 4 - Backreaction from Cosmic Structure Formation:

This section talks about the backreaction hypothesis, which states that the accelerating cosmic expansion could be due to cosmic backreaction rather than dark energy. This removes the requirement for dark energy in cosmology and its associated problems and challenges.

The universe is assumed to be homogeneous and isotropic on large scales. However, it contains smaller, complex structures such as galaxies and voids, which evolve nonlinearly.[22] The universe's expansion rate can be changed because of the uneven growth of the cosmic web, which is formed by these structures. These small-scale inhomogeneities are not smoothed over the fabric of the universe. According to Einstein's field equations, these inhomogeneities can change the average expansion rate and change the evolution path of the universe from that of an ideal FLRW universe. An ideal FLRW universe is a homogenous, isotropic, and expanding universe that is path-connected. Therefore, it is not possible to include the dynamics of the universe using a perfectly smooth model.[23]

Λ is interpreted as the energy density of dark (vacuum) energy in modern cosmology and accounts for the accelerating expansion of the universe. But the backreaction hypothesis tries to explain this phenomenon without utilising Λ. The emphasis is thereby shifted to the distribution of matter and the geometry of spacetime. By rendering Λ unnecessary, this hypothesis proposes a new way to integrate acceleration of the expansion rate with general relativity by ignoring one of the most fundamental assumptions in modern cosmology.

Backreaction is a geometrical effect that occurs because of the averaging of expansion rates across the universe. The expansion of regions with lower density is faster than the collapse of regions with higher density. As a result, the average expansion rate can increase even though no local region is accelerating because of the average combined effect.[24] Even if the expansion of a local region of space is not accelerating, the average expansion rate might still accelerate. The effects of the lower-density regions that have a higher growth rate can overshadow the effects of the higher-density regions that have a lower growth rate. This effect mimics that of a positive cosmological constant.[25]

The Buchert formalism helps us to average Einstein's Field Equations over the regions in the universe that have an uneven distribution of matter. It also gives us additional terms that can affect the expansion of the universe.[24] If these terms grow much larger over time, they can produce an acceleration in the average expansion rate of the universe without needing a component that has negative pressure. Theoretically, this hypothesis is viable as an alternative to the ΛCDM model.

The ΛCDM model can explain the observed supernovae data without using the cosmological constant. However, this hypothesis requires additional assumptions to explain all the cosmological data, such as BAO and CMB anisotropies. Furthermore, for the universe after recombination to be consistent with CMB data, it has to be extremely close to being

perfectly homogeneous and isotropic. As a result, only a limited amount of inhomogeneity can develop in the universe. At high redshifts, the backreaction hypothesis predicts a different expansion history than the one in the ΛCDM model, which is different from the data provided by various probes.[26]

If the accelerating expansion of the universe is caused by backreaction, there is no longer a need for dark energy. As a result, there would no longer be any challenges associated with energy conservation due to dark energy. If acceleration is caused only by the matter distribution and geometry of the universe, there would no longer be a violation. Local energy conservation would still apply regionally, but the average expansion rate would still accelerate due to backreaction. In this hypothesis, Noether's theorem would not play any role. This is because time translation symmetry in such a universe would be broken by inhomogeneity on a large scale.[27] As a result, the conservation principles would depend on geometry and would only work locally. This would offer an extremely different interpretation of the dynamics of the universe. The concept of time translation symmetry is explained in the next section.

Section 5 - Noether's Theorem and Its Implications:

5.1. - History of Noether's Theorem:

Instead of indicating an outright violation of the conservation of energy, dark energy's constant density may be explained by a different symmetry in the evolving universe.[28] Noether's Theorem provides a simple explanation for the constant density of dark energy by connecting symmetry to the conservation laws. Emmy Noether's theorem was formulated in 1915 and published in 1918.[29] Now it has become an integral part of modern theoretical physics. It talks about the relation between the various symmetries of a system and the associated conserved quantities in those systems. In essence, if the laws of the system remain unchanged even after certain transformations, a need for a conserved quantity arises. For example, the unchanging symmetry of physical systems with respect to time gives way to the energy conservation principle. This helps us to explain why some properties do not change with the evolution of a system. Another idea that can be inferred from the law is that if a conserved quantity is present, it refers to the presence of a specific law of a system that remains unchanged even after transformation.[29] Mathematically, Noether's Theorem states that for every continuous symmetry of the action S, there exists a conserved current J^{μ}.[30]

$$\partial_{\mu} J^{\mu}=0 \quad (2)$$

This equation means that the divergence of the current J^{μ} disappears, so the total amount of the associated conserved quantity remains constant over time when integrated across space. Here, ∂_{μ} represents the derivative with respect to space-time coordinates, and J^{μ} is the conserved current related to a symmetry of the system. In the case of time-translation symmetry, the conserved quantity is energy. This means that the integral of the conserved quantity over space remains constant in time, which is the principle behind local energy conservation according to Noether's Theorem.[30]

5.2. - Noether's Theorem and the ΛCDM model:

When Noether's theorem is applied to our current model of the universe, the ΛCDM model, in general relativity, the flat but dynamic nature of spacetime complicates the usual time translational symmetry. This is because the universe is expanding, which affects the concerned symmetries. As a result, the idea of globally conserved energy becomes complicated. Consequently, the regular time translational symmetry used along with energy conservation cannot be directly applied. Hence, the idea that our current energy conservation laws work on a global scale is challenged.[14] Regardless, local energy conservation is still valid as the covariant divergence of the energy-momentum tensor disappears. This is because time translational symmetry is present in an unchanging state, which allows for the definition of a conserved quantity.[31]

Noether's Theorem works best in flat universes that are static. This is because time translational symmetry is enough to reconcile the constant dark energy density with energy conservation. [32] It provides a mathematical framework that contains formulas that permit dark energy to be constant without violating energy conservation. Therefore, energy conservation needs to be approached in a novel manner by considering the symmetries that affect spacetime.[21] Hence, dark energy should be viewed as a natural consequence of the structure of spacetime rather than an anomaly.[32] Noether's Theorem also works in flat universes that are expanding, but to a more restricted extent.

A modified conservation law compatible with the constant density could come into existence if the expansion of space-time itself encodes a symmetry.[32] As of now, no symmetry directly solves this paradox with respect to expanding curved spacetimes. This is because the symmetries of curved spacetimes differ from those in flat ones, since the spacetime undergoes evolution and gets stretched. However, with further research, new symmetries can be discovered that help to reconcile this constant density with the broader energy conservation principle, as these evolving symmetries can help in the adaptation of conservation laws in an expanding universe.

Accordingly, the problem concerning the constant density of dark energy gives rise to a need for the revision of the traditional form of energy conservation. It should be replaced with conservation laws that are based on symmetry and are hence suitable for an evolving universe. If we can apply Noether's Theorem to curved spacetimes, we would be able to resolve this paradox of constant energy density in the most general case very easily.[34] As a result, the need for more assumptions, such as those needed in Quantum Field Theory and modified gravity theories, is avoided, and the question now focuses more on finding the correct spacetime symmetry.

5.3. - Advantages of Noether's Theorem:

Unlike in Quantum Field Theory and modified gravity, Noether's theorem has minimal assumptions in its framework.[31] It is assumed that symmetries are continuous, transformations are well defined, and the boundary conditions vanish. Other models that have been used to explain the constant dark energy density often utilize complex physics and assumptions.

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However, Noether's Theorem offers a model that explains this in a simpler and mathematical way.[9] By applying Noether's Theorem to our current cosmological model, astrophysicists can strive to obtain a new modified conservation law that is in agreement with the observed constant density of dark energy in the expanding universe. The approach using Noether's Theorem suggests that the violation of conventional energy conservation exists because we apply traditional definitions without taking into consideration the change in spacetime symmetries, rather than considering it as a direct violation of the energy conservation principle.

Conclusion

A significant challenge to the principle of energy conservation on large scales is presented by the assumption of constant density of dark energy in an expanding universe. This review goes over a few theoretical attempts that try to solve this paradox, from general relativity and quantum field theory, to large-scale backreaction and symmetry. Some further questions that may arise from this paper are:

a) Could there be a theory of quantum mechanics that completely integrates cosmic expansion and its effects with conservation laws? b) What further conditions are required for backreaction to completely replace dark energy as the driving force for accelerating expansion of the universe in cosmology?

By reviewing quantum and relativistic models and the effects of cosmic backreaction, it becomes obvious that this paradox is still unsolved in many popular approaches. Although Noether's Theorem is not accepted as the final answer, it provides a mathematically valid framework that connects modified forms of conservation principles to evolving cosmological symmetries. However, alternative models and theories also offer compelling ideas that do not violate the conventional principle of energy conservation. Further research is essential to solve this paradox. Solving this paradox would help us to properly incorporate quantum theory into our current model of cosmology. Furthermore, it could help us to ultimately understand the fundamental forces in our universe by developing a true theory of everything backed by quantum mechanics.

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References

1. Perlmutter, Saul, G. Aldering, G. Goldhaber, R. A. Knop, P. Nugent, P. G. Castro, S. Deustua, *et al.* 1999. "Measurements of Ω and Λ from 42 High-Redshift Supernovae." The Astrophysical Journal 517 (2): 565–86. https://iopscience.iop.org/article/10.1086/307221/pdf
2. Mantz, Adam, Steven W. Allen, and David Rapetti. 2008. "New Constraints on Dark Energy from the Observed Growth of the Most X-Ray Luminous Galaxy Clusters." Monthly Notices of the Royal Astronomical Society 387 (3): 1179–88. https://www.slac.stanford.edu/pubs/slacpubs/12750/slac-pub-12852.pdf
3. Hoekstra, Henk, and Bhuvnesh Jain. 2008. "Weak Gravitational Lensing and Its Cosmological Applications." Annual Review of Nuclear and Particle Science 58 (1): 99–123. https://arxiv.org/pdf/0805.0139
4. Planck Collaboration. 2021. "Planck 2018 Results. VI. Cosmological Parameters." Astronomy & Astrophysics 641: A6. https://arxiv.org/abs/1807.06209
5. O'Raifeartaigh, Cormac, Michael O'Keeffe, Werner Nahm, and Simon Mitton. 2018. "One Hundred Years of the Cosmological Constant: From 'Superfluous Stunt' to Dark Energy." The European Physical Journal H 43 (1): 73–117. https://arxiv.org/pdf/1711.06890
6. Weinberg, Steven. 1989. "The Cosmological Constant Problem." Reviews of Modern Physics 61 (1): 1–23. https://profchristophberger.com/wp-content/uploads/2015/02/wei89.pdf
7. Harko, Tiberiu, Francisco S. N. Lobo, G. Otalora, and Emmanuel N. Saridakis. 2014. "f(T, T) Gravity and Cosmology." arXiv preprint arXiv:1405.0519. https://doi.org/10.1088/1475-7516/2014/12/021
8. Riess, Adam G., Alexei V. Filippenko, Peter Challis, Alejandro Clocchiatti, Alan Diercks, Peter M. Garnavich, Ron L. Gilliland, *et al.* 1998. "Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant." The Astronomical Journal 116 (3): 1009–38. https://doi.org/10.1086/300499
9. Padmanabhan, T. 2008. Dark Energy and Gravity. arXiv preprint arXiv:0802.1798. https://arxiv.org/pdf/0705.2533
10. Ellis, George F. R. 2006. "Physics in the Real Universe: Time and Spacetime." arXiv preprint arXiv:gr-qc/0605049. https://arxiv.org/pdf/gr-qc/0605049
11. Wu, Zhaoyan. 2007. No-Go Theorem for Energy-Momentum Conservation in Curved Spacetime. arXiv preprint arXiv:gr-qc/0702059. https://arxiv.org/pdf/gr-qc/0702059v1
12. Pachner, Jaroslav. 1965. "Problem of Energy in an Expanding Universe." Physical Review 137 (5B): B1379. https://doi.org/10.1103/PhysRev.137.B1379
13. Peebles, P. J. E., and Bharat Ratra. 2003. "The Cosmological Constant and Dark Energy." Reviews of Modern Physics 75 (2): 559–606. https://arxiv.org/pdf/astroph/0207347
14. Carroll, Sean M. 2001. Dark Energy and the Preposterous Universe. arXiv preprint arXiv:astro-ph/0107571. https://arxiv.org/abs/astro-ph/0107571
15. Eisenstein, Daniel J., Idit Zehavi, David W. Hogg, Roman Scoccimarro, Michael R. Blanton, Robert C. Nichol, Ryan Scranton, *et al.* 2005. Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies. arXiv preprint arXiv:astro-ph/0501171. https://arxiv.org/abs/astro-ph/0501171
16. Martin, Jérôme. 2012. "Everything You Always Wanted to Know About the Cosmological Constant Problem (But Were Afraid to Ask)." https://arxiv.org/pdf/1205.3365v1
17. Scolnic, Dan, Dillon Brout, Gautham Narayan, Adam G. Riess, Dragan Huterer, Jessica E. Yoachim, Armin Rest, *et al.* 2024. "The Hubble Tension in Our Own Backyard: DESI and the Nearness of the Coma Cluster." The Astrophysical Journal Letters 974 (1): L12Planck Collaboration. 2021. "Planck 2018 Results. VI. Cosmological Parameters." Astronomy & Astrophysics 641: A6. https://arxiv.org/pdf/2409.14546
18. Ford, L. H. 2005. "Spacetime in Semiclassical Gravity." arXiv preprint arXiv:gr-qc/0504096. https://arxiv.org/pdf/gr-qc/0504096
19. Sotiriou, Thomas P., and Valerio Faraoni. 2010. "f(R) Theories of Gravity." Reviews of Modern Physics 82 (1): 451–97. https://arxiv.org/pdf/0805.1726
20. Capozziello, Salvatore, and Shinji Tsujikawa. 2008. "Solar System and Equivalence Principle Constraints on f(R) Gravity by the Cha-

meleon Approach." Physical Review D 77 (10): 107501. https://arxiv.org/pdf/0712.2268
21. Brown, J. David. 1993. "Action Functionals for Relativistic Perfect Fluids." Classical and Quantum Gravity 10 (8): 1579–1606. https://arxiv.org/pdf/gr-qc/9304026
22. Clarkson, Chris, George Ellis, Julien Larena, and Obinna Umeh. 2011. "Does the Growth of Structure Affect Our Dynamical Models of the Universe? The Averaging, Backreaction, and Fitting Problems in Cosmology." Reports on Progress in Physics 74 (11): 112901. https://arxiv.org/pdf/1109.2314
23. Buchert, Thomas. 2000. "On Average Properties of Inhomogeneous Fluids in General Relativity: Dust Cosmologies." General Relativity and Gravitation 32: 105–25. https://arxiv.org/pdf/gr-qc/9906015
24. Kolb, Edward W., Sabino Matarrese, Alessio Notari, and Antonio Riotto. 2005. "Effect of Inhomogeneities on the Expansion Rate of the Universe." https://arxiv.org/pdf/hep-ph/0409038
25. Kolb, Edward W., Sabino Matarrese, and Antonio Riotto. 2006. "On Cosmic Acceleration without Dark Energy." New Journal of Physics 8 (12): 322. https://iopscience.iop.org/article/10.1088/1367-2630/8/12/322/pdf
26. Bolejko, Krzysztof, Andrzej Krasiński, Charles Hellaby, and Marie-Noëlle Célérier. 2011. "Inhomogeneous Cosmological Models: Exact Solutions and Their Applications." Classical and Quantum Gravity 28 (16): 164002. https://arxiv.org/pdf/1102.1449
27. Buchert, Thomas, Alan A. Coley, Hagen Kleinert, Boudewijn F. Roukema, and David L. Wiltshire. 2015. "Is There Proof That Backreaction of Inhomogeneities Is Irrelevant in Cosmology?" Classical and Quantum Gravity 32 (21): 215021. https://arxiv.org/pdf/1505.07800
28. Paliathanasis, Andronikos, Michael Tsamparlis, Salvatore Basilakos, and Spyros Capozziello. 2011. "Constraints and Analytical Solutions of f(R) Theories of Gravity Using Noether Symmetries." Physical Review D 89 (6): 063532. https://arxiv.org/pdf/1111.4547
29. Noether, Emmy. 1971. "Invariant Variation Problems." Translated by M. A. Tavel. Transport Theory and Statistical Physics 1 (3): 186–207. https://arxiv.org/abs/physics/0503066
30. Barnich, Glenn, and Friedemann Brandt. 2002. "Covariant Theory of Asymptotic Symmetries, Conservation Laws and Central Charges." Nuclear Physics B 633 (1–2): 3–82. https://arxiv.org/pdf/hep-th/0111246
31. Capozziello, Salvatore e Antonio De Felice. 2008. "f(R) Cosmology by Noether's Symmetry." Journal of Cosmology and Astroparticle Physics 2008 (08): 016. https://arxiv.org/pdf/0804.2163
32. Vakili, Babak. 2008. "Noether Symmetry in f(R) Cosmology." Physical Review D 77: 044023. https://arxiv.org/pdf/0804.3449v1
33. Tsamparlis, Michael, and Andronikos Paliathanasis. 2018. "Symmetries of Differential Equations in Cosmology." Symmetry 10 (7): 233. https://arxiv.org/pdf/1806.05888
34. Brown, J. David, and James W. York. 1993. "Quasilocal Energy and Conserved Charges Derived from the Gravitational Action." Physical Review D 47 (4): 1407–19. https://web.archive.org/web/20180728121612id_/http://cds.cern.ch/record/244126/files/9209012.pdf

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RESEARCH ARTICLE

The Impact of Multilingualism: Innovation in Linguistically Diverse Workplaces (LDWs)

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ABSTRACT: Multilingualism and language diversity are key resources in multinational companies, fostering innovation through diverse perspectives and improved knowledge sharing. This study investigates how multilingualism among employees enhances innovation in linguistically diverse workplaces (LDWs). It was hypothesized that multilingualism in LDWs increases innovation by facilitating more effective communication among employees, broadening perspectives, and enabling adaptation to multiple global markets. The research centers on an exploratory case study of Crimson Education, a multinational college preparation consultancy, with a small sample of 10 multilingual employees. The study employed qualitative semi-structured interviews as well as a survey consisting of both quantitative Likert-scale questions and open-ended questions for multilingual employees at Crimson Education. The findings were supplemented by interviews with employees of three multinational technology companies. The results indicate that multilingualism improves communication, knowledge sharing, and creative problem-solving by bridging linguistic and cultural gaps. Moreover, employees reported that multilingualism supports innovation through effective communication and collaboration, serving as a competitive advantage. Overall, multilingualism emerges as an essential cultural and cognitive resource that drives innovation in LDWs.

KEYWORDS: Behavioral and Social Sciences, Sociology and Social Psychology, Multilingualism, Innovation, Business.

Introduction

Multilingualism is the ability of individuals to engage in their daily interactions using more than one language,[1] while language diversity refers to the presence of multiple languages, due to the presence of speakers of diverse backgrounds, within a particular organization.[2] The relationship between multilingualism and language diversity is complementary: multilingualism highlights an individual's proficiency in languages, and language diversity encompasses the collective linguistic variety within a workplace. The increase, since the last century, of companies operating across borders results in engagement with a larger scale and variety of customer bases. These companies collaborate with international partners, enabling the integration of multiple perspectives that contribute to innovative outcomes within global business environments.

According to a 2005 study by international business communication expert Jane Henderson, language diversity influences team members' perception in unique ways, aside from the pure communication in various mother tongues.[3] These unique ways include social identities within teams, power dynamics, and communication norms. It is essential to note that language diversity can create challenges and opportunities, and this interaction impacts how innovation occurs in linguistically diverse workplaces (LDWs) by fostering an exchange of ideas enriched with cultural insights.

This paper investigates the central question: How does multilingualism among employees enhance innovation in LDWs? Multilingualism relates to innovation at work by improving communication, expanding knowledge sharing, and broadening perspectives from individuals with diverse linguistic backgrounds. In this context, innovation encompasses the creation of new products, the generation of creative ideas, and problem-solving within the organizational context. This paper examines how multilingualism in LDWs enhances innovation when communication and knowledge sharing are improved, and when adaptive solutions are enabled as perceived through evidence from employees' perceptions and concrete examples from multinational companies.

This study distinguishes itself from the existing literature by emphasizing the significance of multilingualism and language diversity in innovative contexts. While multilingualism has been previously studied in relation to communication and organizational behavior, existing research has often undervalued and positioned language as a medium of information transmission rather than a social and cultural resource.[3] However, recent studies have begun to uncover the socio-cultural dimensions of language use in workplaces, highlighting how language shapes interpersonal dynamics. Based on this foundation, this study addresses a gap regarding the specific role of multilingual interpersonal interaction in fostering innovation, an area less explored in prior research.[4] Furthermore, this paper highlights the competitive advantage that companies gain when multilingualism is leveraged. By examining language implications such as knowledge sharing, sociolinguistic competence, and cross-linguistic collaboration, the present study analyzes challenges and opportunities presented by linguistic diversity. Therefore, these dynamics help organizations unlock the full potential of their multilingual workforce.

This study adopts an exploratory case study approach focusing on Crimson Education, a multinational college preparation consultancy. It includes seven interviews and responses from 10 multilingual employees to a survey comprising Likert-scale

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and open-ended questions. Additionally, supplementary interviews were conducted with three multilingual employees, each representing one of three multinational technology companies, to provide additional contextual insights.

When managed effectively, language diversity strengthens team cohesion, interpretive frameworks, and communication strategies. As Information Systems Science expert Farhan Ahmad and Information Studies expert Gunilla Widen argue, "Knowledge sharing is a product of the collaborative and supportive environment formed by socialization and informal communication between employees."[5] However, unmanaged language diversity often leads to language clustering, which restricts knowledge flows and limits informal communication across the organization.[5]

Furthermore, this research aims to offer practical guidance for organizations seeking to boost the potential of their linguistic resources by investigating the mechanisms through which multilingualism fosters innovation outcomes in LDWs. Overall, by understanding how multilingualism among employees specifically enhances innovation, this study fills the gap left by prior research, which has frequently underestimated language as a key element of culture and society.

This paper hypothesizes that multilingualism among employees enhances innovation in linguistically diverse workplaces through effective knowledge sharing, integration of diverse perspectives, and communication strategies such as code-switching and language coverage. These mechanisms enable employees to bridge knowledge silos through cross-linguistic collaboration, develop sociolinguistic competence, and cultivate inclusive environments in which language diversity is leveraged. The potential of multilingualism for innovation depends on organizational efforts to support sociolinguistic competence and address social dynamics — such as language clustering and shadow structures — that impact language use in daily practices.

Key Concepts / Background:

The impact of language diversity in organizational dynamics and innovation has shown promise in recent linguistic and business studies. Language fluency — the ability to write and speak a language effectively — enables basic communication, while sociolinguistic competence is the capacity to interpret, negotiate, and respond to meaning in social contexts; together, these allow for effective language use for innovation.[2] As Henderson points out, employees with language proficiency skills may encounter several difficulties in communicating when they lack this sociolinguistic competence.[3]

Language diversity plays a crucial role in companies by helping them to progressively reach global clients and markets. However, this valuable element also raises challenges that need to be identified.[3] The literature indicates that language clustering — the tendency of employees to interact mainly with the members of their own linguistic community — can hinder informal communication and the flow of knowledge throughout the team.[5] Those fluent in the principal language of the company can also be affected by language clustering. This highlights the importance of effective social dynamics within innovative multilingual teams.

The connection between language and innovation manifests itself through knowledge sharing, in which multilingual employees serve as bridges, facilitating the cross-pollination of ideas, thus eradicating language barriers that exclude employees from key decision-making processes and create "islands" within the organization.[4]

Recent research highlights specific language practices such as code-switching — alternating between languages in the same discourse — and language convergence — adapting one's linguistic behavior to a specific audience. Those strategies facilitate knowledge sharing in multilingual companies by fostering inclusive environments where perspectives from different linguistic groups can be integrated into discussions and ongoing networking.[6]

Moreover, the concept of shadow structures — informal, language-based networks — illustrates how languages impose their own pattern on communication and in personal connections, as employees with superior language skills access broader networks within the multinational.[5] Companies must implement additional practices beyond simply hiring multilingual staff to maximize the innovative potential of linguistically diverse workplaces (LDWs). They need to promote mechanisms that influence language use to foment inclusive environments in which all voices are valued through knowledge-sharing initiatives.[5]

Methods

This study investigates innovation supported by multilingualism in linguistically diverse workplaces (LDWs), using Crimson Education — a multinational university admissions consultancy — as a case study. This research employs a qualitative and quantitative approach, using survey results and in-depth interviews to explore the implications of a phenomenon in its real-world context. Although Sociologist Peter Swanborn's approach emphasizes triangulation through survey results, in-depth interviews, and participant observation,[7] in the present study, the first two methods — survey results and in-depth interviews — were utilized. Future studies may include participant observation to corroborate and expand on the study's findings related to multilingualism and innovation.

A careful literature review was done using JSTOR, Google Scholar, and ResearchGate, reviewing papers published from the year 1993 to the present and using keywords such as "multilingualism," "innovation," and "linguistic diversity." Out of 26 academic papers and articles initially selected, the 16 most relevant ones were analyzed for this study. In addition, two books were used for reference, including Swanborn's book, Case Study Research: What, Why, and How? (2010) and Lee and Saunders' book Conducting Case Study Research for Business and Management Students (2017).

The case company, Crimson Education, was selected based on the inclusion criteria of having international operations and a workforce composed of employees proficient in multiple languages. Within Crimson Education, this study focused on the Latin America office and operations of the company. In

addition to the company selected for the case study (Crimson Education), three other multinational companies — Google, Amazon, and Uber — that also meet the abovementioned inclusion criteria were included in the study to a more limited extent for the purpose of additional context and comparison. Companies operating solely in monolingual environments or that lack practices supporting multilingualism were not considered in the present study.

A questionnaire with 30 questions was distributed to multilingual employees at Crimson Education. The survey participants were selected according to the following inclusion criteria: they were required to be current employees of Crimson Education, to have worked at the company for at least one year, and to be proficient in at least two languages used in a professional context. Employees were excluded from the survey if they had less than one year of tenure or lacked proficiency in more than one language, in order to ensure that all employees had relevant experiences with multilingual workplace dynamics.

The initial five questions of the questionnaire gathered demographic and profile information, such as tenure, the number of languages in which employees are proficient, and their job roles. Additionally, the questionnaire incorporated 16 Likert-scale statements — ranging from 1 ("strongly disagree") to 5 ("strongly agree") — to evaluate the employees' experiences related to multilingualism, collaboration, communication, creativity, knowledge sharing, and innovation. For instance, two of the 16 Likert-scale items were the following: "Multilingualism enhances communication between me and my colleagues" and "Multilingualism has allowed for greater innovation by my team." Subsequently, nine open-ended questions explored the challenges and benefits of multilingualism and examples of how it influences innovation — including prompts such as "What challenges do you face when communicating in a multilingual environment?" and "Do you think that multilingualism influences your company's ability to adapt to new technologies or markets? If so, how?" In addition, the start of the questionnaire included four questions for ascertaining the employees' eligibility for the study and one question about the employees' professional role.

Ten Crimson employees responded to the survey. These employees have a variety of job titles and functions, as follows: one "LATAM Regional Team Lead and U.S. Senior Strategist," who oversees regional operations; one "Country Manager for Brazil & LATAM," who manages country-specific strategies; one "Student Success Manager," who supports student outcomes; one "LATAM Student Success Team Lead," who coordinates team performance; one "Head of Marketing for Brazil & LATAM," who is responsible for promotional strategies; one "Academic Advisor," who guides Crimson's available academic programs; one "Academic Advisor and Former Regional Manager," who combines advising expertise with management experience; and three "Senior Strategists," who focus on students' university application strategy.

In addition, seven of the ten Crimson employees who responded to the survey — all except for the three "Senior Strategists" — were interviewed, for the purpose of obtaining more in-depth information and perspectives from them. These interviews explored a variety of areas: the perceptions of multilingual staff, the innovation outcomes, the companies' initiatives to leverage language diversity, strategies for mitigating language hierarchy, mechanisms for integrating multilingual perspectives into market strategy, investments in multilingual infrastructure, operational costs in contrast to innovation benefits, Key Performance Indicators (KPIs) for multilingual teams, examples of multilingual teams solving problems, unrealized opportunities due to underleveraged multilingualism, and recommendations to boost multilingualism's impact.

Four of the interviewed employees were interviewed individually, in one-on-one conversations: the "LATAM Regional Team Lead and U.S. Senior Strategist," the "Country Manager for Brazil & LATAM," the "Student Success Manager," and the "LATAM Student Success Team Lead." A group interview was held with the other three interviewed staff members — the "Head of Marketing for Brazil & LATAM," the "Academic Advisor," and the "Academic Advisor and Former Regional Manager."

To broaden the contextual understanding and compare practices across industries, supplementary interviews were conducted with one former or current employee from each of the following multinational technology companies: Amazon, Google, and Uber at the offices of those companies in England, Spain, and the United States, respectively. These participants were selected for their multilingual backgrounds and their direct experience working in international teams. The overall sample size for the supplementary interviews was three multilingual employees, one from each company. The interviews focused on how multilingualism is managed, perceptions of innovation in LDWs, strategies and initiatives for effective integration of multiple languages in the workplace, and concrete examples of multilingual perspectives having led to innovative solutions.

The qualitative analysis of the responses to the interview and open-ended survey was organized thematically, following an inductive approach to identify patterns related to key themes, complementing the insights of the literature review. Furthermore, survey data from the Likert-scale questions were analyzed using statistics to identify overall trends pertaining to multilingualism and innovation.

Results

Survey data from ten Crimson Education staff members highlights a workplace with employees who are fluent in multiple languages, with each respondent reporting proficiency in at least two languages; several reported fluency in three or more, including English, Portuguese, Spanish, French, Mandarin, Italian, Macedonian, Serbo-Croatian, Bulgarian, and Arabic. The respondents' tenure ranged from one year to more than six years, which indicated an experienced, linguistically diverse team. As shown in Table 1, all responses to the 16 Likert-scale survey questions (L1-L16) were on the standard five-point Likert scale: Strongly Disagree (SD), Disagree (D), Neutral/Unsure (N/U), Agree (A), and Strongly Agree (SA).

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This section presents how communication and knowledge-sharing related to multilingualism enhance innovation within teams with the support of the evidence from quantitative survey data and qualitative interview insights. It is important to mention that the measure of innovation used in this study is based on employees' perceptions and self-reported experience rather than objective organizational performance metrics.

Table 1: Responses to the 16 Likert-scale survey questions.

L#	SD	D	N/U	A	SA
L1	1	1	0	0	8
L2	0	0	0	1	9
L3	0	0	0	2	8
L4	0	0	0	0	10
L5	1	1	1	3	4
L6	0	0	0	0	10
L7	0	0	0	1	9
L8	0	0	0	2	8
L9	0	0	3	3	4
L10	0	0	0	4	6
L11	0	0	1	2	7
L12	0	1	1	2	6
L13	0	0	0	4	6
L14	0	0	2	3	5
L15	0	1	0	1	8
L16	0	0	1	2	7

Multilingual usage is prevalent in the daily operations of Crimson Education employees. Specifically, 80% of respondents strongly agreed with statement L1, "At work, I frequently communicate in two or more languages," while 10% strongly disagreed and another 10% disagreed. Of the respondents, 90% strongly agreed with L2, "Multilingualism (proficiency in more than one language) is important for my job performance." Additionally, all respondents strongly agreed with L4, "I often collaborate with colleagues who are multilingual," signaling a workplace culture in which multilingual collaboration is integral. Notably, statement L5, "I often collaborate with colleagues who speak a language that I don't," received the strong agreement (SA) of only 40% of the participants; 30% agreed (A), 10% remained neutral or unsure (N/U), 10% disagreed (D), and 10% strongly disagreed (SD). This indicates that direct interaction among multilingual employees who have different language sets (non-shared languages) is less frequent than interaction among multilingual employees who are proficient in the same set of languages.

The role of multilingualism in enhancing knowledge sharing within teams was emphasized by the survey participants. All ten respondents either strongly agreed or agreed with L3, "Multilingualism enhances communication between me and my colleagues"; 80% strongly agreed, while 20% agreed. Similarly, for both L7, "Multilingualism encourages the sharing of knowledge among members of my team," and L8, "I believe that multilingualism in the workplace helps employees to understand each other's ideas," all respondents either strongly agreed or agreed, with most of them strongly agreeing (90% for L7, and 80% for L8) — thereby evidencing multilingualism's impact on fostering a deeper understanding within teams and clearer communication. Furthermore, for L11, "My company actively fosters multilingualism through its hiring and educational policies," 70% of the participants strongly agreed, 20% agreed, and 10% remained neutral or unsure, while for L12, "My company leverages employees' multilingual capabilities," 60% strongly agreed, 20% agreed, 10% remained neutral or unsure, and 10% disagreed. This variation in responses may reflect differences in job roles, where some employees use their multilingual skills more than others, or differences in perceptions regarding how the company leverages these abilities, based on the insights from the interviews. Although agreement with L11 and L12 was not universal, as for L3, L7, and L8, the level of agreement was nevertheless high. This was elucidated in an open-ended response: "Multilingualism brings a richer, more inclusive workplace culture. It fosters curiosity, empathy, and openness to diverse perspectives. At the same time, it challenges teams to be more intentional and mindful in how they communicate — which can lead to more thoughtful collaboration overall." Additionally, respondents noted that multilingual capabilities help adapt services to regional needs while enhancing effective knowledge transfer.

Survey respondents perceived multilingualism as a driver of innovation, with 70% of participants strongly agreeing, 20% agreeing, and 10% disagreeing with L16, "Multilingualism has allowed for greater innovation by my team." These perceptions were corroborated by in-depth interview data that provide concrete examples of innovation. It is facilitated by multilingual collaboration, such as the localization of products and decision-making based on distinct cultural settings. Furthermore, all participants strongly agreed with L6, "Multilingualism enhances my ability to understand different cultural contexts," and 100% of participants agreed or strongly agreed with both L10, "Multilingualism gives my organization a competitive advantage," and L13, "I believe that multilingualism in companies has a positive impact on creativity and innovation." Likewise, 80% strongly agreed and 10% agreed with L15, "Multilingualism allows my team to access and apply knowledge from sources in different languages, contributing to innovative solutions."

One respondent's comment illustrated this impact: "Multilingualism accelerates our ability to localize products, campaigns, and services for different markets. It also makes it easier to understand user feedback in native languages, which helps us iterate faster and make more culturally relevant decisions." This example reflects essential themes of cross-cultural collaboration and the benefits of linguistic diversity found in the data. Another innovation-related statement, L14 — "Multilingualism has allowed for greater creativity in brainstorming sessions on my team" — also had a high level of agreement, at 80% (with 50% responding "SA" and 30% responding "A"), and no disagreement, with the other 20% remaining neutral or unsure. This evidences the employees' recognition of the role of multilingualism in promoting creativity. However, statement L9, "Multilingualism reduces misunderstandings in my team's communication," had a somewhat lower rate of agreement, at 70% — with 40% strongly agreeing (SA), 30% agreeing (A), and 30% remaining neutral or unsure (N/U) — suggesting the possibility of some remaining communication challenges, though no respondents disagreed with the statement.

Respondents also highlighted obstacles faced by employees in multilingual workplaces. The most frequently identified issues included misunderstandings due to cultural differences, difficulties adapting to unfamiliar accents, and loss of nuance in translation. Some participants pointed out that holding training in only one language can limit knowledge absorption for multilingual employees. Open-ended responses further described how expressing ideas with full nuance across languages requires cognitive effort, and how this difficulty can lead to the unintentional silencing of innovative contributions.

Interview data provided insights into how multilingualism enhances innovation within the company. Employee 1, LATAM Student Success Team Lead, explained that cross-language collaboration is essential for effective knowledge sharing and that multilingual staff often interpret and clarify information, ensuring inclusive communication for colleagues and clients alike. Complementing this, Employee 2, Head of Marketing Brazil & LATAM, described how multilingualism supports content adaptation and brainstorming: "We create content daily … and multilingualism really helps us adapt to different cultures. When we brainstorm, trends from Brazil, China, or Colombia influence our content and strategies." This illustrates how multilingual perspectives shape innovation efforts.

The strategic importance of language diversity in recruitment was emphasized by Employee 3, the Regional Team Lead, who stated that approximately one-third of current openings require specific language proficiency, which supports regional market entry and hybrid team innovation. This approach confirms that the company leverages multilingual human resources as an advantage in product development.

Interviews, including responses from Employee 4, Country Manager Brazil & LATAM, revealed that multilingual expertise enables service customization. Specifically, Employee 4 described how knowledge of local languages supported expansion from Mexico into Brazil, building trust with new clients and developing tailored offerings such as SAT group classes in Portuguese, reinforcing the link between localized innovation and languages.

Technological tools were identified by interviewees as facilitators of multilingual innovation. Employee 5, Academic Advisor, highlighted the AI "Copilot" tool, which translates session notes into English instantly, making information accessible across teams: "The AI tool translates local language meeting notes into English instantly, saving time and making information accessible." This reduces communication overhead and accelerates knowledge flow without overburdening staff.

Innovation outcomes arise through effective use of multilingualism and language diversity to facilitate communication, localize content, and tailor solutions to specific markets. Teams utilized cultural and linguistic knowledge to localize sales proposals and marketing materials, thereby enhancing revenue and engagement in new regions. Employee 1 recounted resolving complex financial aid misunderstandings through multilingual support, preventing loss of scholarships and increasing clients' satisfaction. Likewise, Employee 3 discussed how a group of three multilingual employees (fluent in various combinations of Portuguese, Spanish, and English) accessed global resources to create educational tools for Latin American students — work that monolingual teams could not have managed as effectively. Furthermore, localized marketing campaigns tested in Brazil and other Latin American countries outperformed English-only versions, as confirmed by Employee 2's observations on improved engagement due to the regionally adapted content.

Despite the benefits of language diversity and multilingualism, interviewees expressed concerns about challenges resulting from language hierarchy. Interviewees noted that the dominance of English as the corporate lingua franca can unintentionally suppress the voices of less fluent employees, limiting their participation and innovative contributions. To address this issue, regional team initiatives have encouraged the use of Portuguese, Spanish, and French, in addition to English, in both formal and informal settings. However, training programs delivered in English can restrict multilingual employees' effective knowledge acquisition, suggesting a potential need for greater investment in inclusive multilingual environments.

Supplementary interviews with multilingual employees from Google, Amazon, and Uber reveal a consistent prioritization of English as the primary language for communication within global teams. Both Google and Uber maintain high English proficiency requirements to ensure collaboration across their international workforce. However, this reliance on English can limit the inclusion of multilingual employees with varying fluency levels. Recognizing this, all three of the multinational tech companies have developed initiatives to support both linguistic diversity and multilingualism. Google provides training and English courses to reduce language barriers and has instituted clear policies that safeguard the right to use native languages in informal settings. Amazon promotes diversity through hiring practices and provides budgets for language learning as part of employee development. Uber draws on insights from multilingual employees on teams spread across more than 30 countries.

Regarding innovation, the interviewees concurred that multilingual employees contribute not only language proficiency but also important cultural perspectives that enhance product development and market strategies. An Amazon employee, who is on Amazon's Alexa team, stated that multilingualism, when combined with diverse cultural experiences, can foster out-of-the-box thinking. Nonetheless, a high-level Google manager noted that investments tend to focus on translation technologies and language training that facilitate efficiency in operations rather than directly driving innovation.

Overall, the external perspectives from the multinational tech companies align with the findings at Crimson Education, highlighting broad recognition of multilingualism's value in fostering innovation.

Discussion

This study has a small sample size of only 10 employees from one main company, combined with reliance on self-reported data, which means that limits the generalization of the findings. However, this exploratory case study offers insights

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for future research with larger samples. The results of the study confirm that multilingual employees contribute to knowledge sharing and increase teams' diversity of perspectives and experiences, thereby promoting innovation outcomes. The following discussion details, in order, these effects and mechanisms that were identified.

Knowledge sharing:

The findings confirmed that the presence of multilingual employees enhances knowledge sharing in LDWs. Survey responses revealed that a large majority of employees (80–90%) agreed or strongly agreed that multilingualism improves communication and knowledge sharing within teams. Moreover, most participants reported frequent communication in two or more languages at work and described active collaboration with colleagues from different linguistic backgrounds. These results corroborate Ahmad and Widen's findings that overcoming language clustering facilitates knowledge flows that are essential for innovation.[5] However, our study expands on their work by providing empirical evidence of how multilingual employees serve as knowledge brokers in terms of bridging linguistic gaps and navigating sociocultural complexities in real organizational contexts. Interview insights from Employee 1 further demonstrated that multilingual employees serve as linguistic and cultural bridges, interpreting, contextualizing, and clarifying information to ensure inclusivity, consistent with Henderson's emphasis on sociolinguistic competence beyond mere language fluency.[3]

Further, the concept of employees acting as "knowledge brokers" emerged from the interviews: multilingual staff not only translate and adapt resources but also channel client insights across regions, enabling opportunities that monolingual teams might miss. For instance, Employee 3, LATAM Regional Team Lead and U.S. Senior Strategist, noted, "We were able to cater to the Latin American audience, making sure that strategists spoke the languages — at least Portuguese and Spanish. That allows us to address what is necessary for clients in those regions." This ensured that strategies and communications were culturally and linguistically aligned with local market needs. Additionally, this employee highlighted how bilingual strategies helped with curating local databases of academic competitions, a task that would have been unmanageable otherwise. This corroborates Ahmad's idea of "dual translation," whereby employees translate both language and contextual meaning.[1] The dual data source verification confirms that multilingualism enhances the effectiveness of knowledge exchange, which is foundational for innovation. The open-ended survey responses highlight how multilingualism brings a "richer, more inclusive culture" that encourages more thoughtful, collaborative processes.

In contrast, several employees noted frequent misunderstandings due to nuances in tone, connotation, and specific terminology, resulting in the dilution of innovative ideas. Respondents mentioned challenges such as "ensuring that ideas are expressed with the same nuance and clarity across languages," and noted that "brilliant insights can be lost or diluted due to differences in fluency or vocabulary." These barriers illustrate the complex nature of multilingual knowledge sharing but do not diminish its role in overcoming knowledge silos — bridging regions, clients, and teams — and creating pathways for innovation. This perspective resonates with Marschan-Piekkari and Welch's identification of "islands" that form communication barriers in multinational contexts. This study demonstrates, with organizational case study evidence, how multilingual practices can transform these isolating islands into innovative channels for formal and informal knowledge exchange.[5]

Teams' diverse perspectives:

The study highlights how language diversity broadens cognitive and cultural perspectives, fostering innovation in global teams. Interviewees noted that the ability to code-switch and use multiple languages during meetings and brainstorming sessions increased participation, especially for staff less confident in a non-native language. These inclusive practices nurture psychological safety and encourage the free exchange of ideas, consistent with Cohen and Henderson's research suggesting that linguistic diversity, when well managed, transforms from a divisive factor into a creativity-enhancing resource.[8] Survey participants reinforced that this diversity promotes "more thoughtful collaboration overall" and "contributes to a more globally empathetic and culturally agile workplace," with 90% of respondents acknowledging multilingualism as a competitive advantage that supports innovation and a workplace culture marked by empathy and openness to diverse perspectives. This was said to encourage new ideas and make colleagues from varied backgrounds feel welcome in contributing to group discussions. Employee 1, LATAM Student Success Team Lead, reflected, "We're even investing even more into learning the languages we work with."

Interviewees described tangible innovation outcomes derived from leveraging local languages, such as adapting SAT training to Portuguese-speaking clients and tailoring region-specific marketing content. This aligns with the findings of Stephen Chen, a scholar of international business management, who has emphasized the role of linguistic diversity in expanding cognitive frameworks, enriching decision-making, and innovation through exposure to multiple perspectives.[9] However, this study extends Chen's work by providing concrete organizational examples that detail how these cognitive benefits are operationalized within specific educational service adaptations to diverse markets. Moreover, the integration of AI-supported translation tools, such as Crimson Education's "Copilot" system that instantly translates meeting notes, illustrates organizational use of technology to enhance cross-linguistic communication and knowledge transfer processes. This reflects Tenzer and Pudelko's advocacy for hybrid language practices and the use of technology as fundamental to innovation in multilingual settings,[10] while offering distinctive insights into real-world company implementation.

Nevertheless, participants cited persistent systemic challenges: formal documentation, training, and development programs often defaulted to a single language (English), which can diminish less proficient speakers and impede profound engagement. These findings echo Ahmad and Widen's call for

organizations to address the social dynamics behind language clustering and to foster environments in which linguistic diversity is embraced to unlock the potential of innovation.[5]

Innovation outcomes:

Survey and interview evidence indicate that multilingualism is a key element of innovation within Crimson Education and other multinational firms. Most survey respondents strongly agreed that multilingualism enhances their team's creativity and capacity for better innovation outcomes. Interviewees detailed how multilingual collaboration enabled product and service innovations, including regional market adaptations, local client engagement strategies, and development of educational resources. Employee 2, Head of Marketing, stated, "Our departments all have meetings where collaborators who speak different languages and live in different countries can share ideas, trends, and solutions based on their own cultural environment," describing how multilingual team members bring rich, regionally informed insights to global content creation. Employee 3, LATAM Regional Team Lead, explained, "We're leveraging our multilingual employees' expertise through different marketing campaigns so that we can speak the language of the families that we're selling to," affirming that language-specific hiring is essential for sustaining hybrid teams that successfully navigate diverse markets. Crimson's capacity to operate across regions such as China, Brazil, and the Middle East relies on multilingual teams who understand local systems, cultural values, and communication styles. This localized expertise has been fundamental in enabling meaningful adaptations to products and services tailored for these varied markets. Additionally, collaboration across regions and the role of multilingual staff in bridging cultural gaps have proven essential in reaching new markets and iterating products based on authentic user feedback.

These observations align with Marschan-Piekkari and Welch's framework of "shadow structures," where multilingual employees act as connectors, bridging formal and informal organizational networks, and enabling richer "cross-pollination" of ideas for innovation.[5] However, our interview data reveal operational challenges, such as adapting to various communication styles and standardizing processes without sacrificing regional adaptation or excluding voices less fluent in dominant corporate languages. These nuances complement Henderson, Marschan-Piekkari, and Welch's findings by highlighting how language hierarchies and shadow structures persist in impeding equitable participation and knowledge flow.[3,5] Moreover, training programs primarily delivered in one language were seen as a barrier to full knowledge absorption by multilingual employees, suggesting that organizational initiatives still need to better support sociolinguistic competence and inclusive learning environments.

The findings highlight that while multilingual teams require operational costs related to multilingual hiring, training, and technology investments, the benefits in market reach, client satisfaction, and innovation strongly outweigh these expenses. As Employee 3 stated, metrics such as Net Promoter Scores were consistently higher in multilingual regions, illustrating tangible returns on investing in multilingual employees and language diversity. These results corroborate Feely and Harzing's argument that language management serves as a strategic asset fostering coordination and innovation.[11] This study advances this discussion by emphasizing the essential role of developing sociolinguistic competence and adaptive technologies to capitalize on this asset. Moreover, recommendations from interviewees to further invest in AI translation tools, language learning, and structured multilingual collaboration sessions align with existing literature urging companies to develop language management strategies.[5] This indicates that maximizing innovation from multilingualism requires organizational initiatives addressing sociolinguistic competence.

Conclusion

This study examined how multilingualism among employees enhances innovation within linguistically diverse workplaces (LDWs), focusing on Crimson Education as a case study alongside contextual insights from multinational technology firms. The findings affirm that multilingualism fosters innovation by improving communication, knowledge sharing, and the integration of diverse cultural perspectives. Multilingual employees serve as bridges across languages and cultural divides, facilitating inclusive dialogue that contributes to innovative outcomes such as localized products, targeted marketing campaigns, and customized client services. Moreover, organizational investments in language management and technological tools, such as AI translation systems, further amplify these benefits. The study also revealed that multilingual strategies, such as code switching and language convergence, facilitate inclusion and the sharing of insights and information. In synthesizing these insights, this study corroborated that multilingualism provides a cognitive and cultural resource that enhances knowledge exchange, creative problem-solving, and adaptation in LDWs.

Despite the research confirming core elements of the hypothesis, some challenges remain unresolved, including communication nuances that lead to misunderstandings, as well as persistent social dynamics that marginalize less proficient speakers when training and formal documentation favor a single dominant language. These issues suggest that while multilingualism is a powerful resource for innovation, its potential depends on sociolinguistic competence development and inclusive organizational policies. This study validates and expands key findings from the literature by showcasing how effectively managed multilingual teams contribute to richer knowledge networks and better localized innovation outcomes.

Important questions emerge from this study, such as "How can companies better balance the dominance of corporate lingua francas with the linguistic diversity present in workplaces?" Future research could explore these dynamics and their direct impact on innovation. Experimental designs might measure innovation through organizational outcomes rather than employees' perceptions. Additionally, exploring the impact of emerging AI language tools on mitigating communication barriers and fostering innovation shows promise for future research.

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This study confirms that multilingualism, when supported by sociolinguistic competence, organizational policies, and technological infrastructure, is a powerful tool for innovation in linguistically diverse workplaces (LDWs). It accentuates the complexity and importance of language's role as not merely a communication tool but also a dynamic cultural and cognitive resource that influences knowledge sharing, creativity, and competitive advantage. Organizations committed to leveraging multilingualism must continue investing strategically in language skills development, inclusive practices, and adaptive technologies to harness the full innovative potential embedded in their multilingual workforces.

Ethics

This study received informed consent from all participants before data collection, while ensuring that they understood the purpose of the study. The identities of the participants were protected through anonymization and appropriate handling of interview transcripts. Furthermore, confidentiality measures were maintained throughout data analysis and reporting to safeguard participant privacy.

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References

1. *Oxford English Dictionary*. 2025.
2. Cambridge Dictionary | English Dictionary. 2025.
3. Henderson, J. K. Language Diversity in International Management Teams. *Int. Stud. Manag. Organ*. 2005, 35(1), 66–82.
4. Ahmad, F.; Widen, G. Language clustering and knowledge sharing in multilingual organizations: A social perspective on language. J. Inf. Sci. 2015, 41(4), 430-443.
5. Piekkari, R.; Welch, L. In the shadow: The impact of language on structure, power and communication in the multinational. *Int. Bus. Rev*. 1999, 8(4), 421-440.
6. Ahmad, F.; Widen, G. Knowledge sharing and language diversity in organisations: Influence of code switching and convergence. *Eur. J. Int. Manag*. 2018, 12(4), 351-373.
7. Swanborn, P. *Case Study Research: What, Why and How?*. SAGE. 2010.
8. Cohen, L.; Henderson, J. K. Revisiting culture and language in global management teams: Toward a multilingual turn. *Int. J. Cross Cult. Manag*. 2017, 17(1), 7-22.
9. Chen, S.; Geluykens, R.; Choi, C. J. The importance of language in global teams: A linguistic perspective. *Manag. Int. Rev*. 2006, 46(6), 679-696.
10. Tenzer, H.; Pudelko, M. The Impact of Language Diversity on Multinational Teamwork. *Research Gate*. 2020.
11. Feely, A.; Harzing, A.W. Language Management in Multinational Companies. *Cross Cult. Manag*. 2002, 10(2).
12. Ahmad, F. Knowledge-sharing networks: Language diversity, its causes, and consequences. *Knowl. Process Manag*. 2017, 24(2), 139-151.
13. Ahmad, F. Knowledge sharing in a non-native language context: Challenges and strategies. *J. Inf. Sci*. 2018, 44(2), 248-264.
14. Gupta, A. K.; Singhal, A. Managing Human Resources for Innovation and Creativity. *Res. Technol. Manag*. 1993, 36(3), 41–48.
15. McAll, C. Language dynamics in the bi-and multilingual workplace. *Bilingual Education and Bilingualism*. 2003, 235-250.
16. García, M. C.; Pérez, M.L. Language and Power: Raising Awareness of the Role of Language in Multicultural Teams. *Lang. Intercult. Commun*. 2005, 5(2), 104-86.
17. Rangus, K.; Drnovšek, M.; Di Minin, A.; Spithoven, A. The Role of Open Innovation and Absorptive Capacity in Innovation Performance: Empirical Evidence from Slovenia. *J. East Eur. Manag. Stud*. 2017, 22(1), 39–62.
18. Tenzer, H.; Terjesen, S.; Harzing, A. W. Language in International Business: A Review and Agenda for Future Research. *Manag. Int. Rev*. 2017, 57(6), 815–854.
19. Welch, L.; Welch, D. The importance of language in international knowledge transfer. *Manag. Int. Rev*. 2008, 48(3), 339-360.

Author

Natsumi Uehara is a recent graduate of Colegio La Unión (La Unión High School) with a strong interest in both business and languages. She aspires to major in business management in college, where she aims to develop her skills further and continue pursuing her love of research.

Appendix

Document 1: Survey:

Introduction:

Dear Participant,

I am Natsumi Uehara, and I am conducting research on how multilingualism among personnel enhances innovation in linguistically diverse workplaces (LDW). This survey is designed for multilingual employees who have worked at their current company for at least one year. Your participation is invaluable, and I am grateful for the time you will dedicate to this survey. Please note that this survey is anonymous unless you choose to provide your email address. If you have any questions or need further clarification, please do not hesitate to contact me at uehara.nat@gmail.com

Thank you again for your participation.

Profile information:

1. How long have you been working for the company?
- Less than 1 year
- 1-3 years
- 4-6 years
- More than 6 years

2. How many languages are you proficient in?
- 1 language
- 2 languages
- 3 languages
- 4 languages
- ●More than 5 languages

3. List the languages in which you are proficient, meaning you can read, write, and speak them effectively in a professional context.

4. What is the name of your company?

5. What is your job title and role in the company?

Agree/Disagree Questions:

For the following questions, please rate your level of agreement with each statement, from 1 (Strongly Disagree) to 5 (Strongly Agree).

6. At work, I frequently communicate in two or more languages.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

7. Multilingualism (proficiency in more than one language) is important for my job performance.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

8. Multilingualism enhances communication between my colleagues and me.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

9. I often collaborate with colleagues who are multilingual.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

10. I often collaborate with colleagues who speak a language that I don't.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

11. Multilingualism enhances my ability to understand different cultural contexts.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

12. Multilingualism encourages the sharing of knowledge among the members of my team.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

13. I believe that multilingualism in the workplace helps employees to understand each other's ideas.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

14. Multilingualism reduces misunderstandings in my team's communication.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

15. Multilingualism gives my organization a competitive advantage.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

16. My company actively fosters multilingualism through its hiring and education policies.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

17. My company leverages employees' multilingual capabilities.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

18. I believe that multilingualism in companies has a positive impact on creativity and innovation.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

19. Multilingualism has allowed for greater creativity in brainstorming sessions on my team.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

20. Multilingualism allows my team to access and apply knowledge from sources in different languages, contributing to innovative solutions.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

21. Multilingualism has allowed for greater innovation by my team.
- 1 Strongly disagree, 2 disagree, 3 neutral/unsure, 4 agree, 5 strongly agree

Free response:

22. What challenges do you face when communicating in a multilingual environment?

23. How do you think multilingualism affects the overall culture of your workplace?

24. What benefits or drawbacks do you see in working in a linguistically diverse environment?

25. Do you think multilingualism has contributed to innovation in your own work at your company? (Yes/No)
- If yes, please give some examples. If no, please explain why. _____

26. Do you think multilingualism has contributed to innovation at your company more broadly? (Yes/No)
- If yes, please give some examples. If no, please explain why. _____

27. Do you think your company could better leverage multilingualism to enhance innovation? If so, how?

28. Do you think that multilingualism influences your company's ability to adapt to new technologies or markets? If so, how?

29. Please share any personal experiences in which speaking two or more languages in the workplace helped you or your team to achieve a goal more effectively.

30. Have you noticed a difference between multilingual teams and monolingual teams in terms of their respective levels of innovation? Please explain.

Closing message:

Closing Message

Thank you for submitting your responses!

Your participation is greatly appreciated, and I wish you all the best in your professional endeavors.

Document 2: Interview questions:

1. How does your company view the connection between multilingual staff and innovation outcomes?

2. What initiatives has the company implemented to leverage language diversity for the promotion of innovation? (Hiring practices, training programs, technology, patent filing, etc.)

3. How do you mitigate "language hierarchy" dynamics where fluency in a dominant language inadvertently silences innovative ideas from less fluent multilingual staff?

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4. What mechanisms exist to ensure multilingual employees' cultural perspectives directly inform product development/ market expansion strategies?
5. Which investments in multilingual infrastructure (translation AI tools, language training programs, and others) have most directly boosted innovation, and why?
6. How are the operational costs associated with coordinating multilingual teams balanced against the potential benefits of increased innovation that they can bring?
7. What KPIs (Key Performance Indicators) track whether multilingual teams out- innovate monolingual ones in areas such as patent diversity?
8. Can you share a recent example where a multilingual team solved a problem or a challenge that monolingual teams had struggled with (or likely would have struggled with)? (For example, thanks to cultural insights, improved communication, greater collaboration, etc.)
9. What industry-specific opportunities remain unexploited because your staff's multilingual capabilities aren't being leveraged fully?
10. If you could implement one policy or approach to amplify multilingualism's impact on innovation at your company, what policy or approach might you propose?

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RESEARCH ARTICLE

The Influence of the Russian Central Bank on the Russian Economy Under the Multiple G7 and EU Sanctions

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ABSTRACT: The sanctions from the EU and G7 have affected the Russian Federation since the 2022 Russia-Ukraine Conflict escalation. Especially the freezing of the foreign reserves was a major strike against the Russian financial stability. This article evaluates the role of the Russian central bank in mitigating these sanctions. Furthermore, the policy impacts of the Kremlin and the Finance Ministry have been elaborated. The author's thesis is that the Russian central bank has successfully managed the Russian economy through unprecedented sanctions. The qualitative data sources used in this research are secondary datasets and an interview with the governor of the Russian central bank. The study found that the Central Bank of Russia has adopted a high Key Interest Rate policy to fight higher inflation than officially communicated. The aim has been to contain a proliferating Money Supply M2, necessary to prevent economic downfall. All of this was caused by both the sanctions and the war economy. The Kremlin and Finance Ministry have been thwarting these efforts by an excessive military budget and privileged loans to war-related companies. Considering all of this, the thesis is true. The Russian central bank has kept its economy afloat with its monetary policies.

KEYWORDS: Economics, Monetary Economics, Russia-Ukraine Conflict, Central Bank of Russia, Sanction Packages.

Introduction

In 2014, Russia annexed Crimea, violating international law.[1] Consequently, Russia faced many sanctions coming from the EU (European Union) and the G7 countries (Germany, France, Italy, Japan, Canada, the USA, and the UK (United Kingdom)).[1,2] This evolved even further when Russia invaded Ukraine in 2022, being the first major armed conflict in Europe since the Yugoslav war ended.[1] Hence, this was a present danger to amity and stability on the continent.[1] The G7 and the EU established a wide variety of financial and economic sanction packages against Russia in response to the invasion.[2] Since the beginning of the war in February 2022, a total of 18 sanction packages have been implemented.[3] This really affects the economy, as one can see in the economic metrics of the Russian Federation.[4-8] Furthermore, the Russian central bank had to intervene with a high Key Interest Rate to fight the extraordinary Inflation Rate.[8] This, combined with other monetary policies, has made the central bank a key player in mitigating the impacts of the sanctions.

This research paper examines how the Russian central bank influences the Russian economy through the multiple US and EU sanctions. This study will focus on the financial sanctions affecting the central banks, for instance, the freezing of the foreign reserves of the Central Bank of Russia (CBR).[2,9] Moreover, it will reflect on the counteractions and thus the effects the CBR has on the Russian economy. This research is based on an in-depth literature review. In addition, empirical qualitative secondary datasets, such as interviews, were used. Quantitative data were aggregated and then analyzed to create qualitative output. Combining these approaches, this paper aims to have an empirical qualitative approach to elaborate on this current topic.

The Results and Discussion have been structured as follows: First, the different kinds of sanctions have been elaborated to enlighten on the wide variety of measures taken against Russia. Second, the impacts on the Russian economy have been expounded to better understand the effects these sanctions have on Russia. Third, the counteractions of the CBR against the sanctions adopted by the EU and G7 countries have been evaluated, looking at their effectiveness and possible antagonists.

The author argues that it will become impossible for the CBR to effectively mitigate the economic downfall if the Kremlin and the Finance Ministry continue to augment the Money Supply in the current way.

Methods

This research utilizes an organized and detailed approach to examine the relevant literature and qualitative data analysis of secondary data. To minimize biases and thus prevent subjective selection of results, a systematic approach has been applied. To explicitly search for adequate sources of information, keywords such as "Russia-Ukraine Conflict", "Inflation", "CBR", and "sanction packages" were utilized when using Google Scholar. First, a look at the *EU Sanctions Map* helped to better understand the scale of the sanctions properly.[10] Regarding the timeline, no restrictions were placed. However, articles published starting in 2022 were preferred when talking about specific war-related topics. This was done to have current databases and include sanctions adopted after the invasion of Ukraine in 2022. In addition to articles from journals, articles from renowned sources such as the *Guardian* and others

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have been used. Most of the sources from scientific journals have been picked before starting the writing process. On the contrary, articles from magazines have been consulted when questions came up during the writing process. For the data, Trading Economics was used to have reliable sources on the GDP, Inflation Rate, and Money Supply M2 of the Russian Federation.[4,5,7] There was a second Inflation Rate mentioned in the paper, the observed Inflation Rate.[11] This was measured by a survey conducted by the Central Bank of Russia.[11] Money Supply M2 includes M1 (checking accounts, physical currency, and other demand deposits) combined with short-term time deposits in banks.[7] Also, the *Center for European Policy Analysis (CEPA)* was used to get data on Russia's National Defense Budget.[12] In addition, Statista was consulted to find trustworthy data on the Key Interest Rate of Russia.[8] An empirical qualitative approach was chosen because the author wanted to enlighten on this topic, rather in depth than in breadth. Furthermore, elaborating on the interconnection between specific economic metrics and expounding the influence of the CBR and other parties were the main reasons for choosing a qualitative approach.

Results and Discussion

Financial sanctions adopted by the EU and G7 countries:

Examining the *EU Sanctions Map*, Russia is the main target of European sanctions, having 59 different sanctions adopted against it, including 25 financial measures.[10]

Arguably, the most powerful was the freezing of the foreign reserve assets. It was referred to as "the most powerful weapon in the West's financial arsenal", according to the Wall Street Journal.[13] Further elaborating, roughly 300 billion US dollars in Russian state assets have been frozen by the EU and G7, a total of 60% of all foreign reserve assets.[14,15] Out of those, 200 billion Euros are being administered by Euroclear in Belgium.[14] However, this interferes with the unspoken rule of not targeting the sovereign immunity of central banks, even though it has happened before (e.g., Iran).[2]

Another set of sanctions referred to the exclusion of several Russian banks from the SWIFT messaging system. Through this, they were cut off from the global financial network and not granted access to central banks' real-time gross settlement systems.[2] This started with the third sanctions package adopted against Russia, established after the first week of the war.[3] Since the beginning of the war, a total of 18 sanction packages have been implemented.[3]

Also, the process of freezing the financial assets of sanctioned entities took place.[2] This included Russian officials, elites connected to the government, and their family members.[2] It is estimated that around 2000 companies and individuals are affected.[14] Reportedly, the magnitude of this confiscation adds up to approximately 58 billion US dollars.[14]

The effects of the sanctions on the Russian economy:

To evaluate the impact of the sanctions on the Russian economy, two economic metrics have been chosen, the Gross Domestic Product (GDP)[4] and the Inflation Rate.[5] They have been picked for specific reasons. First, the GDP offers an insight into the well-being of the economy. One could argue that the higher the GDP, the better the economy is working. On the other hand, the Inflation Rate shows the change in prices in a country. This can indicate economic booms or depressions, as well as a high or low Money Supply. There has been a limitation in using the GDP as an economic metric. This is why the production volumes were depicted after the GDP to better understand the state of the Russian economy.

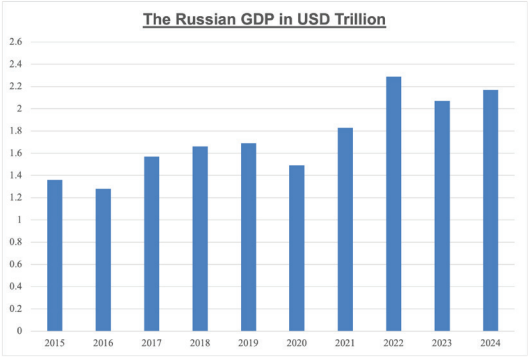

Figure 1: The Russian GDP in USD Trillion from 2015 to 2024. After several years of hardly any growth, the national GDP strongly increased in 2022. Figure created by author, data aggregated from Trading Economics.[4]

Both real and nominal GDP development for Russia suggest an economic boom, the nominal one being depicted in Figure 1.[4,16] In the year 2022, the Russian GDP was the highest of the 10 year-period depicted above (2,29 trillion USD). The years after 2022, respectively 2023 and 2024, had a lower GDP than in 2022, still exceeding the 2 trillion-dollar mark.[4] One may wonder how the Russian economy can boom on paper whilst being sanctioned by the G7 and the EU.[2] However, the GDP of these years is misleading. By further exploring this topic, one realizes that this does not mean that Russia is having a growth boom. "*It means the Russian government is pouring money into the economy, particularly industries that support the war effort. Russia's Ministry of Finance estimates that fiscal support alone amounted to 11 % of GDP in 2022–2024, representing a sharp break from earlier budget policy.*"[17] To further elaborate on the contraction of growth of the Russian economy, the production volumes of the first two quarters of 2022 have been compared with the same timespan the year before (2021). They are stated in the table below.[18]

Table 1: The production volumes of the Russian Federation during the first two quarters of 2022 compared with the year before.

Economic sector	Growth
Motor vehicles and (semi-)trailers	-62,2%
Tobacco goods	-32,3%
Ready-made metal products, except for machines and equipment (including construction structures)	-16,9%
Wood processing, wood production, and cork products	-14,6%
Computers and their components, computer peripherals, electronic and optical products	-12,0%
Textile products	-7,9%
Chemical industry	-7,7%
Metallurgical production	-6,4%
Clothing	-5,1%

In Table 1, the effects of the sanctions are clearly visible. As the sanctions were adopted in early 2022, the immense effects

the Russian economy had to face due to the measures against Russia are visible.[2] Regardless, three sectors had economic growth in the period between June 2021 and June 2022. The first one being extractive industries with a growth of 20,1%, followed by the production of medicine with a progression of 16,5%, and the production in the sector of services for extractive industries (8.1%).[18] There is a significant reason why exactly these three sectors have grown. For instance, the extractive sector was pushed to increase production due to the Russian government's need for revenue to finance the war.[19] It is logical that the growth in production in the sector of services for extractive industries goes hand in hand with this. Regarding the production of medicine, the Russian "Pharma 2030 Strategy" aims to double the national production of pharmaceutical goods.[20] Furthermore, Russia offered local pharmaceutical companies weighty government deals. Due to the foreign distributors not importing medicine into Russia, the domestic companies benefited from the war.[21] Arguably, the rising demand for medication may be linked to war-related injuries.

Figure 2: The Inflation Rate from July 2020 to July 2025. After a steep increase in 2022, the Inflation Rate decreased, reaching a new low in April 2023. From then on, it gradually increased again up to roughly 10%. Figure created by author, data aggregated from Trading Economics.[5]

In Figure 2, the Inflation Rate of the Russian Federation is portrayed, which has been relatively high compared to the worldwide average.[5,22] As mentioned before, Russia invaded Ukraine in February 2022, which was immediately answered by sanctions. The sanctions' impacts on the Russian economy can be perfectly seen in Figure 2 as the Inflation Rate went from 9,2% (February 2022) to 16,7% (March 2022).[5] Furthermore, this was accompanied by an immense fall in the exchange rate of the Russian national currency, the Ruble. The Ruble devalued by 41,5% on the first market opening after the adoption of the sanctions.[23] This changed the exchange rate from Ruble to USD from 83,7 Ruble per Dollar to 119 Ruble per Dollar.[23] Even though the inflation rate fluctuates a lot, as one can see above, one can argue that the sanctions had an immediate impact on the Russian economy.[5] However, one year after the adoption of the sanctions, the situation changed.[5] From February 2023 to March 2023, the inflation rate declined from 11% to 3,5%, eventually being at a long-time low of 2,3% in April 2023.[5] This happened due to the base effect, which refers to the influence of the high Inflation Rate in the same period the year before.[24] Thus, a basic mathematical phenomenon.

The role of the Russian Central Bank:

The Central Bank of Russia has played a central role in mitigating and responding to the impact of sanctions on the national economy.

As an attempt to cover the shortage in Russia's budget, the "printing press" was activated.[25] According to calculations, since the beginning of the war, the CBR has printed 8,2 trillion Rubles (equal to 103 billion USD).[6,25]

Figure 3: The Russian Money Supply M2 in RUB Trillion from June 2020 to June 2025. The Money Supply M2 has continuously increased since June 2020, with a strong incline starting in 2022. Figure created by author, data aggregated from Trading Economics.[7]

In Figure 3, one can see the extent of the usage of the printing press.[7] In the ten years depicted, the Money Supply M2 is continually increasing. However, the gradient surged drastically starting with the outbreak of the war.[7] In January 2022, shortly before the beginning of the Russia-Ukraine Conflict, the Russian Money Supply amounted to 65,3 trillion Rubles.[7] This number skyrocketed to 119 trillion Rubles in June 2025, almost doubling.[7] Nevertheless, a high Money Supply is associated with increasing inflation.[26] Thus, it may seem counterintuitive to increase the Money Supply M2 when inflation is high.[5,7] However, increasing the Money Supply M2 is caused by the National Defense Budget.

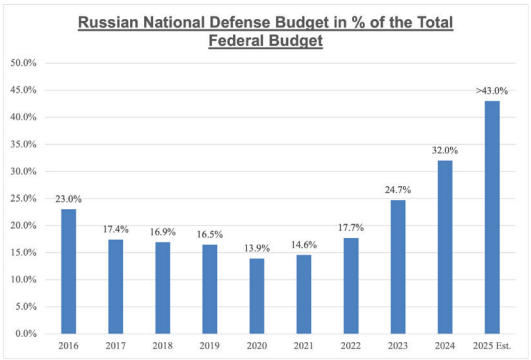

Figure 4: The Russian National Defense Budget as a percentage of the Total Federal Budget of Russia. Since 2022, the National Defense Budget of Russia has more than doubled as a percentage of the total household budget. Figure made by author, data aggregated from references 12, 27, 28, 29, 30, 31, 32, 33 (data on the absolute Russian National Defense Budget was put into relation with the Total Federal Budget of Russia in each year shown above).

As a matter of fact, Russia's National Defense Budget amounted to 13 trillion Rubles in January 2024.[12] Russia's Minister of Defense stated in December 2024 that 32,5% of the total federal budget of 40,6 trillion Rubles was used for

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defense spending.[27] Furthermore, the amount needed in 2025 is estimated to be even higher.[27] According to the State Duma, the funding of army requirements as well as the supervision of society will represent more than 43% of the budget in 2025.[28] The need for money to finance the war may be the reason for adopting a high Money Supply policy. It seems as if the invasion of Ukraine is the main target of the Russian Federation, resulting in high inflation and economic decrease.

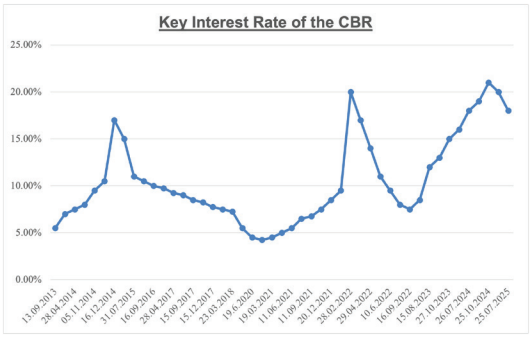

Figure 5: The CBR's Key Interest Rate from September 13, 2013, to July 25, 2025. The Key Interest Rate of the CBR shows three spikes. One in 2014, one in 2022, and one in 2024. Figure created by author, data aggregated from Statista.[8]

In Figure 5, the Key Interest Rate of the Central Bank of Russia is depicted.[8] It shows how the Russia-Ukraine Conflict heavily impacted the regulation of the CBR's Key Interest Rate.[8] To further elaborate, from February 11th, 2022, to February 28th, 2022, the Key Interest Rate was raised from 9,5% to 20%.[8] As a matter of fact, Figure 5 displays two spikes of the key interest rate.[8] The first took place during the initial days of the war in February 2022, when the sanctions kicked in, bringing the Ruble value to an all-time low.[2,34] The second spike occurred gradually in 2023 and 2024, with a peak in October 2024.[8] Now what is interesting about Figure 5 is that the CBR continually lowered the Key Interest Rate up until September 2022 (-12,5%).[8] However, from this point on, a drastic increase took place, reaching 21% Key Interest Rate in October 2024.[8] This was due to the rising inflation, as shown in Figure 2.[5,35] At first, the Inflation Rate may not seem too high, being 9,4% in June 2025.[8] Nevertheless, a survey conducted by the Central Bank of Russia shows a different perspective.[11] The respondents' perception is that the prices are growing 14-15% per annum.[11] What would speak in favor of this observed inflation is the history of the Key Interest Rate and Inflation Rate in Russia.[11] In fact, ever since the establishment of a Key Interest Rate in Russia, the Key Interest Rate never surpassed the Inflation Rate by more than 5-6% points.[11] Therefore, a 14-15% inflation would mean a maximum of 20-21% Key Interest Rate, which is what became reality.[8] This would explain why the CBR significantly increased its Key Interest Rates, fighting a higher inflation than officially communicated.

The governor of the CBR, Elvira Nabiullina, stipulates in her press conference of April 25th, 2025: "*We will maintain tight monetary conditions for a long period. This is reflected in our forecast of the average key rate for this year that will be in the range of 19,5–21,5%. A high key rate will ensure a slowdown in current price growth to 4% by the end of this year and will help stabilize inflation at 4% in the future.*"[36] Through this, one can argue that inflation is a big problem as the Central Bank of Russia is willing to keep key interest rates at record high levels. This would once again support the hypothesis that the real inflation rate is moving around 14-15%.

Interestingly, the Money Supply's mean rate of change from September 2022 up until October 2024 increased immensely compared to the rest of the ten-year timespan.[7] This is similar to the Key Interest Rate.[8] The reason for the increase in the Key Interest Rates may be to lower the growing Money Supply M2. It is very likely that the Central Bank of Russia tries to fight the high Inflation Rate by trying to diminish the Money Supply M2. They are trying to do that by adopting high interest rates to reduce the amount of money in circulation. Regardless, this measure alone did not live up to its expectations.[11] The lack of efficiency of this measure is due to the powerful and influential antagonists of the CBR, the Finance Ministry of Russia, and the Kremlin.[37,38] The Finance Ministry pours money into circulation through the creation and financing of military orders.[37] The hence created increase in Money Supply M2 causes the Inflation Rate to increase.[37] "The Central Bank tries to keep a lid on inflation caused by the Finance Ministry, but is unable to as it has no control over what the ministry does, and the ministry doesn't manage its expenses. Those figures are decided by war."[37] Regarding the other key player, the Kremlin, the influence is quite different.[38] In December 2021, shortly before the outbreak of the war, the Kremlin silently introduced a new policy.[38] The policy implements the legal obligation of banks to provide loans to war-related businesses at preferential terms decided by the Kremlin.[38] This counteracts the measures taken by the CBR to fight inflation.[38] When gradually increasing the Key Interest Rate to 21%, the market responded in two different ways.[8,38] Money borrowed from regular companies decreased in line with economic theory.[38] However, war-related companies that continue to enjoy attractive terms backed by the state continue to engage in excessive borrowing.[38]

It seems as if the Central Bank of Russia has its hands tied to some degree. The effects of fighting the economic degrowth and high inflation seem to be mitigated by the Kremlin itself and the Finance Ministry.

■ Conclusion

This study found that the Central Bank of Russia's influence on the Russian economy during the war sanctions has been considerably high. Regardless, the CBR faces challenges in lowering the Inflation Rate and bettering the national economy. This is due to the war policies adopted by the Kremlin and the Finance Ministry. The Russian economy struggled because of the adoption of sanctions from the EU and G7 countries. Especially the freezing of the foreign reserves was a major strike against the Central Bank of Russia as it limits its capabilities of stabilizing the Ruble exchange rate. The effects have been visible in Russia's economic metrics. For instance, the GDP only grew because of war-related spending, and the Inflation Rate skyrocketed as the Money Supply M2 augmented. Therefore, the Key Interest Rate had to be adjusted to a record 21%. The author finds that the CBR could have miti-

gated these outcomes if the Finance Ministry and the Kremlin had not interfered. Due to the war-related spending and state-backed privileged loans, the Money Supply M2 continuously soared. This drove inflation beyond official rates, hence inhibiting the room for maneuver of the CBR to cut the very high Key Interest Rate that is crowding out the non-war-related businesses. The author argues that it will become impossible for the CBR to effectively mitigate the economic downfall as long as the Kremlin and the Finance Ministry continue to augment the Money Supply in the current way. The sustainability of this internal conflict, and what economic or political breaking point it might create, are subjects for future research. The author particularly recommends further investigating the real inflation rate vs the officially communicated inflation. Another scope of research should cover the contraction of the non-military-related parts of the economy. Drawing on public choice theory of sanctions and grievance theory, the implications for household incomes and thus social/political stability.

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References

1. Duschanek, M. All quiet on the east? A political and economic analysis of the EU sanctions against Russia over the Ukrainian Crisis. M.S. Thesis, Vienna School of International Studies, 2022. https://phaidra.univie.ac.at/detail/o:1543380.pdf
2. Quaglia, L.; Verdun, A. Weaponization of finance: the role of European central banks and financial sanctions against Russia, West European Politics. *West European Politics* **2023**, 46:5, 872-895, DOI: 10.1080/01402382.2022.2155906
3. European Council. Timeline - Packages of sanctions against Russia since February 2022. *European Council*. https://www.consilium.europa.eu/en/policies/sanctions-against-russia/timeline-packages-sanctions-since-february-2022/
4. *Trading Economics*. Russia's GDP. https://tradingeconomics.com/russia/gdp
5. *Trading Economics*. Russia Inflation Rate. https://tradingeconomics.com/russia/inflation-cpi
6. *Google Finanzen*. Russischer Rubel in US-Dollar. https://www.google.com/finance/quote/RUB-USD?sa=X&ved=2ahUKEwin_ZSQufiOAxUJ9wIHHVsaE3IQmY0JegQIHxAv (accessed 2025-08-07)
7. *Trading Economics*. Russia Money Supply M2. https://tradingeconomics.com/russia/money-supply-m2
8. *Statista*. Leitzinsentwicklung der russischen Zentralbank von 2013 bis 2025. https://de.statista.com/statistik/daten/studie/1293248/umfrage/leitzins-der-zentralbank-russlands/
9. Obasun, O. Sanctioning of Russian Central Bank assets and consequential impacts on other central banks and international trade and investments. *African Journal of Business Management* **2024**, 123-135, 75318E472368. DOI: 10.5897/AJBM2024.9535
10. European Union. *EU Sanctions Map*. https://www.sanctionsmap.eu/#/main
11. Belkin, V. Losing the inflation battle: Why the Central Bank can't contain Russia's rising prices and what it means for the economy. *The Insider*, December 28, 2024. https://theins.ru/en/economics/277585
12. The Moscow Times. Russia Moves to Revise 2025 Budget on Lower Energy Revenues and Wider Deficit. *The Moscow Times*, June 11, 2025. https://www.themoscowtimes.com/2025/06/11/russia-moves-to-revise-2025-budget-on-lower-energy-revenues-and-wider-deficit-a89416
13. Fairless, T. Sanctions on Russia's Central Bank Deal Direct Blow to Country's Financial Strength. *The Wall Street Journal*. https://www.wsj.com/livecoverage/russia-ukraine-latest-news-2022-02-26/card/sanctions-on-russia-s-central-bank-deal-direct-blow-to-country-s-financial-strength-AGe2bBTKmYW2bzqRnNWI
14. Moiseienko, A. Frozen Russian State Assets. *Verfassungsblog*, 4 April 2025. https://verfassungsblog.de/frozen-russian-state-assets/
15. Boocker, S.; Connor, A.; Wessel, D. Making Russia Pay. *Milken Institute Review*, April 5, 2024. https://www.milkenreview.org/articles/making-russia-pay#:~:text=Where%20are%20the%20Russian%20Reserves,$5%20billion%20in%20the%20U.S
16. *World Bank Open Data*. GDP (constant 2015 US$) - Russian Federation. https://data.worldbank.org/indicator/NY.GDP.MKTP.KD?end=2024&locations=RU&start=2015
17. Simola, Heli. Russia's GDP growth reflects military spending, not economic strength. *Bank of Finland Bulletin. Articles on the Economy*. November 28, 2024. https://www.bofbulletin.fi/en/blogs/2024/russia-s-gdp-growth-reflects-military-spending-not-economic-strength/#:~:text=It%20means%20the%20Russian%20government,break%20from%20earlier%20budget%20policy
18. Shapran, N.; Britchenko, I.; Haponiuk, M.; Shapran, V. The impact of the sanctions on the economy of the Russian Federation. *VUZF Review* **2022**, 7 (3), 13-22. DOI: 10.38188/2534-9228.22.3.02
19. Khokhlov, O. From Decline To Overheating: Russian Industry Thrives Amid Military Fever. https://re-russia.net/en/analytics/079/
20. DrugPatentWatch. The Russian Pharmaceutical Industry: Strategic Evolution and Key Players. *DrugPatentWatch*, April 24, 2025. https://www.drugpatentwatch.com/blog/the-russian-pharmaceutical-industry-strategic-evolution-key-players-and-technological-innovation/#:~:text=A%20primary%20objective%20during%20the,12
21. Djankov, S.; Golovchenko, A. Who benefits from Russia's war in Ukraine? *CEPR*, January 6, 2025. https://cepr.org/voxeu/columns/who-benefits-russias-war-ukraine
22. *World Bank Open Data*. Inflation, consumer prices (annual %). https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG
23. Farrer, M.; Roth, A.; Borger, J. Ukraine War: sanctions-hit Russian rouble crashes as Zelenskiy speaks of 'crucial' 24 hours. *Guardian*, February 28, 2022. https://www.theguardian.com/world/2022/feb/28/ukraine-war-sanctions-hit-russian-rouble-crashes-as-zelenskiy-speaks-of-crucial-24-hours
24. Reuters. Russian consumer inflation drops below 4% target for the first time in a year. *Reuters*, April 12, 2023. https://www.reuters.com/markets/europe/russian-consumer-inflation-drops-below-4-target-first-time-year-2023-04-12/
25. *Why did Russia launch the «printing press»?* Center for Countering Disinformation. https://cpd.gov.ua/en/results/rf-en/why-did-russia-launch-the-printing-press/ (accessed 2025-08-07)
26. USAFacts team. What is the money supply, and how does it relate to inflation? *USAFacts*, September 29, 2022. https://usafacts.org/articles/what-is-the-money-supply-and-how-does-it-relate-to-inflation-and-the-federal-reserve/

DOI: 10.36838/IJHSR811.172

27. Luzin, P. Russia's Year of Truth: The Runaway Military Budget. *CEPA*, January 22, 2025. https://cepa.org/article/russias-year-of-truth-the-runaway-military-budget/
28. Wiśniewska, I. Russia's budget for 2025: war above all. Center for Eastern Studies (OSW), November 22, 2024. https://www.osw.waw.pl/en/publikacje/osw-commentary/2024-11-22/russias-budget-2025-war-above-all
29. *Law on 2020 federal budget execution signed*; President of Russia. http://en.kremlin.ru/acts/news/67001 (accessed 2025-08-17)
30. *2019 federal budget execution report approved*; President of Russia. http://en.kremlin.ru/acts/news/64235 (accessed 2025-08-17)
31. *Law on the 2018 Federal Budget execution*; President of Russia. http://en.kremlin.ru/acts/news/61825 (accessed 2025-08-17)
32. Cis-Legislation. Federal Law of the Russian Federation. About the execution of the federal budget for 2017. *Cis-Legislation*, October 11, 2018. https://cis-legislation.com/document.fwx?rgn=110648
33. *Law on the 2016 Federal Budget executio*n; President of Russia. http://en.kremlin.ru/acts/news/55860 (accessed 2025-08-17)
34. *Trading Economics*. Russian Ruble. https://tradingeconomics.com/russia/currency
35. Boffa, C. Ruble tumbles as Russia's war economy comes under increasing strain. *Politico*, 27 2024. https://www.politico.eu/article/ruble-value-falls-russia-war-economy-ukraine-oil-prices-sanctions-inflation-interest-rates-oligarchs/
36. Elvira Nabiullina. Statement by Bank of Russia Governor Elvira Nabiullina in follow-up to Board of Directors meeting on 25 April 2025. *Central Bank of Russia*, April 25, 2025. https://www.cbr.ru/eng/press/event/?id=23577
37. Kanevskaya, S. Vested interest. How might the Central Bank's decision to raise Russia's key interest rate to 21% affect ordinary Russians? *Novaya Gazeta*, October 30, 2024. https://novayagazeta.eu/articles/2024/10/30/vested-interest-en
38. Kennedy, C. Russia's Hidden War Debt (full report). *Navigating Russia*, February 14, 2025. https://navigatingrussia.substack.com/p/russias-hidden-war-debt-full-report

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Viability of an Oblique Wing in Commercial Flight: Performance, Design, and Barriers to Implementation

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ABSTRACT: An oblique wing offers improved aerodynamic performance at a wide range of airspeeds, but it comes with a complex design as well as logistical and experimental barriers. By assessing the oblique wing's viability in commercial flight, the potential of the concept can be proved, giving the go-ahead for further exploration. This paper explores the viability, examining how the oblique wing compares to other wings in commercial flight, as well as some limitations that it faces. The working thesis of this paper is that the oblique wing offers a more efficient aerodynamic performance across a wide range, but suffers from stability issues and design limitations that make it difficult to control. This thesis will mainly be explored through experimental data (NASA AD-1, wind tunnel testing) and design solutions for oblique wings.

KEYWORDS: Aerospace Engineering, Aerodynamics, Aircraft Design, Oblique Wing, Commercial Flight, Stability and Control, Implementation Barriers.

Introduction

The oblique wing presents in its design and capabilities a promising alternative to conventional wing configurations like variable sweep wings and swept wings.[1] This is due to its ability to shift its wing position in accordance with its airspeed, reducing drag at high speeds like a swept wing but still maintaining aerodynamic performance at low speeds.[2] However, any regular variable sweep wing could also accomplish this– what differentiates the oblique wing even further is that the design complexity is much lower. A variable sweep wing has two pivot points that must withstand many forces, whereas an oblique wing has one pivot point that only has to withstand one. Its experimental advantages over these conventional wing designs have prompted research into its viability in supersonic commercial flight, where it may address challenges previous attempts have faced.[3,4]

However, there are some issues that come up when utilizing oblique wings, like control difficulties and instability caused by an uneven distribution of forces.[5-7] Furthermore, creating a design solution for an oblique wing commercial aircraft is difficult, as there are many more factors to consider than when creating a design for a conventional wing commercial aircraft, like configuration, structure, materials, aircraft dynamics, and more. However, there has been little to no research or testing into the field since the AD-1 tests of the 70s and 80s.[8,9] This research paper will explore the benefits and drawbacks of an oblique wing in commercial flight as well as the challenges that dissuade further design, testing, and implementation.

Through this, the paper can clarify the performance of oblique wings in commercial flight in comparison to conventional wing types, as well as the issues preventing the practical application of an oblique wing. By identifying these aspects, this paper aims to assess the viability of the oblique wing in future commercial flight.

Based on aerodynamic theory and past experimental data, the working thesis of this paper is that an oblique wing aerodynamically outperforms a standard wing at transonic speeds, bringing with it, however, several significant challenges, like stability, maintenance, and logistical issues such as cost and risk. This will be explored in three body sections. The first section is on the performance of an oblique wing in comparison to standard wing types. The second section is on the design challenges presented by an oblique wing, how the other design components of an aircraft would be affected by the presence of an oblique wing, and potential design solutions for oblique-wing commercial aircraft. The third examines the logistical and commercial barriers that are preventing the implementation of oblique wings in commercial flight.

Aerodynamic Performance of Oblique Wings

In this section, there will be an introduction to oblique wings, their history, and an analysis of their aerodynamics. This section will focus on explaining the aerodynamic forces of oblique wings and comparing them to those of conventional wing designs.

In order to assess how viable oblique wings are in commercial flight, one of the most important factors is aerodynamic capabilities. Forces like lift, drag, and wave drag at different speeds are what distinguish an oblique wing's capabilities from those of swept or variable sweep wings. Using both theoretical and experimental data, this section will compare the performance of the three wings.

1.1. Oblique Wing:

An oblique wing is, in essence, a variable sweep wing that features a single pivot. This single pivot allows for either side

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of the wing to achieve a high sweep angle, with the test aircraft reaching up to a 60-degree sweep.[10]

What separates this wing type from a conventional swept-wing is its ability to fluidly shift configuration and sweep angle in accordance with airspeed and Mach number. What separates it even further from a regular variable sweep wing is its single pivot point, which causes the wing to undergo fewer forces and less stress.[10]

1.2. History of the Oblique Wing:

In 1942, the chief engineer of the Aircraft Manufacturing Department of Blohm and Voss (BuV] Shipworks, Richard Vogt, proposed the P202, a radical new jet fighter design in the midst of World War II. The design featured a fighter plane that had a "straight, pivoted variable-sweep wing…"[11] The plane would take off and land with the wing at a 0 degree sweep position, but at high speeds it would pivot and reach up to a 35 degree sweep, becoming an oblique wing. However, Vogt's proposal would stay just that–a proposal. The P202 never made it past the conceptual stage, not even receiving an aircraft designation from the German Air Ministry.[11]

After the conclusion of World War II, Vogt was brought to the US through Operation Paperclip, a secret United States intelligence program that employed thousands of engineers and scientists from Nazi Germany.[12]

From there, the concept of the oblique wing was revitalized by NASA aeronautical engineer Robert T. Jones. Before this, Jones had "independently identified the benefits of swept-back wings for high-speed aircraft, regarded as one of the most important discoveries in the history of aerodynamics".[13] He also contributed heavily to concepts like aircraft-piloting control schemes for improved safety.

His work on the oblique wing began in 1945, when, at the NASA Ames Research Center in California, Jones began a multitude of analytical and wind tunnel studies. These studies indicated that a transport-sized oblique-wing aircraft would have distinctly better aerodynamic performance than a more conventional-winged aircraft at speeds up to Mach 1.4.[8]

With these discoveries, the concept of an oblique wing garnered more attention at NASA. This led to the creation of the NASA Oblique Wing, an uncrewed propeller oblique wing aircraft.[11] After obtaining this physical proof-of-concept, NASA designed and built the AD-1, the tests of which were conducted from 1979 to 1982.[11]

Since the AD-1 program, however, all physical testing for oblique wing aircraft has ceased, and only conceptual work has progressed.[8]

1.3. Lift Force of an Oblique Wing:

When looking at the oblique wing, its appearance and asymmetrical shape make it seem as if any aircraft sporting such a wing would corkscrew at any nonzero sweep angle. However, this is not the case, as the principles of lift generation still apply to the oblique wing and mostly disregard the shape.[9]

An oblique wing's asymmetrical shape, while causing asymmetrical lift distribution, still applies lift across its entire body. Similarly to conventional wing types, as long as the angle-of-attack remains positive, so too does the lift generated by the wing.

The concept that the oblique wing (and other variable sweep wings) are built around is that, according to the sweep angle of the wing, an aircraft can undergo variable amounts of lift, with the Coefficient of Lift (CL) decreasing rapidly as the sweep angle increases. A variable sweep wing is built to address the fact that with swept-back, delta, or straight wings, a plane is set on a configuration favoring either a specific speed or a wide range of speeds. In the former case, the wing performs poorly at speeds outside the targeted range, and in the latter, the wing performs at a mediocre level across a wide range. With a variable-sweep wing, you can achieve the positives of targeting a specific speed while avoiding the drawbacks of being locked into a configuration by shifting the sweep angle and modifying the generated lift.[15]

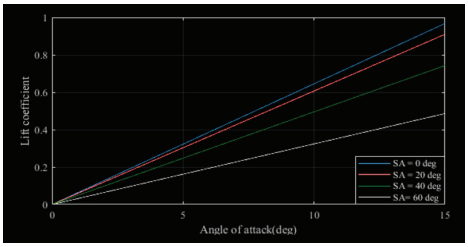

Figure 1: Sweep Angle vs Coefficient of Lift. This figure shows that as the sweep angle increases, the coefficient of lift significantly decreases, highlighting why oblique-wing aircraft display versatility across a wide range of speeds (Rahman *et al.*,).[16]

This effect can be seen in Figure 1, where the coefficient of lift (CL) decreases while the sweep angle increases in an oblique wing, starting at 1 for an AOA of 15 degrees, and at the maximum 60-degree sweep angle, the CL drops to 0.5. Due to the fixed nature of conventional wing configurations, the CL stays constant, which is why the oblique wing is more versatile. This can be seen in the delta wing–the high sweep angle leads to stellar performance at supersonic speeds, and this performance is reflected in the dominating presence of delta wings in modern interceptors and stealth jets of today.[1] However, these high-performance aircraft scrape by at lower speeds with their low lift coefficients. While the delta wing design works for its intended purpose, when taking into consideration the size and transonic speed of the average commercial aircraft, having insufficient lift at lower speeds can have more impactful consequences.[17]

$$L = Cl \times r \times \frac{V^2}{2} \times A$$

Lift = coefficient x density x $\frac{\text{velocity squared}}{\text{two}}$ x wing area

Figure 2: This figure presents the standard lift equation (NASA, n.d.).[17]

When analyzing the equation that gives us lift, it becomes apparent that the only variable that can be "tuned" mid-flight without causing any fatal stability errors is the surface area of the wing exposed to the airflow.

So, by changing the sweep angle of the wing and therefore modifying the CL, an oblique wing aircraft can tweak the amount of lift needed midflight, a process that can be automated, such as in the F-14 Tomcat.

Another important quality of an oblique wing is its asym-

metrical shape. As mentioned prior, the oblique wing's asymmetrical shape creates a respective asymmetrical distribution of lift.

This is due to an oblique wing having a higher local angle of attack in the side that is swept forward, and a lower angle of attack in the side that is swept back. This difference in angle of attack results in higher lift on the side that is swept forward, and lower lift on the side that is swept back. Through this, the center of lift gets shifted towards the forward-swept side in such a way that rolling and yawing moments are created, making the plane less stable, with a twitchier and jerkier flight path. [18]

1.4. Drag Force of an Oblique Wing:

Similar to the lift force an oblique wing experiences, the drag force is also impacted in multiple ways by the asymmetrical shape.

One of the most distinct ways that drag is influenced by an oblique wing's design is a significant reduction in wave drag.

Wave drag is a type of aerodynamic drag caused by shock waves that form when an aircraft begins to approach and exceed the speed of sound. The increased air pressure and energy loss caused by these shockwaves cause a sudden increase in drag and a reduction in efficiency at transonic and supersonic speeds.[1]

Table 1: This table shows how induced drag decreases as sweep angle increases at 300 meters/second (Adapted from Zandsalimy, 2021).[19]

Λ (Degrees)	Total Induced Drag
0	0.0164236
30	0.0164083
45	0.0163848
60	0.0163361

By pivoting the wing such that the leading edge aligns closer to the direction of the airflow and shock waves, an oblique wing delays shock formation and minimizes the effect of these shocks. This effect can be seen in Table 1.

This allows for a smoother airflow transition and directly causes a reduction in wave drag. In Figure 3, we can see the induced drag of an oblique wing as the sweep angle changes.

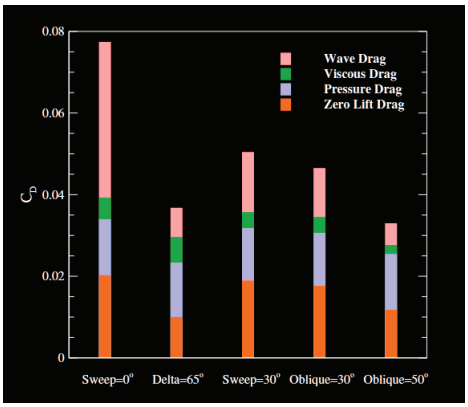

Figure 3: Drag components of different wing configurations at Mach 0.9. This figure demonstrates how the lowest total drag is found in an oblique wing at a 50-degree sweep (Zandsalimy).[19]

In Figure 3, we can see that the oblique wing, at a sweep of 50 degrees, has a significantly lower CD than every other wing configuration at Mach 0.9. As an aircraft with a conventional wing approaches the speed of sound, the drag begins to spike sharply. However, with an oblique-wing aircraft, the drag is mitigated by the shifting sweep angle as the airspeed approaches Mach 1. This reduction in wave drag is a direct advantage over conventional wing types in aerodynamics.[7]

Figure 3 is also helpful in that it objectively defines the Coefficient of Drag (CD) difference between the different wing configurations. In terms of CD, an oblique wing swept at 50 degrees has an advantage over all other wing types, even those tuned for high-speed low-drag performance like the delta wing. While it does fall short in terms of pressure drag and zero lift drag to the delta wing, the oblique wings overall improved drag performance as well as the ability to change sweep angle according to airspeed puts it, relative to the drag of other wing configurations, as the prominent design.

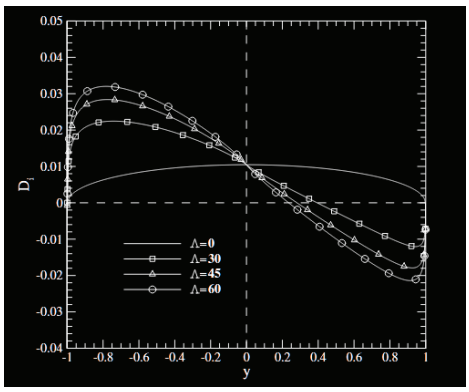

Figure 4: Induced drag distribution across the span of an oblique wing at 300 m/s. This figure illustrates the asymmetrical nature of drag distribution on an oblique wing, explaining the yawing moments an oblique-wing aircraft experiences (Zandsalimy, 2021).[19]

Just like how an oblique-wing aircraft experiences asymmetrical lift, it too undergoes asymmetrical drag. The aircraft experiences this drag at different levels across the span of the wing.

The forward-swept part of an oblique wing, due to increased lift and complex flow patterns, undergoes increased drag as well, and the back-swept part undergoes decreased drag. This can be confirmed in Figure 3, where the drag difference between the sides of the wing can get up to as much as ~0.054.[19]

This drag difference is what creates the yawing moments that are one of the causes of an oblique-wing aircraft's instability.

1.5. Comparison to Conventional Wings:

Throughout this section, both the lift and drag forces of an oblique wing have been explored, and the oblique wing's unique qualities and how they affect these forces cause key differences in its aerodynamic performance in comparison to conventional wing types.

In Figure 1, we can clearly see that where other wing types stay at a constant amount of lift (due to a constant sweep angle), the oblique wing shifts its sweep angle to adjust the lift needed according to the airspeed.[15]

In Figure 4, the fact that this nonzero sweep angle can cause an imbalance in drag that forces rolling and yawing moments

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can be observed. These moments require a counteraction for the aircraft to maintain its course.[20,21]

In Figure 3, we can see that due to the oblique wing's unique shape, it has a lower drag coefficient than other wing types (hence less drag), which allows for a smoother performance at transonic speeds.[1,7]

Overall, the oblique wing presents clear advantages in aerodynamic adaptability, with the fluid sweep angle allowing for peak performance across a wide range of airspeeds. This puts it above other wing types in terms of pure aerodynamic efficiency. However, it also experiences significant instability and control issues due to the imbalance in lift and drag forces caused by the innate asymmetrical shape of the wing.

■ Design Challenges of an Oblique Wing

This section will explore the challenges presented by the oblique wing in terms of design. Oblique wings have never been tried and tested in a commercial setting, so when creating a design solution for an oblique wing aircraft, there is no precedent and many different avenues to explore.

2.1. Oblique Wing Aircraft Designs:

After establishing what an oblique wing actually is in the first section, it is now important to explore what it would look like on an aircraft.

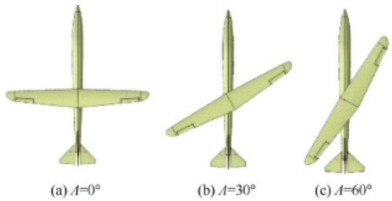

Figure 5: Visualization of an Oblique-Wing Aircraft. This figure illustrates how the oblique wing rotates around its single pivot and what different sweep angles look like on an oblique-wing aircraft. (Yue *et al.*)[14]

In Figure 5, it is shown that the oblique wing typically sits around the midspan of the plane and rotates around that point. This design uses a conventional configuration, with a fuselage and the wing being two separate parts of the aircraft.[19]

Another proposed design solution is an oblique all-wing aircraft. This type of airplane would consist solely of a wing, with all control surfaces, engines, and cabin space being contained in one structure.[3]

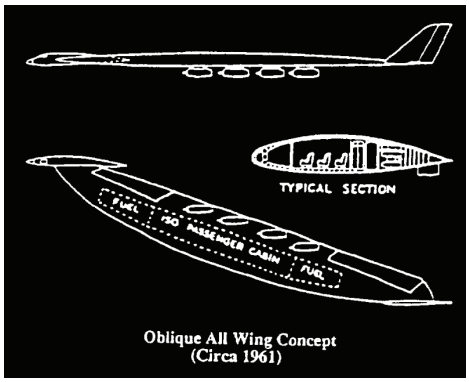

Figure 6: Oblique All-Wing Aircraft Concept. This figure depicts the conceptual layout of an aircraft designed with the fuselage doubling as an oblique wing (Galloway *et al.*).[8]

Figure 6 showcases the proposed design for an oblique all-wing (OAW). As pictured, everything from cabin space to control surfaces and turbines is all on the same structure, the body of the aircraft. In this design solution, the aircraft assumes a gentler sweep angle for takeoff and landing, and then rotates to a higher sweep angle for cruising. It does this by rotating everything on the aircraft, from engines to the rudder, as seen in Figure 6.

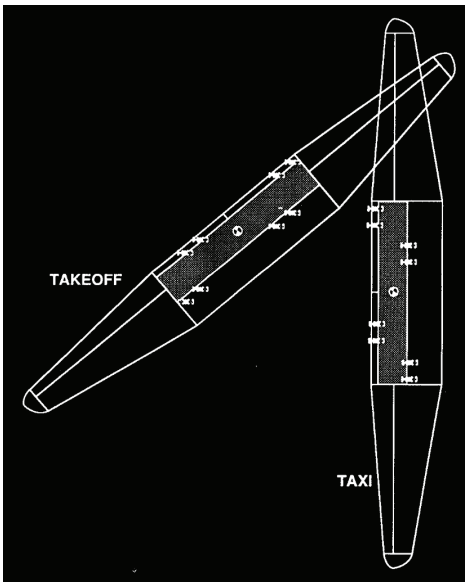

Figure 7: Alternative Oblique All-Wing Aircraft Concept. This figure is an alternative concept for the oblique all-wing aircraft seen in Figure 6, offering a more conventional configuration and design (Waters *et al.*).[22]

In Figure 7, an alternative design can be seen, where the aircraft consists of a single wing, and through rotation of engines and wheels, can change its sweep angle. What differs here is that there is no distinct pilot cabin, and the plane resembles a conventional design to a higher degree.

These two designs are both viable solutions to creating an oblique-wing commercial aircraft, and as such, will both be covered in this section.

2.2. Structural Integration & Airframe Modification:

Having an oblique wing alters many key aspects of an aircraft's design, and even with the same aircraft, just swapping out the wing can make the new design stray from the old by a significant amount.

For example, when the Vought F-8 Crusader was being considered for oblique wing testing, there were many aspects to take into consideration, like wing placement, angle, and pivot mechanism, as seen in the study conducted by Koltko *et al.* in 1975.

The first issue that comes up is that of the pivot–due to the single-pivot design of an oblique wing, a significant amount of stress is placed upon that pivot, whereas in a normal variable-sweep wing design, there are two pivots to take the brunt of the force.[18]

In order to address this problem, the researchers at Vought Systems considered two paths forward, considered two paths forward: a turntable concept and a cantilevered post bearing concept.[23]

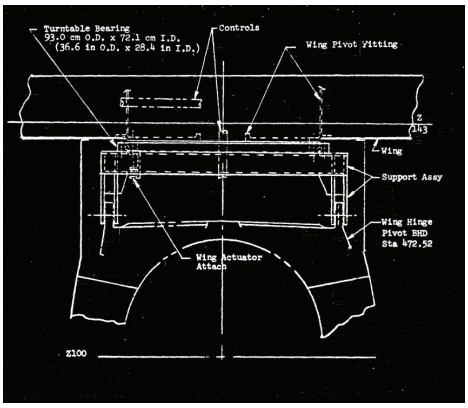

Figure 8a: Turntable concept. This figure presents the turntable pivot mechanism, the preferred design for an oblique-wing pivot (Koltko *et al.*).[23]

In Figure 8a, the turntable concept is displayed. It had many benefits that ultimately led to Vought picking it as their primary choice over the cantilever concept.[18] Some of these benefits include structurally superior wing load paths into the fuselage, a smaller wing pivot actuator, and a minimal size, allowing more room for controls and routing from the fuselage through the center of the wing.

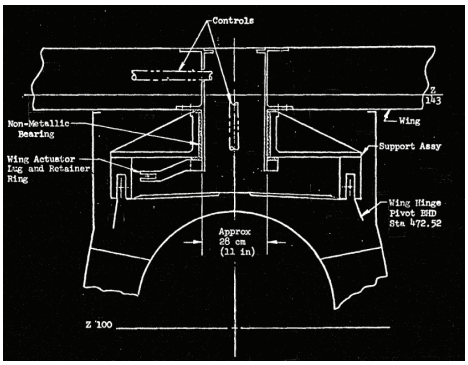

Figure 8b: Cantilever post concept. This figure depicts the cantilever post pivot concept, which was discarded due to poor distribution of load (Koltko *et al.*).[23]

The cantilevered post bearing concept, while still being viable, had a few key drawbacks that led to the turntable concept being picked, such as undesirable load paths and little to no structural redundancy. In Figure 8b, the cantilever concept is shown.

The concepts and principles explored by the researchers at Vought Systems scale to transport and commercial aircraft, and are actually more critical as the pivot mechanism would have to withstand more force and stress.[3]

In the case of the F-8, the researchers determined that there would need to be little to no change to the actual airframe, as the oblique replaced the F-8 wing fairly simply. All that was needed to be done was to take the wings off, cover up the holes, and attach and hook up the oblique wing.[23]

In the case of a commercial aircraft, if using the conventional airframe, the case is similar, just on a larger scale. Many transport aircraft feature high-set wings, so taking them off and replacing them with an oblique wing would be just as simple a process as with the F-8.[18]

2.3. Weight & Balance Considerations:

For a conventional aircraft, and even aircraft sporting variable-sweep wings, the balance of the aircraft is constant or predictably and controllably shifting. However, in the case of an oblique wing, its asymmetric shape as well as force distribution (see 1.3 and 1.4) cause the center of lift to shift relative to the center of gravity, requiring exact and constant control to maintain level flight.[5,9]

The center of balance for the oblique wing is far more volatile than that of other configurations, and hence the importance of the aircraft being able to manage those shifts due to imbalance.[5,18]

Beyond intricate control, keeping in mind the placement of passenger and cargo space is important for maintaining a manageable center of gravity in a commercial oblique-wing aircraft.

In Figure 6, the design shows a cross-section of the aircraft, where the cabin space and cargo areas are clearly defined.[3] A format like this is conducive to a balanced commercial oblique all-wing aircraft, because even as the engines and control surfaces change their orientation, the center of gravity remains the same, allowing for a sweep that does not cause pitching, rolling, and yawing moments.[24]

2.4. Control Solutions:

As explained, an oblique wing's asymmetrical geometry causes complex aerodynamic moments that make stability and control far more difficult to maintain than in conventional aircraft.[18] Furthermore, the uneven distribution of lift, as well as induced drag, causes coupling moments, where if the plane pitches, it rolls, or if it rolls, it yaws, and so on.

At transonic speeds, these coupling moments are exacerbated by the sensitivity of the controls as airspeed increases.[1,7]

At high sweep angles, however, normal control surfaces may be insufficient, and so a fly-by-wire system is preferred. Fly-by-wire is, in essence, a computer that makes rapid, micro corrections to the control surfaces of an aircraft that allow for the plane to fly level, even if the plane is inherently unstable.[10,24] This fly-by-wire system can even correct for the many coupling moments produced by the asymmetrical design of an oblique wing, which is why it is an optimal control solution.

■ Barriers to Implementation

In this section, the paper explores what logistical and commercial barriers hold back the oblique wing from being further explored as a concept, much less becoming implemented on a wider level. These issues span from regulatory to financial in nature.

3.1. Logistical Barriers:

For an oblique wing aircraft, no matter what the configuration is, the point stands that the variable sweep element of the wing remains, meaning a constant and high level of stress is placed on a single pivot.[18] This pivot, no matter how efficient or effective the design, would need regular and attentive maintenance, increasing upkeep and production costs.

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To add to the issue of complex parts, oblique-wing aircraft are nowhere near popular, and if they were introduced to commercial flight, it would take focused effort over an extended period of time to set up a strong supply chain.[3] In the initial years, there would likely be a shortage of repair parts.

Finally, due to the complex nature of an oblique-wing aircraft, airlines would need highly trained pilots, engineers, and technicians to maintain even a few planes, much less an entire fleet.[3,7]

3.2. Regulation & Certification Issues:

Current FAA and EASA regulations are built around symmetric wing designs, meaning that radical asymmetrical configurations like oblique wings would require entirely new standards and certification protocols.[5]

The asymmetry of an oblique wing, as already established, can complicate aerodynamic characteristics such as stall speed, controllability with and without fly-by-wire, and structural integrity.[1] These factors could lengthen the certification process by many years, deterring further development.

Furthermore, there is no precedent for an asymmetric-wing aircraft in any commercial sense, increasing both cost and perceived risk for manufacturers.

3.3 Market and Economic Viability:

The main holdup that overshadows other barriers is that, for the last half-century, existing aircraft designs and configurations have worked reliably and economically.[10] Current designs maximize what is economically important and operate efficiently at subsonic speeds, where drag is minimized, and fuel economy is highest.[1]

Even if the barrier of supersonic flight's fuel inefficiency is overcome, there still stand market and economic obstacles. Airlines often focus on a "family" of aircraft, and introducing an oblique-wing aircraft would require unique crew training and maintenance. Public perception also matters, since if passengers believe the design is unsafe or unstable, acceptance could become a major hurdle.

3.4. Summary:

The main logistical and commercial barriers holding back further development of oblique wing aircraft in commercial flight are regulatory hurdles due to a lack of precedent, increased manufacturing and maintenance complexity, and economic uncertainty caused by the risks and perception of asymmetrical wings. Despite these obstacles, however, new opportunities for the concept can be made through advances in control systems and materials. If these logistical and regulatory challenges were resolved, the oblique wing could make a resurgence as a viable option for commercial flight, but until then, it will remain a research subject dependent on constant innovation and exploration.

■ Conclusion

The thesis explored in this paper is that an oblique wing aerodynamically outperforms a conventional wing design, but brings with this performance a host of challenges in stability, control, market and economic barriers, and overall a lack of commercial feasibility.

The paper first explored the aerodynamic characteristics of the oblique wing concept, including lift and drag performance at transonic speeds and asymmetrical force distribution. This section demonstrated that while the oblique wing does introduce some problems with stability, it also achieves a lower drag and maintains lift more effectively than other conventional wing configurations.

Next, the discussion shifted to the various design challenges and solutions surrounding the oblique wing, analyzing how such a design could become structurally and technically viable. Finally, the logistical and commercial barriers preventing the adoption of the oblique wing concept were presented, such as regulatory uncertainty, complexity of manufacturing, and the lack of an incentive in the market.

Despite these challenges, however, advances in computational modeling and control systems could make future implementation of the oblique wing concept viable and more feasible. Future research should have a focus on computational fluid dynamics and wind tunnel testing in order to gain a clearer understanding of aerodynamic stability across a range of sweep angles. Further exploration into lightweight composite materials could reduce the weight of the oblique wing structure while increasing durability and efficiency of the single-pivot mechanism. On top of this, improvements in fly-by-wire technology and control systems may mitigate the stability issues caused by the asymmetrical shape of the wing that limit the concept's viability in commercial flight.

These developments hold promise for the oblique wing and also carry broader implications for the overall field of aerospace engineering. The advancement of adaptive aerodynamic design and further research on oblique wings could serve as the base for next-generation aircraft, allowing the designs to achieve higher fuel efficiency and lower emissions. Additionally, collaboration between the disciplines of materials science, avionics, and aerodynamics could transform the oblique wing from an experimental concept to a feasible component of sustainable transonic flight.

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■ References

1. Kulfan, R. M.; Nisbet, J. W.; Neuman, F. D.; Hamilton, E. J.; Murakami, J. K.; McBarron, J. P.; Kumasaka, K. *Study of the Single Body Yawed-Wing Aircraft Concept*; NASA-CR-137483; 1974. https://ntrs.nasa.gov/citations/19740019372
2. Nelms, W., Jr. *Applications of Oblique-Wing Technology—An Overview*. In Aircraft Systems and Technology Meeting; American Institute of Aeronautics and Astronautics, 1976. https://doi.org/10.2514/6.1976-943

3. Bradley, E. S.; Honrath, J.; Tomlin, K. H.; Swift, G.; Shumpert, P.; Warnock, W. *An Analytical Study for Subsonic Oblique Wing Transport Concept*; NASA-CR-137896; 1976. https://ntrs.nasa.gov/citations/19770003103
4. McDaniel, M.; Wilks, B. Oblique Wing Aerodynamics. In *22nd Applied Aerodynamics Conference and Exhibit*, American Institute of Aeronautics and Astronautics: Providence, Rhode Island, 2004. https://doi.org/10.2514/6.2004-5194
5. Fantino, R. E.; Parsons, E. K.; Powell, J. D.; Shevell, R. S. *Effects of Asymmetry on the Dynamic Stability of Aircraft*; NASA-CR-142857; 1975. https://ntrs.nasa.gov/citations/19750016684
6. Nafi, A. S.; Barman, S.; Sayef, A. *An Analysis of Aerodynamic Forces on an Oblique Wing*. 2015.
7. Galloway, T. L.; Phillips, J. A.; Kennelly, R. A.; Waters, M. H. *Large Capacity Oblique All-Wing Transport Aircraft*; 1996. https://ntrs.nasa.gov/citations/19960023626
8. *Thinking Obliquely: Robert T. Jones, the Oblique Wing, NASA's AD-1 Demonstrator, and Its Legacy—NASA*. 2013. https://www.nasa.gov/aeronautics/thinking-obliquely-robert-t-jones-the-oblique-wing-nasas-ad-1-demonstrator-and-its-legacy/
9. Kulfan, R. M.; Neumann, F. D.; Nisbet, J. W.; Mulally, A. R.; Murakami, J. K.; Noble, E. C.; McBarron, J. P.; Stalter, J. L.; Gimmestad, D. W.; Sussman, M. B. *High Transonic Speed Transport Aircraft Study*; NASA-CR-114658; 1973. https://ntrs.nasa.gov/citations/19740009637
10. Wang, L.; Xu, Z.; Yue, T. *Dynamic Characteristics Analysis and Flight Control Design for Oblique Wing Aircraft. Chinese Journal of Aeronautics* 2016, 29 (6), 1664–1672. https://doi.org/10.1016/j.cja.2016.10.010
11. *Robert T. Jones—NASA*. 2015. https://www.nasa.gov/centers-and-facilities/langley/robert-t-jones/
12. Jacobsen, A. *Operation Paperclip: The Secret Intelligence Program That Brought Nazi Scientists to America*; Little, Brown, 2014.
13. Sim, A. G.; Curry, R. E. *Flight Characteristics of the AD-1 Oblique-Wing Research Aircraft*. NASA Technical Report, 1985. https://ntrs.nasa.gov/citations/19870009137
14. Yue, T.; Xu, Z.; Wang, L.; Wang, T. *Sliding Mode Control Design for Oblique Wing Aircraft in Wing Skewing Process. Chinese Journal of Aeronautics* 2019, 32 (2), 263–271. https://doi.org/10.1016/j.cja.2018.11.002
15. Jones, R. T. *The Oblique Wing—Aircraft Design for Transonic and Low Supersonic Speeds. Acta Astronautica* 1977, 4 (1), 99–109. https://doi.org/10.1016/0094-5765(77)90035-2
16. Rahman, M. H.; Aljibory, M. W.; Rashid, F. L.; Hussein, E. Q. *Sweep Angles Influence on the Aerodynamic Characteristics of NACA 2412 Wing with Supersonic Flow. Mathematical Modelling of Engineering Problems* 2022, 9 (3), 797–804. https://doi.org/10.18280/mmep.090323
17. *The Lift Equation*. NASA Glenn Research Center. https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/lifteq.html
18. McMurtry, T.; Sim, A.; Andrews, W. *AD-1 Oblique Wing Aircraft Program. In the 1st Flight Test Conference*, American Institute of Aeronautics and Astronautics, 1981. https://doi.org/10.2514/6.1981-2354
19. Zandsalimy, M. *Investigation of Aerodynamic Characteristics and Stability of Oblique Wing Airplanes*.
20. Li, P.; Seebass, R.; Sobieczky, H. *Manual Aerodynamic Optimization of an Oblique Flying Wing. In 36th AIAA Aerospace Sciences Meeting and Exhibit*; American Institute of Aeronautics and Astronautics: Reno, NV, U.S.A., 1998. https://doi.org/10.2514/6.1998-598
21. Andrews, W. H.; Sim, A. G.; Monaghan, R. C.; Felt, L. R.; McMurtry, T. C.; Smith, R. C. *AD-1 Oblique Wing Aircraft Program. SAE Transactions* 1980, 89, 3571–3577.
22. Waters, M.; Ardema, M.; Roberts, C.; Kroo, I. *Structural and Aerodynamic Considerations for an Oblique All-Wing Aircraft*. In *Guidance, Navigation and Control Conference*; American Institute of Aeronautics and Astronautics, 1992. https://doi.org/10.2514/6.1992-4220
23. Koltko, E.; Katz, A.; Bell, M. A.; Wyatt, F. G.; Jobe, C. L.; Orr, T. F.; Klapprott, C.; Overstreet, C. T.; Smith, W. D.; Lauridia, R. *F-8 Oblique Wing Structural Feasibility Study*. NASA Technical Reports Server. https://ntrs.nasa.gov/citations/19770023163
24. *AD-1 Oblique Wing—NASA*. NASA Reference. https://www.nasa.gov/reference/ad-1/

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RESEARCH ARTICLE

Bridging the Digital Divide: Supporting Aging Small Business Owners in a Rapidly Modernizing Economy

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ABSTRACT: This paper evaluates the growing difficulty small business owners encounter as digital technologies and AI evolve faster than many can adapt. A combination of interviews with five small business owners and secondary market analysis was used to identify the main barriers keeping aging entrepreneurs away from digital transformation. The findings reveal substantial gaps in digital literacy, widespread skepticism toward available digital tools, and differences in needs by industry. They also show that although many business owners recognize the importance of adopting digital technologies, they often lack the resources, guidance, or confidence to take meaningful action. Based on these insights, this paper proposes principles for designing accessible digital transformation services for small businesses that are struggling to adapt to the fast-changing digital world. The research contributes to understanding technology adoption in small business contexts and provides practical guidance for narrowing the generational digital divide.

KEYWORDS: Economics, Entrepreneurship, Small Businesses, Digital Transformation, Technology Adoption.

Introduction

The modern landscape of small businesses has fundamentally transformed as digital technologies have evolved and become a competitive necessity for any business in the modern age. Recent findings show that small and medium-sized enterprises (SMEs) struggle to adopt digital tools at the pace required to keep up with the market.[1] This digital adoption gap has grown considerably in recent years. It is estimated that the COVID-19 pandemic accelerated digital transformation timelines by five to seven years across most industries.[2] This forces businesses that previously relied largely on word of mouth and referrals to adapt to the modern industry, which depends on search engine optimization, social media engagement, and online customer reviews.

This challenge disproportionately affects older business owners who started their businesses before the large-scale adoption of digital systems and social media marketing.[3] These entrepreneurs built successful businesses through traditional methods, emphasizing personal relationships, physical storefronts, advertising, and community reputation. However, consumer behavior has shifted fundamentally, with approximately 97% of consumers now searching online for local businesses,[4] and 88% of consumers claiming to trust online reviews as much as personal recommendations.[5] These changes in consumer behavior make it so that businesses without strong digital presences become invisible to large segments of potential customers, regardless of their product quality or service excellence.

Over 50 percent of U.S. small business owners are aged fifty-five or older,[6] representing a substantial demographic that is becoming vulnerable to displacement. This reality creates an urgent policy and economic concern. Baby Boomer entrepreneurs control an estimated $10 trillion in business assets,[7] and their businesses employ millions of workers in communities nationwide. If these enterprises fail to compete digitally, the consequences extend far beyond individual business losses. This will have a large effect on employment, tax revenues, and the economic strength of each community. This generation of business owners possesses decades of professional expertise, customer relationships, and valuable knowledge that risk being lost if their enterprises cannot successfully transition to digital business models.

The Technology Adoption Gap:

Analyzing the adoption of e-commerce among SMEs outlines key barriers preventing the adoption of digital tools among business owners. These barriers include low technological literacy among business owners, resource constraints, and resistance to change.[8] All of which have the greatest impact on older business owners, thus driving a wedge between older and younger entrepreneurs. This is partly because individuals who did not grow up with digital technologies experience higher cognitive load when learning new digital systems, leading to increased frustration and lower adoption rates.[9]

To understand the current market, the development of AI software and its different uses must be analyzed. Current AI tools enable AI-powered marketing automation through the use of AI to create templates, designs, and content schedules. AI-powered website builders such as Lovable, Bolt, and Base 44 enable non-technical entrepreneurs to create fully functional and aesthetic websites. Customer relationship management systems use AI to keep track of clients and follow up to ensure all leads are pursued and targeted efficiently and optimally. AI-powered data analytics platforms specifically designed for small businesses help to keep track of performance and highlight areas to focus on for maximum results.[10] These tools are

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becoming essential to the efficiency of every business in the current market. Additionally, the AI consulting services market was estimated at roughly $22.27 billion in 2025 and is expected to explode, with a compound annual growth rate of 35.8%, to $257.60 billion by 2033.[11] This growth will greatly benefit large companies that have sufficient technology budgets and a designated IT staff. However, the small businesses, especially those owned by aging entrepreneurs, are at a disadvantage in that they lack the necessary knowledge and budget to adopt these tools and therefore cannot benefit from the anticipated market growth. A particular concern is the unique complexity of AI adoption faced by small businesses. While these AI tools offer tremendous competitive advantages, such as allowing personalized customer experiences, automating marketing campaigns, predicting inventory levels, and basing decisions on data, they add incredible layers of complexity to a business. Many older business owners consider AI to be confusing, unpredictable, or even threatening to personal relationships, which are often the core of their business models.[12] Service providers who do not address these concerns cannot help these businesses and thus cannot succeed in selling their services.

Broader Economic and Social Consequences:

Small businesses losing market share to digitally sophisticated competitors will have consequences that will be felt economically and socially. The loss of local small businesses will result in the loss of employment opportunities, community character, and alternatives to corporate retail chains.[13] Small businesses account for 44% of U.S. economic activity and employ 47.1% of the private workforce,[14] further proving the scope of the problem. The decline of small businesses would have a fundamental impact on the American economy and society and would bring undesired consequences. From a market competition perspective, the increase in consumer spending toward large enterprises may reduce price competition and consumer choice.[15] Large corporations possess advantages that enable them to implement sophisticated digital marketing operations, personalized customer experiences, and seamless integration, giving them an unfair edge over local businesses. Amazon, for example, employs thousands of engineers focused on its continual development and improvement in line with cutting-edge innovations. These investments are unreasonable and impossible for individual small businesses.

There are also social and cultural implications to this shift in market share as local businesses serve functions beyond simply selling items or providing services. They create gathering places, make community events possible, provide first jobs for young people, and contribute to neighborhood identity.[16] The replacement of locally-owned businesses with national chains reduces this community attachment and engagement. Research shows that communities with more local businesses demonstrate stronger community unity, friendship between neighbors, and increased political participation.[17] The displacement of local businesses threatens not only the economy, but also the social fabric that binds communities together.

The Affordability Paradox:

The vast majority of small business owners understand the importance and necessity of adopting online methods. One major limiting factor keeping small businesses from adapting to digital methods is the cost. Approximately 66 percent of small business owners allocate less than $1,000 annually towards marketing.[18] This reveals a critical market failure: business owners recognize the value of online marketing, but cannot access solutions at reasonable prices. For businesses with thin profit margins, spending thousands of dollars on unproven digital marketing services is an unreasonable financial risk. Every dollar must be spent strategically with priorities like inventory, payroll, and facilities, and other immediate costs. When positioned in a place where they are forced to allocate money towards business necessities or digital marketing, spending on marketing becomes difficult to justify. Many small business owners also lack financial analysis capabilities, leading them to default to minimal spending. This explains why so many small businesses fall victim to marketing services that make fake promises. The combination of limited marketing budgets, low digital literacy, and an urgent need for presence creates conditions of desperation, hence enabling exploitation. To treat small businesses ethically, producers must do more than offer products and services at an affordable cost; they must earn trust through transparency, demonstrate results, and enable business owners to make informed decisions.

Current Service Inadequacies:

Current providers attempting to address this issue, primarily digital marketing agencies and freelancers, inadequately address the needs of small businesses. Major agencies typically charge $5,000–$30,000 for project-based work and $1,000–$10,000 monthly for ongoing services.[19] These prices reflect the agency's reliability; however, they are simply inaccessible to the average small business. These small businesses, which make $50,000–$250,000 in annual revenue, are the businesses most vulnerable to digital displacement. The agency business model optimizes for larger clients who generate substantial recurring revenue, making small business clients economically unattractive despite their numerical prevalence.

Freelancers, while more affordable at $500–$5,000 per project,[20] still exceed most small business marketing budgets. Also, they do not cover all the needs of small business owners, leaving various digital tasks still in their hands. Freelancer quality varies, and small business owners lack the expertise to evaluate technical competence before opting in to their services. They are also unaware of what skills are necessary for their specific task or project, making it difficult to choose a freelancer whose abilities align with the business's needs. Small business owners risk wasting limited budgets on ineffective services, reinforcing their reluctance to invest in digital transformation.

Furthermore, many existing providers have not fully integrated emerging AI capabilities or communicated their abilities in accessible terms for non-technical business owners. The service provider landscape is split between traditional agencies using established methods and technology-focused startups emphasizing cutting-edge tools. Neither model serves

aging small business owners optimally. Traditional agencies may lack expertise in new AI-powered tools. Tech-heavy start-ups, on the other hand, often communicate in jargon-heavy language that alienates non-technical clients. There is also a misalignment in the targets of these small businesses and existing service providers. Providers often focus on technical metrics such as website traffic, social media engagement, and click-through rates, while business owners care primarily about bottom-line outcomes: customer acquisition, revenue growth, and profitability.

Research Objectives and Significance:

This research addresses the following question: What barriers prevent aging small business owners from effectively adopting digital transformation tools, and what characteristics should accessible digital services possess to address these barriers? Through exploratory qualitative interviews supplemented by market analysis, this study examines the various obstacles facing older entrepreneurs. It then identifies the principles for effective intervention strategies.

The significance of this study spans several areas. It adds to existing research by documenting how generational differences in digital literacy affect small business competitiveness. It also offers practical guidance for service providers working with older entrepreneurs. In addition, the findings make the case that supporting small businesses contributes to community and economic development.

Methods

Research Design:

This study used a variety of methods, combining semi-structured interviews with secondary market research and case studies. In the absence of prior research into specific barriers to digital transformation for aging small business owners, an open-ended approach was appropriate to uncover themes and inform areas of further investigation.[21] The study did not test one specific pre-defined hypothesis; it aimed to explore the experiences, perceptions, and needs of participants regarding digital business tools.

Data Collection:

Five small business owners were selected to represent a diverse range of experiences from diverse industries. Selection criteria included: business ownership for at least five years, relatively few employees (under 50), primary decision-making authority over business operations, and willingness to discuss technology use and personal challenges. The sample included owners from retail (international supply chain), real estate development, manufacturing (rug production, 40+ years of operation), professional services (licensed psychologist), and real estate investment. Ages ranged from 45 to 85 years, though exact ages were not formally recorded.

Interview Protocol:

Semi-structured interviews were conducted via telephone following proper protocols for educational research. Each interview lasted 10–20 minutes. Before the interview, participants were informed about the study's purpose, provided verbal consent, and were assured of confidentiality. While the interview duration was shorter than ideal for deeper research, the format enabled a level of consistency across participants while allowing flexibility for follow-up questions based on individual responses.

Table 1: Interview questions organized by focus area.

Question	Focus Area
Do you currently use any online tools for your business? If so, which ones and how do you use them?	Current adoption
Have there been moments where using technology for your business has made you frustrated or overwhelmed? Example?	Pain points
What is the hardest part about keeping your business up to date with new technology?	Barriers
What specific things online do you believe you are missing out on?	Awareness gaps
What's something you saw other businesses doing that you considered but didn't try? Why not?	Observational learning
If someone offered help improving your online presence, what would you need to know in order to trust them?	Trust factors
What is your goal in improving your digital presence? What would success look like for you?	Desired outcomes
What are your views on the implementation of digital tools and AI in your industry?	Industry context

Data Analysis:

Interviews were analyzed thematically, following Braun and Clarke's six-phase framework.[22] This systematic process involves identifying areas of interest recurring between participants, organizing these into broader thematic groups, and refining those groups to reach clear, coherent, and distinguishable categories. Given the limited sample size (n = 5) for this analysis, priority was placed on the most prominent and consistently observed patterns.

Secondary Data Collection and Analysis:

Secondary sources provided context to the interview findings and included industry reports on the size and growth of the digital transformation market, survey data regarding small business technology spending and attitudes, case studies published on digital transformation efforts, and price lists from providers of digital marketing services. Materials were selected for their recency, credibility, and relevance to this study's focus.

Limitations:

There are several limitations regarding the generalizability of the study. First, it is based on a small sample size (n=5), which restricts the accuracy of the conclusions drawn. Second, convenience sampling may be a source of selection bias toward business owners who are already interested in digital issues or have faced digital problems. Finally, the geographic focus and industry distribution may or may not be representative nationally. Future research with larger and more demographically diverse samples and longer interview protocols would strengthen findings.

Results and Discussion

Analysis of the interviews revealed three primary patterns regarding small business owners' relationships with digital

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technology: (1) recognition of the importance of a strong digital presence, despite describing challenges with implementation, (2) skepticism toward existing service providers, and (3) variation in digital needs between industries based on the nature of the business. These findings are presented below with supporting evidence from the interviews and are compared with secondary market data.

Theme 1: Acknowledged Importance with Implementation Barriers:

All five participants expressed that, based on their own personal experiences, having a strong online presence is essential for growth. Many participants also expressed personal struggles with the implementation of online tools, some describing having to rely on younger family members or employees for assistance. This gap between recognition and implementation was particularly noticeable among older participants. Participants identified several obstacles keeping them from adopting new technology, including time constraints for learning new systems, information overload from various options, fear of implementing tools incorrectly, and a lack of technical skill. These findings align with existing data, which documents technology adoption barriers among older entrepreneurs, including limited digital literacy, resistance to change, and perceived lack of relevance.[23]

Theme 2: Skepticism Toward Current Service Providers:

When asked about experiences with or perceptions of marketing agencies and digital service providers, participants were often skeptical. Concerns largely involved cost, customization, and measurability of current solutions. Another deterring factor for many participants was price, with the majority of them categorizing current options as expensive. This perception aligns with the industry pricing: marketing agencies typically charge $5,000–$30,000 for project work and $1,000–$10,000 monthly for retainers.19 Participants also felt existing services offered generic solutions rather than industry-specific strategies. This suggests higher demand for providers with a specific industry specialty rather than general approaches.

Several participants questioned how they would measure return on investment when spending money on online marketing. One owner described a negative experience with a marketing agency that was selling clicks, explaining how he did not see direct results based on these metrics. This indicates that service providers should emphasize outcome-focused metrics such as leads, conversions, and revenue, rather than internal metrics such as views and likes. Regarding trust, when asked what they would need to know to trust a service provider, many participants emphasized the importance of a strong track record, including viewing past work.

Theme 3: Industry-Specific Variation in Digital Transformation Needs:

Comparing results across industries revealed important distinctions in a business's digital priorities based on its customer acquisition model. Businesses serving one-time or infrequent customers (retail, manufacturing, real estate development) expressed a greater need for a strong digital presence than those with recurring client relationships.

The psychologist, whose practice operates on long-term relationships and a referral system, expressed how most clients come through referrals from other therapists or other current or former clients. This contrasts with the retail owner who described the importance of a strong digital presence for attracting customers and business partners. This pattern suggests digital transformation services should prioritize businesses requiring continuous new customer generation, such as retail, services for new clients, and project-based work, and should emphasize reach over engagement when developing content marketing strategies. Established businesses with mature referral networks may have different needs than growth-stage enterprises.

Table 2: Summary of interview themes and supporting evidence.

Theme	Participant Evidence	Interpretation
Acknowledged importance with implementation barriers	All 5 participants expressed awareness of digital importance; 3 of 5 rely on younger employees/family for tech management	Recognition-implementation gap driven by time constraints, technical complexity, and information overload
Skepticism toward current providers	Consistent concerns about cost (4/5), customization (4/5), and measurability (3/5)	Demand for affordable, industry-specific, outcome-focused services
Industry-specific variation	Businesses with recurring clients (1/5) express lower urgency than those requiring continuous acquisition (4/5)	Digital transformation priorities vary by business model; the highest need among businesses is for ongoing new customer generation

Secondary Market Findings:

Market research data supports and provides more context for interview findings. The AI consulting services market demonstrates substantial growth, valued at approximately $22.27 billion in 2025 and projected to reach $257.60 billion by 2033, representing a compound annual growth rate (CAGR) of 35.8% (Figure 1).11 This exceptional growth indicates expanding recognition of AI-driven digital transformation and potentially increasing service availability. However, market concentration among enterprise-focused providers suggests small businesses remain underserved despite this expansion.

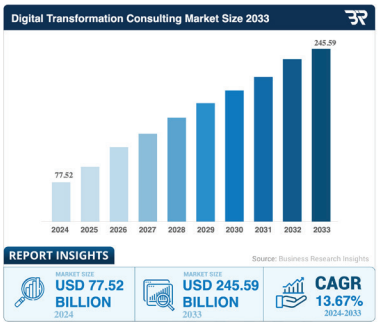

Figure 1: Global AI consulting services market size overview showing historical data and forecast from 2023 to 2033, with a CAGR of 35.8% from 2025 to 2033. Source: Market Data Forecast Analysis.

Survey data confirms that 66% of small business owners spend under $1,000 annually on marketing, yet 80% consider online presence important for success.[18] This contrast between budget constraints and perceived importance validates interview findings regarding affordability concerns.

Research documents persistent disparities in digital tool adoption between small businesses and larger enterprises. Only 64% of small businesses maintain websites compared to 94% of larger companies,[24] and small businesses lag in social media marketing, e-commerce integration, and data analytics adoption.[25]

Studies of older entrepreneurs confirm that digital literacy declines with age and that older business owners face unique challenges in technology adoption, including reduced exposure to emerging tools during formative career years.[26] However, research also indicates a high willingness among older entrepreneurs to adopt technology when appropriate support is available.[27]

Case Study Insights:

Analysis of various published case studies provides evidence for effective approaches to digital transformation and the related outcomes. An analysis of digital transformation initiatives for major brands illustrates the idea that personalized customer experiences are what drive engagement and loyalty.[28]

While these are large enterprises, the principle of customization rather than generic approaches applies across business sizes and aligns with interview findings regarding demand for tailored solutions.

Research into B2B content marketing trends found that 71% of B2B marketers consider content marketing increasingly important.[29] This would indicate that content creation through blogging, social media, and educational content is a good strategy regardless of industry, not just businesses that sell directly to consumers. Other research on effective digital platforms identifies specific strategies to retain customers. These include gamification, personalized recommendations, and the simplification of user experiences.[30] These are all potential ideas that could be utilized to further improve a business's digital presence.

Interpretation of Findings:

This exploratory study identified significant barriers preventing aging small business owners from effectively competing in digitally mediated markets. The findings reveal a recognition-implementation paradox: business owners understand digital presence's importance but lack resources, knowledge, or confidence to act on this understanding. This gap creates a market opportunity for accessible digital transformation services while simultaneously highlighting the limitations of existing provider models.

The skepticism toward current service providers documented in this research reflects misalignment between available services and small business needs. High-cost agency models designed for larger companies with substantial marketing budgets fail to attract businesses allocating less than $1,000 annually to marketing. The emphasis on vanity metrics (clicks, impressions, followers) rather than business outcomes (leads, conversions, revenue) suggests many providers optimize for easily measurable indicators rather than client success. The perceived lack of industry-specific customization indicates providers may prioritize operational efficiency through standardized offerings over effectiveness through tailored strategies.

Industry-specific variation in digital transformation needs represents an important distinction that must be taken into account when analyzing this industry. Businesses with recurring revenue structures and mature referral networks require fundamentally different digital strategies than those that depend on continuous new customer acquisition. This suggests successful digital transformation services must conduct thorough business model analysis before proposing solutions rather than using a broader approach for all clients.

The reliance on younger family members or employees for technology management among older business owners indicates both a barrier and a problem. While delegation may temporarily address immediate technological needs, it creates concerns if key personnel leave and business owners are left without help in situations they are not capable of managing.

Implications for Practice:

Based on these findings, effective digital transformation services for small businesses should incorporate the following design principles: affordability with pricing models aligning with small business marketing budgets (packages under $1,000 for initial implementations, monthly retainers under $500 for ongoing support); outcome orientation emphasizing business outcomes rather than technical metrics; industry customization demonstrating understanding of specific industry contexts; comprehensive support through "done-for-you" models including initial setup, ongoing management, and technical support; trust building through case studies, testimonials, and trial periods; and AI integration explaining concrete applications in accessible terms (AI-powered chatbots for customer service, automated social media scheduling, predictive analytics for inventory management, personalized email marketing campaigns).

Theoretical Implications:

This research contributes to technology adoption literature by documenting specific barriers facing aging entrepreneurs in contexts of rapid technological change. The findings extend diffusion of innovation theory[31] by illustrating how generational digital literacy gaps create adoption barriers even when relative advantage is acknowledged. The recognition-implementation paradox documented here suggests that awareness of innovation benefits is necessary but insufficient for adoption when complexity, cost, and implementation support are inadequate.

The industry-specific variation in digital transformation needs contributes to contingency perspectives on technology adoption, suggesting that business model characteristics (one-time versus recurring customers, referral-dependent versus marketing-dependent acquisition) moderate the value proposition of digital tools. This implies that technology adoption research should account for contextual business factors beyond individual or organizational characteristics typically examined.

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Limitations and Future Research:

This study's limitations suggest several directions for future research. The small sample size (n=5), as well as bias, which may have influenced the selection of interview participants, limit the study's generalizability. Future studies with larger, more demographically representative samples across diverse geographic markets would strengthen the themes and patterns that would be found. The short length of the interviews (10-15 minutes) naturally limited how in-depth each interview could be. Any follow-up work would be improved by longer interviews, or even better, more activity-based interviews in which participants demonstrate their difficulties rather than simply describing them.

The absence of quantitative data makes it really hard to precisely identify the exact effectiveness of digital transformation efforts. Research studying businesses that received one or more of the intervention services in comparison to others that did not, and following them over time, might show which initiatives tend to be most successful and why certain attempts at digital transformations fail.

Further research might investigate differences in rates of technology adoption by age, determine best practices for particular industries, study the experiences and strategies of service providers, monitor the entire implementation process of digital tools, and find practical means of measuring success for small businesses.

Policy Implications:

The implications of the digital divide between small and large firms have potential consequences on policy, community development, and economic equity. Policymakers interested in supporting small business competitiveness may consider subsidized technical assistance programs that provide consulting to qualifying small businesses and digital literacy initiatives specifically designed for older entrepreneurs.

■ Conclusion

This study examined barriers preventing aging small business owners from effectively adopting digital transformation tools necessary for competitive participation in modern markets. Through interviews and secondary analysis, the research identified a recognition-implementation gap where business owners acknowledge digital presence's importance but lack resources, knowledge, or confidence to act. Current service providers inadequately address small business needs through high costs, generic approaches, and emphasis on technical metrics rather than business outcomes.

The findings suggest that to be effective, digital transformation services must prioritize affordability, outcome orientation, industry customization, comprehensive support, and trust building. Variation across industries indicates that business model characteristics, particularly customer acquisition patterns, should inform service design rather than applying uniform approaches.

While this study's small sample size and open-ended nature limit its credibility, the findings provide a foundation for future research and practical guidance for service providers, business owners, and policymakers. As digital technologies continue evolving and potentially widening gaps between digitally sophisticated and digitally disadvantaged enterprises, addressing small business adoption barriers becomes increasingly urgent for maintaining competitive markets, community strength, and economic opportunity.

The research question-what barriers prevent adoption, and what characteristics address these barriers-has been partly answered by specifying particular obstacles that include cost, complexity, and trust deficits, and corresponding principles of affordability, customization, and demonstration. However, many questions about the effectiveness of the implementation, scalability, and long-term outcomes of digital transformation interventions remain. Larger samples, experimental designs, and different approaches can extend these exploratory findings toward evidence-based model development that supports small business digital competitiveness.

Ultimately, the aim is not just the success of one or more businesses but to ensure that diverse and competitive markets will allow small enterprises to stand alongside large corporations. This necessitates an integrated response by the service providers, business owners, industry associations, and policymakers if the digital divide is not to go too far.

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■ References

1. Daniel, T. A.; McInerney, M. L. E-Commerce and the "Reluctant" Small Business Owner: How Technology Is Changing the Business Model for Small and Medium-Sized Enterprises (SMEs). *ResearchGate* (accessed July 24, 2025).
2. McKinsey & Company. How COVID-19 has pushed companies over the technology tipping point—and transformed business forever. https://www.mckinsey.com/capabilities/strategy-and-corporate-finance/our-insights/how-covid-19-has-pushed-companies-over-the-technology-tipping-point (accessed October 2020).
3. Benton Institute for Broadband & Society. The Digital Divide Isn't Getting Any Younger. https://www.benton.org/blog/digital-divide-isnt-getting-any-younger (accessed May 7, 2025).
4. BrightLocal. Local Consumer Review Survey. https://www.brightlocal.com/research/local-consumer-review-survey/ (accessed 2023).
5. Spiegel Research Center. How Online Reviews Influence Sales. *Northwestern University* (accessed 2017).

6. U.S. Census Bureau. Annual Business Survey (ABS) Program. https://www.census.gov/programs-surveys/abs.html (accessed July 24, 2025).
7. Guidant. 2023 Small Business Trends. https://www.guidantfinancial.com/2023-small-business-trends/ (accessed July 24, 2025).
8. Daniel, T. A.; McInerney, M. L. op. cit.
9. Wang, L.; Rau, P. L. P.; Salvendy, G. Older adults' acceptance of information technology. *Educ. Gerontol*. **2011**, 37 (12), 1081-1099.
10. McKinsey & Company. Technology Trends Outlook 2025. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/the-top-trends-in-tech (accessed July 21, 2025).
11. Market Data Forecast. AI Consulting Services Market. https://www.marketdataforecast.com/market-reports/ai-consulting-services-market (accessed 2025).
12. Davenport, T. H.; Ronanki, R. Artificial Intelligence for the Real World. *Harv. Bus. Rev*. **2018**, *96* (1), 108-116.
13. National League of Cities. Embracing Experience: Two Sides of the Coin Demystifying Small Business Ownership. https://www.nlc.org/article/2024/06/24/embracing-experience-two-sides-of-the-coin-demystifying-small-business-ownership/ (accessed June 24, 2024).
14. U.S. Small Business Administration. 2023 Small Business Profile. https://advocacy.sba.gov/2023/03/07/2023-small-business-profiles-for-the-states-territories-and-nation/ (accessed 2023).
15. Bizplanr.ai. 50+ Small Business Statistics for 2025 | Key Insights & Trends. https://bizplanr.ai/blog/small-business-statistics (accessed June 15, 2025).
16. Fleming, D. A.; Goetz, S. J. Does local firm ownership matter? *Econ. Dev. Q*. **2011**, *25* (3), 277-281.
17. Tolbert, C. M.; Lyson, T. A.; Irwin, M. D. Local capitalism, civic engagement, and socioeconomic well-being. *Soc. Forces* **1998**, *77* (2), 401-427.
18. Upflip. Small Business Marketing Budget Statistics. https://www.upflip.com/reports/small-business-marketing-budget-statistics (accessed July 28, 2025).
19. HawkSEM. Marketing Agency Pricing: How Much Do Marketing Agencies Charge? https://hawksem.com/blog/marketing-agency-pricing/ (accessed July 28, 2025).
20. MarketingSherpa. Digital Marketing Pricing Packages. https://marketingsherpa.com/article/chart/digital-marketing-pricing (accessed July 28, 2025).
21. Creswell, J. W.; Creswell, J. D. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 5th ed.; SAGE Publications: Thousand Oaks, CA, 2018.
22. Braun, V.; Clarke, V. Using thematic analysis in psychology. *Qual. Res. Psychol*. **2006**, *3* (2), 77-101.
23. Sycamore Institute. Digital Literacy Among Tennessee's Older Adults. https://sycamoretn.org/digital-literacy-older-adults/ (accessed July 29, 2024).
24. Zippia. 20+ Essential Small Business Website Statistics: How Many Businesses Have A Website. https://www.zippia.com/advice/small-business-website-statistics (accessed March 28, 2023).
25. Amra & Elma. Best Digital Transformation Statistics 2025. https://www.amraandelma.com/digital-transformation-statistics/ (accessed August 18, 2025).
26. Sycamore Institute. *op. cit*.
27. Shepard, D. 2024 Boomer Entrepreneurs Report. *LendingTree* https://www.lendingtree.com/business/small/best-places-for-boomer-entrepreneurs/ (accessed June 17, 2024).
28. NDIT Solutions. Digital Transformation for SMBs in 2025: Adapt and Thrive. https://www.nditsolutions.com/post/digital-transformation-for-smbs-in-2025-adapt-and-thrive (accessed December 31, 2024).
29. Content Marketing Institute. B2B Content Marketing Trends. *CMI* **2023**.
30. Digital Commerce 360. Temu's Gamification Strategy: A Case Study. **2025**.
31. Rogers, E. M. Diffusion of Innovations, 5th ed.; Free Press: New York, 2003.

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REVIEW ARTICLE

Relationship Between Opioids and TLR4: Effects on Neuroglia

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ABSTRACT: 125 million opioid prescriptions were dispensed in America in 2023. With more people relying on opioids for their pain-relieving effects, evident from the increase in prescriptions from 2009, with 79.5 million prescriptions being dispensed then, unaware that they are building up tolerance and opioid-induced hyperalgesia (OIH) caused by taking the same drug. Opioids have the ability to bind to the toll-like receptor 4 (TLR4) in a manner similar to the lipopolysaccharide (LPS), irrespective of their stereochemistry. In this review, we focus on previous research aimed at answering the question: What effect does opioid binding to TLR4 have on the neuroglia? Long-term use of opioids can result in OIH. This mostly occurs because of glial cell activation and the opioids binding to the TLR4, reducing the analgesic efficacy of the drug. This suggests that focusing on blocking or reducing glial cell activation, or perhaps blocking opioids from binding to the TLR4 by using antagonists, might reduce pain sensitivity and increase the pain-relieving effects.

KEYWORDS: Cellular and Molecular Biology, Genetics, Glia, TLR4, Opioid Induced Hyperalgesia, Neuroinflammation.

Introduction

The pharmacology and treatment of pain have a long and complicated history. The first documented treatment was the use of opium poppy extracts around 1550 BCE.[1,2] Over time, opium and its compounds became the foundation of pain-relieving treatments. However, while it was recognized for its potential, its addictive properties and risk of misuse became more evident. The risk of opioid overdose has led to an increased exploration for more effective treatments to relieve pain, increase significantly. However, pain remains a public health challenge as nearly two-thirds of pain patients experience little to no relief from the available treatments.[3] Although opioids are widely used clinically to relieve pain, they are also able to induce inflammation in the brain and modulate the immune system in the body. Opioids induce the release of high mobility group box 1 protein (HMGB1), a danger-associated molecular pattern (DAMP) that also has the ability to activate the TLR4, triggering a signaling cascade of pro-inflammatory cytokines and chemokines.[4] In response to an infection, opioids can impair the number of macrophages responding to it.[5] Opioids can also modulate the release of hypothalamic-pituitary-adrenal (HPA) axis hormones, which in turn are able to regulate glucocorticoids, known for playing an important role in regulating cellular immune response.[6] Can blocking the opioids from binding to the TLR4 or blocking the upregulation of the DAMPs reduce immune suppression? Will it reduce the number of inflammatory cytokines released? The mechanisms that play a role in the immunosuppressive effects of opioids are still unknown.[4] Further research could help bridge the gap between chronic use of opioids and immune dysfunction.[7]

Therefore, the purpose of this review is to examine the relationship between opioids and toll-like receptor 4 (TLR4) and its potential impact on the neuroglia. TLR4 is a part of the Toll-like receptor family (TLR), a pattern recognition receptor specific to both intracellular and extracellular regions.[4] The TLR4 can activate the innate immune response through the detection of pathogen-associated molecular patterns (PAMPs), such as those from bacteria or viruses, and danger-associated molecular patterns (DAMPs) emerging from endogenous signals indicating cell death.[4] TLR4 is usually activated by its natural ligand, lipopolysaccharide (LPS), which requires the involvement of several additional proteins, including lipopolysaccharide-binding protein (LBP), cluster of differentiation 14 (CD14), and myeloid differentiation protein 2 (MD-2).[7]

This subsequently activates the My-D88 signaling pathway, which induces transcription factors such as NF-κB, IRF5, AP-1, and CREB, enabling the formation of pro-inflammatory cytokines. Opioids such as morphine were found to release glia-derived proinflammatory cytokines by binding to the MD-2 accessory protein, which plays a key role in neuroinflammation.[8] It has been widely documented to induce nociceptive sensitization known as opioid induced hyperalgesia (OIH); a condition where long-term opioid use leads to an increased sensitivity to pain, even the pain that was not originally present or was previously controlled by opioids.[9] Observed primarily in patients with chronic pain, where it has been enhanced by an underlying pain condition.[9]

Discussion

Mechanisms underlying morphine tolerance and allodynia:. Opioids, like morphine, can activate the spinal glial cells — The main types of glial cells in the spinal cord are astrocytes, oligodendrocytes, and microglia —, which then induces a strong proinflammatory response (causing inflammation) that rejects both acute and chronic pain relief provided by the opioid.[8] The proinflammatory response, as a result of TLR4 signaling in the ventrolateral periaqueductal gray (vIPAG) — a specific region within the brain's periaqueductal gray (PAG) that plays a crucial role in pain modulation and emotional responses — can also lead to the development of opioid induced hyperalgesia

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(OIH) and allodynia, a condition where non-painful stimuli are perceived as painful; The pathway by which this happens is still unknown.

Several pathways have been explored to better understand the interaction between opioids and spinal glial cells, including mu opioid receptor (MOR) decoupling, internalization and downregulation, enhanced N-methyl-D-aspartate receptor (NMDAR) activity, reduced glutamate transporter expression, and increased nitric oxide production.[3] Although these pathways are mainly for neuronal adaptations, additional research has focused on understanding the relationship between these processes and the effect they have on opioid tolerance. Evidence suggests that cytokines released by glial cells increase with the amount of morphine administered,[10] proposing the idea that these excitatory mediators are critical in the development of morphine tolerance. Thus, suggesting that inhibiting these cytokines could reduce the development of tolerance. However, it is also known that these inflammatory cytokines are involved in normal immune function and brain homeostasis; inhibiting these cytokines could disrupt these processes. This shows that simply targeting the cytokines wouldn't be the best solution to reverse the effects of morphine tolerance. Given the relationship between opioids and glial cells, it is understood that the production of proinflammatory cytokines opposes the chronic and acute analgesic effects of opioids.[3]

Researchers have found that morphine can bind to the neuronal MORs, which are primarily found on the GABAergic neurons, resulting in analgesia and tolerance. The pathway by which this happens is shown in Figure 1. In the vlPAG, activation of the MORs reduces the inhibition of GABAergic neurons to the PAG-RVM pathway; the neural pathway connecting the periaqueductal gray (PAG) and the rostral ventromedial medulla (RVM), resulting in a net excitation of the neurons in the spinal cord. Parallel glial activation intensifies the excitability of the MOR neurons, consequently reducing the analgesic effect of morphine and building up tolerance.[11]

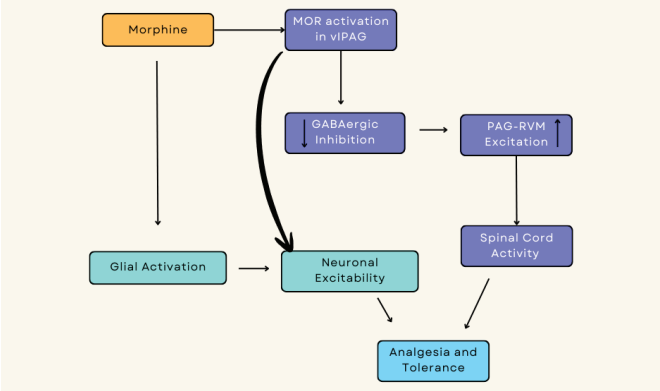

Figure 1: A pathway diagram demonstrating how the binding of morphine induces analgesia and tolerance. The light blue boxes highlight the neuronal pathway, the orange boxes highlight the glial pathway, and the red box highlights the outcome. Morphine first binds to the mu opioid receptor (MOR) in vlPAG, which leads to the inhibition of the GABAergic neurons, leading to the increased net excitation of PAG-RVM. The activation of the MOR also affects the neuronal excitability, just like the glial activation. The neuronal excitability and the excitation of the spinal cord enhance tolerance and decrease analgesia. Understanding that the pathway through which these effects take place involves the vlPAG, GABAergic neurons, and the PAG-RVM.

TLR4 signaling in opioid-induced neuroinflammation and its role in addiction:

A study showed that opioids such as morphine interact with the MD2 protein.[14] Once TLR4 is activated by opioids, it increases the amount of proinflammatory cytokines and chemokines released, altering the neuronal plasticity.[15] Opioid-induced glial activation is considered to contribute to the reinforcement of reward-like effects, achieved by binding to TLR4. The known neuronal mechanism in relation to opioid addiction involves the suppression of the GABAergic tone on the dopaminergic reward pathway from the ventral tegmental area (VTA) to the nucleus accumbens (NA), leading to enhanced dopamine release, hence the reward-like feeling.[15] Tumor necrosis factor-alpha (TNFα), a downstream effector of TLR4 signaling, demonstrated that it can mediate morphine-induced neuroinflammation, and inhibiting it reduced TLR4-dependent inflammatory responses.[12] Like TNFα, activating TLR4 also increases the amount of interleukin-1β (IL-1β) expression.[16] The role of IL-1β is to mediate long-term potentiation (LTP), which plays a role in memory.[17] IL-1β can inhibit the glial glutamate transporter, which reduces the amount of glutamate, disrupting the glutamate-glutamine cycle-dependent GABA synthesis. The processes stated above play a key role in synaptic plasticity, which may affect TLR4-related drug actions.[15] TLR4-mediated central immune response to opioids such as morphine can only function with respect to well-constituted reward neuronal pathways, since immune signaling alone cannot induce behavioral changes.[18] The neuroinflammation caused by opioids has been associated with morphine analgesia, dependence, tolerance, and withdrawal effects.[12] Enhanced morphine induced analgesia was observed in TLR4/MD2 knockout mice, which shows that interference with TLR4/MD2 signaling inhibits morphine induced proinflammatory responses. However, some studies oppose the idea that TLR4 has much to do with opioid addiction.[13] This is backed by the findings of Stevens and colleagues that showed morphine inhibits LPS-induced activation of TLR4 in a concentration-dependent manner. Keeping in mind how two different pathways are being considered for the same effect, this begs the question of what other signaling pathways are involved in this interaction, opening areas to further research.

From this, we can understand that opioid induced neuroinflammation is mediated partially through the TLR4 signaling, which in turn contributes to the analgesic, addictive, and inflammatory effects of the opioid by allowing the release of pro-inflammatory cytokines, as stated above. However, it is also good to note that contrasting evidence of TLR4's involvement in opioid addiction suggests that there are other pathways involved.

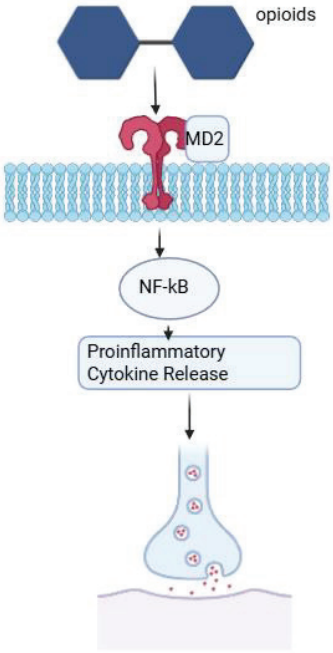

Figure 2: Shows the opioid binding to the accessory protein MD2, which results in the downstream signaling of the NF-kB. This leads to the release of proinflammatory cytokines.

Role of TLR4 activation and M3G in mediating opioid induced hyperalgesia and tolerance:

Depending on the location of the activation, TLR4 activated by opioids can cause neuroinflammation,[19] leading to opioid induced hyperalgesia, dependence, reward, and reinforcement.[20] The effects of pharmacological blocking of TLR4 were evaluated by Gabr *et al.* The evaluation brought to light that the analgesic efficacy of morphine improved when morphine was administered along with a TLR4 blocker or a peptide that blocks the Toll-Interleukin-1 receptor domain.

An earlier paper suggests that morphine-3-glucuronide (M3G) can elicit pain enhancement and develop hyperalgesia.[22] However, the details of the mechanism are still unknown.[23] Furthermore, an *in vitro* study showed that M3G can activate the TLR4, suggesting that the pain enhancement of M3G could be a result of the proinflammatory response. Enhanced allodynia and thermal hyperalgesia were observed when M3G (0.75 μg) was administered intrathecally — a route of drug administration where a substance is injected into the cerebrospinal fluid (CSF) (the fluid surrounding the brain and spinal cord) — *in vivo*. This effect was also reduced when M3G was co-administered with glial inhibitors, proinflammatory cytokine inhibitors, and either isomer of naloxone.[24] Figure 2 shows the experimental setup used to show how these conclusions were drawn. Studies have shown that repeated use of morphine leads to increased activation of the glial cells in the vlPAG.[25] Further research showed that TLR4 signaling in these cells played a role in developing opioid tolerance. The administration of glial inhibitors, proinflammatory cytokine inhibitors, or naloxone into the vlPAG blocked the development of opioid tolerance. However, the administration of morphine in vlPAG induced tolerance.[10]

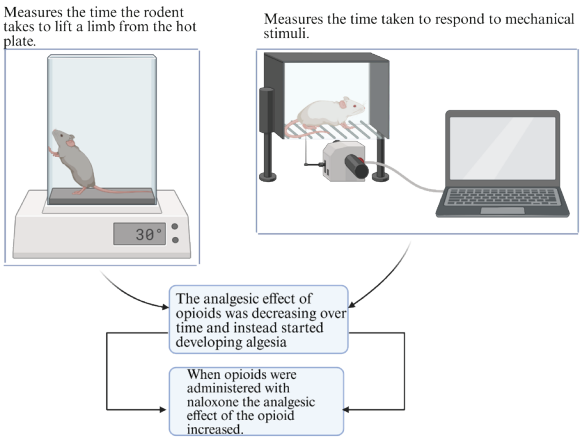

Figure 3: The experimental setup used to measure the time taken for a response to be recorded for both the thermal and mechanical stimuli. 2 groups of mice were tested, the first group being rodents administered with only the opioid, in this case M3G, and the second group being rodents administered with both the opioid, M3G, and naloxone, an opioid antagonist. The first group of rodents showed decreasing analgesic efficacy of the drug and the development of analgesia over time as more M3G was administered. However, the second group of rodents showed increasing analgesic efficacy of M3G compared to the first group. Suggesting that the administration of opioids with their antagonist could increase their analgesic efficacy. However, this investigation only focused on the effects of opioids on sensitivity and how the administration of an antagonist helped with the efficacy; it's important to note that this method did not highlight the effects… had on the immune system or brain homeostasis. Activation of TLR4 by opioids induces neuroinflammation, tolerance, hyperalgesia, and dependence. It can be seen that blocking the TLR4 increases morphine's analgesic effects. We can also understand through the study above that the proinflammatory pathways activated by the binding of opioids to the TLR4 can be diminished by cytokine or glial inhibitors.

Downstream NF-kB and MAPK activation in neuroinflammation and tolerance:

Opioid receptor agonists are able to activate the TLR4 without the use of additional proteins, even without the need for LPS.[26] This ability, in particular, is also exhibited by endogenous opioids, a few of which originate from immune cells.[27] Traditionally, the interaction between opioids and their receptors is stereoselective. However, the binding of opioids to the TLR4 is non-stereoselective, meaning all stereoisomers of the opioid can bind to the TLR4. Uniquely, Morphine-3-glucuronic acid (M3G) — a morphine metabolite processed in the liver lacking affinity to bind to opioid receptors — can activate the TLR4. HGMB1, an endogenous antagonist of TLR4, interacts with danger signals produced both exogenously and endogenously to induce inflammation. HGMB1 is said to be activated by both immune cells and neuronal cells.[28] Surprisingly, the activation of the TLR4 has been linked to the morphine-induced HMGB1 production.[27,29] Increased levels of HMGB1 in our body have been thought to play a role in the development of inflammation, tolerance, hyperalgesia, and allodynia.[26]

MD2, a key component of the TLR4 signaling, detects the LPS and initiates the innate immune response. Opioids bind to the MD2, activating the nuclear factor kappa-light-chain enhancer of activated B cells (NF-kB), a protein complex that plays a crucial role in regulating gene transcription, cytokine production, and cell survival. Inducing the release of

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proinflammatory cytokines such as TNFα and IL-1β [30] all the while activating the MAPK pathway — a crucial signaling cascade in cells that transmits extracellular signals to the nucleus — allowing for the development of inflammation.[26] This suggests a possible interaction between immune cells and glial cells.[19] The interaction between opioids and the TLR4 may contribute to the development of hyperalgesia, allodynia, and tolerance, most of which are also linked with opioid-induced activation of proinflammatory glia.[27,31] Studies suggest that opioid-induced immune response and the key role played by neuroglia may be the reason behind the drugs' reduced efficacy.[28] Activating the transmembrane TLR4 initiates the innate immune response, leading to nuclear factor kappa B (NF-κB) activation, a protein complex that plays a crucial role in regulating gene expression, particularly in response to inflammation, immunity, and cell survival; while simultaneously activating the transcription of proinflammatory cytokines in macrophages, monocytes, and glial cells.[27] This highlights the decreasing effect of opioids.

Previous studies have shown that continuous morphine administration enhances HMGB1 release and induces mechanical allodynia — a condition where a non-painful stimulus, like light touch or pressure, is perceived as painful — that can continue even after the morphine treatment has been stopped.[27] In regard to this, increased IL-1β from activated spinal microglia has been noted, in addition to the activation of the NOD-like receptor protein 3 (NLRP3) inflammasome; a multi-protein complex that plays a crucial role in innate immunity by activating caspase-1 and the inflammatory cytokines interleukin (IL)-1β and IL-18.[32] Studies in TLR4 knockout mice have shown the involvement of TLR4 in reducing the pain relieving effect of the opioid. Indicating that the anti-analgesic effect of the opioids may not be entirely mediated through the TLR4, but it can support or enhance the effect.[15,27] Opioids and their metabolites can non-stereospecifically bind to the TLR4, activating the NF-κB and MAPK pathways.

Conclusion

The studies and the evidence stated above show how opioids bind to the TLR4 to initiate the proinflammatory signaling. This interaction leads to opioid-induced hyperalgesia, tolerance, and allodynia. The mechanisms that underlie these consequences are TNF-α and IL-1β, HMGB1-mediated amplification of inflammation, and NLRP3 inflammasome activation. While we now realize that TLR4 is not the sole mediator of these effects, it does play a role in enhancing the effects caused by opioids.

Targeting the TLR4 signaling directly or through inhibition of glial and cytokine pathways could be a potential solution to the above-stated consequences or increase the analgesic efficacy of the opioid. Future direction for this research could focus on distinguishing the contributions of TLR4 in the development of tolerance, OIH, and allodynia, and the contributions of the pathways and their link to the effects. Additionally, the direction could be steered towards the hormones of the immune system and using developing genetic technology to engineer them to combat the consequences of opioid misuse. A good idea would be to use the DREADDS technology to find specifically which neuronal pathways play a key role in leading to opioid misuse and target the proteins in those pathways to reduce the consequences of opioid misuse. This review is limited in the number of clinical trials referred to.

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References

1. Volkow, N. D.; McLellan, T. A.; Cotto, J. H.; Karithanom, M.; Weiss, S. R. Characteristics of Opioid Prescriptions in 2009. *Jama* **2011**, *305* (13), 1299–1301.
2. Stefano, G. B.; Pilonis, N.; Ptacek, R.; Kream, R. M. Reciprocal Evolution of Opiate Science from Medical and Cultural Perspectives. *Med. Sci. Monit. Int. Med. J. Exp. Clin. Res.* **2017**, *23*, 2890.
3. Hutchinson, M. R.; Bland, S. T.; Johnson, K. W.; Rice, K. C.; Maier, S. F.; Watkins, L. R. Opioid-induced Glial Activation: Mechanisms of Activation and Implications for Opioid Analgesia, Dependence, and Reward. *Sci. World J.* **2007**, *7* (1), 98–111.
4. Zhang, P.; Yang, M.; Chen, C.; Liu, L.; Wei, X.; Zeng, S. Toll-like Receptor 4 (TLR4)/Opioid Receptor Pathway Crosstalk and Impact on Opioid Analgesia, Immune Function, and Gastrointestinal Motility. *Front. Immunol.* **2020**, *11*, 1455.
5. Plein, L. M.; Rittner, H. L. Opioids and the Immune System–Friend or Foe. *Br. J. Pharmacol.* **2018**, *175* (14), 2717–2725.
6. Friedman, H.; Newton, C.; Klein, T. W. Microbial Infections, Immunomodulation, and Drugs of Abuse. *Clin. Microbiol. Rev.* **2003**, *16* (2), 209–219.
7. Gabr, M. M.; Saeed, I.; Miles, J. A.; Ross, B. P.; Shaw, P. N.; Hollmann, M. W.; Parat, M.-O. Interaction of Opioids with TLR4—Mechanisms and Ramifications. *Cancers* **2021**, *13* (21), 5274.
8. Eidson, L. N.; Murphy, A. Z. Blockade of Toll-like Receptor 4 Attenuates Morphine Tolerance and Facilitates the Pain-Relieving Properties of Morphine. *J. Neurosci.* **2013**, *33* (40), 15952–15963.
9. Grace, P. M.; Strand, K. A.; Galer, E. L.; Urban, D. J.; Wang, X.; Baratta, M. V.; Fabisiak, T. J.; Anderson, N. D.; Cheng, K.; Greene, L. I. Morphine Paradoxically Prolongs Neuropathic Pain in Rats by Amplifying Spinal NLRP3 Inflammasome Activation. *Proc. Natl. Acad. Sci.* **2016**, *113* (24), E3441–E3450.
10. Eidson, L. N.; Murphy, A. Z. Blockade of Toll-like Receptor 4 Attenuates Morphine Tolerance and Facilitates the Pain-Relieving Properties of Morphine. *J. Neurosci.* **2013**, *33* (40), 15952–15963.
11. Eidson, L. N.; Murphy, A. Z. Persistent Peripheral Inflammation Attenuates Morphine-Induced Periaqueductal Gray Glial Cell Activation and Analgesic Tolerance in the Male Rat. *J. Pain* **2013**, *14* (4), 393–404.
12. Eidson, L. N.; Inoue, K.; Young, L. J.; Tansey, M. G.; Murphy, A. Z. Toll-like Receptor 4 Mediates Morphine-Induced Neuroinflammation and Tolerance via Soluble Tumor Necrosis Factor Signaling. *Neuropsychopharmacology* **2017**, *42* (3), 661–670.
13. Wu, R.; Li, J.-X. Toll-like Receptor 4 Signaling and Drug Addiction. *Front. Pharmacol.* **2020**, *11*, 603445.
14. Shah, M.; Anwar, M. A.; Yesudhas, D.; Krishnan, J.; Choi, S. A Structural Insight into the Negative Effects of Opioids in Analge-

sia by Modulating the TLR4 Signaling: An in Silico Approach. *Sci. Rep*. **2016**, *6* (1), 39271.
15. Wu, R.; Li, J.-X. Toll-like Receptor 4 Signaling and Drug Addiction. *Front. Pharmacol*. **2020**, *11*, 603445.
16. Latz, E.; Xiao, T. S.; Stutz, A. Activation and Regulation of the Inflammasomes. *Nat. Rev. Immunol*. **2013**, *13* (6), 397–411.
17. Rizzo, F. R.; Musella, A.; De Vito, F.; Fresegna, D.; Bullitta, S.; Vanni, V.; Guadalupi, L.; Stampanoni Bassi, M.; Buttari, F.; Mandolesi, G. Tumor Necrosis Factor and Interleukin-1β Modulate Synaptic Plasticity during Neuroinflammation. *Neural Plast*. **2018**, *2018* (1), 8430123.
18. Coller, J. K.; Hutchinson, M. R. Implications of Central Immune Signaling Caused by Drugs of Abuse: Mechanisms, Mediators and New Therapeutic Approaches for Prediction and Treatment of Drug Dependence. *Pharmacol. Ther*. **2012**, *134* (2), 219–245.
19. Wang, X.; Loram, L. C.; Ramos, K.; de Jesus, A. J.; Thomas, J.; Cheng, K.; Reddy, A.; Somogyi, A. A.; Hutchinson, M. R.; Watkins, L. R. Morphine Activates Neuroinflammation in a Manner Parallel to Endotoxin. *Proc. Natl. Acad. Sci*. **2012**, *109* (16), 6325–6330.
20. Aguado, D.; Bustamante, R.; de Segura, I. A. G. Toll-like Receptor 4 Deficient Mice Do Not Develop Remifentanil-Induced Mechanical Hyperalgesia: An Experimental Randomised Animal Study. *Eur. J. Anaesthesiol. EJA* **2018**, *35* (7), 505–510.
21. Hutchinson, M. R.; Zhang, Y.; Brown, K.; Coats, B. D.; Shridhar, M.; Sholar, P. W.; Patel, S. J.; Crysdale, N. Y.; Harrison, J. A.; Maier, S. F. Non-stereoselective Reversal of Neuropathic Pain by Naloxone and Naltrexone: Involvement of Toll-like Receptor 4 (TLR4). *Eur. J. Neurosci.* **2008**, *28* (1), 20–29.
22. Sakurada, T.; Komatsu, T.; Sakurada, S. Mechanisms of Nociception Evoked by Intrathecal High-Dose Morphine. *Neurotoxicology* **2005**, *26* (5), 801–809.
23. Shah, M.; Anwar, M. A.; Yesudhas, D.; Krishnan, J.; Choi, S. A Structural Insight into the Negative Effects of Opioids in Analgesia by Modulating the TLR4 Signaling: An in Silico Approach. *Sci. Rep*. **2016**, *6* (1), 39271.
24. Lewis, S. S.; Hutchinson, M. R.; Rezvani, N.; Loram, L. C.; Zhang, Y.; Maier, S. F.; Rice, K. C.; Watkins, L. R. Evidence That Intrathecal Morphine-3-Glucuronide May Cause Pain Enhancement via Toll-like Receptor 4/MD-2 and Interleukin-1β. *Neuroscience* 2010, *165* (2), 569–583.
25. Eidson, L. N.; Murphy, A. Z. Persistent Peripheral Inflammation Attenuates Morphine-Induced Periaqueductal Gray Glial Cell Activation and Analgesic Tolerance in the Male Rat. *J. Pain* **2013**, *14* (4), 393–404.
26. Zhang, P.; Yang, M.; Chen, C.; Liu, L.; Wei, X.; Zeng, S. Toll-like Receptor 4 (TLR4)/Opioid Receptor Pathway Crosstalk and Impact on Opioid Analgesia, Immune Function, and Gastrointestinal Motility. *Front. Immunol*. **2020**, *11*, 1455.
27. Echeverria-Villalobos, M.; Tortorici, V.; Brito, B. E.; Ryskamp, D.; Uribe, A.; Weaver, T. The Role of Neuroinflammation in the Transition of Acute to Chronic Pain and the Opioid-Induced Hyperalgesia and Tolerance. *Front. Pharmacol*. **2023**, *14*, 1297931.
28. Shah, M.; Choi, S. Toll-like Receptor-Dependent Negative Effects of Opioids: A Battle between Analgesia and Hyperalgesia. *Front. Immunol*. **2017**, *8*, 642.
29. Qian, J.; Zhu, Y.; Bai, L.; Gao, Y.; Jiang, M.; Xing, F.; Zhang, J.; Zhao, W.; Gu, H.; Mi, Y. Chronic Morphine-Mediated Upregulation of High Mobility Group Box 1 in the Spinal Cord Contributes to Analgesic Tolerance and Hyperalgesia in Rats. *Neurotherapeutics* **2020**, *17* (2), 722–742.
30. Liu, X.; Yang, W.; Zhu, C.; Sun, S.; Wu, S.; Wang, L.; Wang, Y.; Ge, Z. Toll-like Receptors and Their Role in Neuropathic Pain and Migraine. *Mol. Brain* **2022**, *15* (1), 73.
31. Hutchinson, M. R.; Bland, S. T.; Johnson, K. W.; Rice, K. C.; Maier, S. F.; Watkins, L. R. Opioid-induced Glial Activation: Mechanisms of Activation and Implications for Opioid Analgesia, Dependence, and Reward. *Sci. World J*. **2007**, *7* (1), 98–111.
32. Grace, P. M.; Strand, K. A.; Galer, E. L.; Urban, D. J.; Wang, X.; Baratta, M. V.; Fabisiak, T. J.; Anderson, N. D.; Cheng, K.; Greene, L. I. Morphine Paradoxically Prolongs Neuropathic Pain in Rats by Amplifying Spinal NLRP3 Inflammasome Activation. *Proc. Natl. Acad. Sci*. **2016**, *113* (24), E3441–E3450.

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REVIEW ARTICLE

Nostalgia and Its Impacts on Patients with Alzheimer's Disease

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ABSTRACT: Dementia is a category of conditions involving a decline in cognitive function that may further influence an individual's typical day-to-day abilities. Recently, there has been a rise in the exploration of the role of nostalgia as a proposed treatment for Alzheimer's disease (AD). This literature review seeks to examine the previous research conducted and consider nostalgia's connection to AD and memory networks, as well as various attempts of administering nostalgia, observing its positive impacts relating to cognitive function, self-esteem, and social connectedness. This review will highlight the prospective benefits of induced nostalgia and introduce its role as an area that should be explored to aid seniors with AD who are unable to access the standard of care.

KEYWORDS: Neuroscience, Memory, Alzheimer's Disease, Nostalgia, Cognitive Function.

Introduction

In 2021, there were 57 million patients with dementia. This number continues to rise as there are an additional 10 million cases each year.[1] Alzheimer's disease (AD) is a neurodegenerative disease. Neurodegenerative diseases involve loss of neurons over time; in AD, there is damage to neurons in the hippocampus, resulting in deterioration in a person's memory that involves a decline in cognitive function and basic skills. The deterioration of the hippocampus prevents the development of new long-term memories.

Nostalgia is a feeling in which an individual recollects a memory from their past; it is a feeling that heavily features one's own typically positive memories. It is involved with brain regions associated with reward processing, autobiographical memory, and self-reflection, including the prefrontal cortex and the amygdala.[2]

In this field, there has been promising research in the exploration of nostalgic reminiscence on the psychological resources of AD patients.[3] It has been observed that music therapy utilizing music that had been encoded over time with standard care can support cognitive function and reduce negative emotions in AD patients.[4] It has also been seen that cues in nostalgia-inducing films can augment emotion and psychological reactions and lead to more retrieval of autobiographical information.[5] When compared to a control group that received ordinary biographical memories--general recollections of the self and personal experiences--members of an experimental group recalling nostalgic memories self-reported greater feelings of optimism, social connectedness, and meaning in life.[6]

Historically, AD has been treated using therapeutic interventions that improve cognitive function in patients but cause unwanted side effects, including nausea, vomiting, confusion, and headaches.[7] These treatments may also prove to come at high costs, making them inaccessible to some patients with a pressing need for them.[8] Recent research indicates the possibility of new treatments for Alzheimer's patients that can improve their quality of life without causing the unwanted side effects that are a result of pharmaceuticals. While there has been extensive research regarding new pharmacological interventions such as rasagiline and ladostigil, the impact of nostalgia has been underexplored in its ability to serve as an alternative to traditional treatments.[9]

This literature review aims to examine the positive impacts of nostalgia on the brain and how it can alleviate the impacts of Alzheimer's disease and impact memory recall, and thus serve as a viable treatment for Alzheimer's patients. This review seeks to examine the positive impacts of nostalgia on Alzheimer's disease by reviewing published papers that provide empirical data and a consensus regarding the possibilities for nostalgia in this field. It is important to consider the uses of induced nostalgia for AD patients as it may outline potential benefits and theoretical possibilities for future clinical applications. This review will demonstrate how nostalgia can aid patients with AD, alleviating various negative psychological emotions and improving cognitive function, and thus may have implications as a future treatment for nostalgia.

The connection between nostalgia and memory will be examined and the relationship between AD and memory will be examined; both nostalgia and AD will be discussed in the following section. It will also outline nostalgia-inducing therapies, including reminiscence therapy and nostalgia induced by stimuli in the senses, concluding with remarks about future research. The review will focus on papers comparing the psychological conditions of various groups of individuals after facing nostalgia-inducing therapies, with individuals in control groups that do not experience nostalgic intervention. The review will examine impacts on self-esteem, overall mood, cognitive function, and emotional reactivity.

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Discussion

Nostalgia and Memory:

Nostalgia has strong connections to long-term memory and, subsequently, may be implemented to aid AD patients. Nostalgia consists of self-reflection, autobiographical memory, emotional regulation, and reward.[2] Nostalgia is closely related to autobiographical memory, which involves memories of specific events that may be recalled and encoded in the hippocampus, and information about oneself.[10] The intrinsic memory-reward network is a reward system in which the hippocampus relays a signal to the nucleus accumbens and ventral pallidum, which continues the signal to the ventral tegmental area (VTA), where activity increases in the VTA dopamine cells, and dopamine may be released.[11] The subiculum is a structure between the hippocampus and the entorhinal cortex and processes information before relaying it to other areas. The nucleus accumbens, located in the basal forebrain, receives dopamine after the hippocampus sends a signal associated with glutamate to the nucleus accumbens and the ventral pallidum. The ventral pallidum is a structure in the basal ganglia that aids in the integration of the signals and consequently regulates behaviors. Along with the signal, the hippocampus releases dopamine, further activating long-term potentiation (LTP). It has been observed that during nostalgic experiences, there is simultaneous activation between memory and reward regions, indicating that both memory and reward systems have an influence on the formation and feeling of nostalgia.[12] Thus, inducing nostalgia can lead to stimulation in both the memory and reward regions, possibly reinforcing positive feelings of reward in AD patients, which will encourage them to adopt a more positive outlook on life as well as improved psychological resources.

Impact of Nostalgia:

The loss of memories caused by AD can lead to the loss of a sense of self and individual identity, leading to anxiety and depression, common conditions that arise from AD.[13] Nostalgia-inducing therapies may be implemented to alleviate this indirect impact caused by the loss of memory because the emotion can stimulate positive feelings about self-esteem and optimism, possibly reducing the impact of negative feelings in AD patients.

Generally, nostalgia has a positive impact on individuals who do not have AD. Along with previously discussed positive impacts, nostalgia can also stimulate motivation. Induced nostalgia in populations has been shown to increase feelings of motivation.[14] Nostalgia's impact on approach, desire to pursue, and avoidance, desire to move away from motivation was examined. About approach motivation, 120 participants were randomly assigned to the experimental group, induced nostalgia, and the control group; the experimental group was instructed to recall a nostalgic event and write down four keywords, and the control group was instructed to do the same while recalling an ordinary event.[15] Then, they self-reported their agreement or disagreement with a set of statements provided. Ultimately, they found that induced nostalgia strengthens the behavioral activation or approach motivation (BAS) on fun seeking and drive, indicating greater approach motivation. Therefore, understanding how nostalgia can create positive feelings and motivation may be utilized to aid AD patients who face difficulties from the condition.

The emotion is also able to increase self-esteem, as seen in a study that required individuals to recall nostalgic experiences or daily occurrences.[16] 72 participants were divided into two groups, with 35 participants in the nostalgic recollections group–the experimental group–and the typical recollections group–the control group. The researchers measured self-esteem using a modified version of the Rosenberg Positive Self-Esteem Scale (SES); it was found that the scores of the group tasked to reminisce about nostalgic events were significantly higher than those of the group tasked to recall regular events. While different from self-esteem, it is seen that optimism also rises when self-esteem rises. This effect had been observed in a study involving 102 participants randomly assigned to either nostalgic or controlled conditions; in the former condition, participants recalled a nostalgic event, whereas in the latter condition, participants recalled an ordinary event. Those in the experimental group experienced a higher proportion of expressions of optimism, indicating that nostalgia may be positively associated with optimism.[17] Hence, nostalgia may induce positive emotions in individuals with AD and limit side effects.

Alzheimer's Disease and Memory:

AD negatively impacts memory and can lead to many negative side effects, including loss of cognitive function and a decline in psychological resources. In AD, neurons become dysfunctional and lose connections, particularly impacting the connections in the hippocampus, an area of the brain associated with memory encoding and recollection. Neurofibrillary tangles, an issue that occurs as a result of abnormal deposits of tau, a protein that stabilizes microtubules, leading to the detachment of neurons from certain molecules and attachment to other molecules, further contribute to the loss of memories by inhibiting interneural action potentials.[18] Additionally, patients experience more declining production of episodic autobiographical memories than healthy older adults, and over time, the ability to recall specific details in memory declines, leading to the shift of autobiographical memories into semantic autobiographical memories that are more general about the self.[13]

It was found that older AD patients were able to recall personal and semantic memories "from the remote past relative to the recent one."[19] This finding is consistent with the idea that the connection between neurons forming older memories has been strengthened over time due to recall in childhood and young adulthood, making those memories the most impactful on the lives of AD patients.[20] Conversely, relatively new memories have not had as much time to develop and strengthen their neural connection and are therefore more vulnerable to neurofibrillary tangles. Since nostalgia involves the recollection of events from the past, inducing nostalgia can strengthen those neural connections and thus may have implications on the rate of memory degradation that occurs due to the entwining of neural fibers.

It has been found that inducing momentary nostalgia, using nostalgic landmarks, has offered benefits to AD patients in their self-esteem, social connectedness, and self-continuity, as well as improved their ability to recognize pictures from their past; this research indicates that nostalgia may have a positive impact on AD patients.[21] Moreover, since both nostalgia and AD are involved with memory networks, stimulating feelings of nostalgia in patients may be able to improve cognitive function and aid in memory recall. Thus, exploring their connection may offer insight into future clinical applications for nostalgia in the field of AD.

Impact of Nostalgia in Alzheimer's (Treatment):

Reminiscence therapy and therapies that target the senses and induce nostalgia for patients have been observed to have overall positive impacts on patients' psychological state. The impacts of both interventions will be discussed.

Reminiscence Therapy Inducing Nostalgia in Alzheimer's:

Reminiscence therapy is a form of therapy that instructs patients to think of a previous action or memory, of which recalling a prior memory is more closely associated with nostalgia, to help patients with dementia reduce indirect impacts and improve cognitive function, as well as improve their psychological condition. It has been seen in a study that the therapy improved subjective observations of patients by close friends and family members.[22] In the study, 14 participants with dementia and 4 participants without dementia performed activity reminiscence therapy to investigate the impact of this form of reminiscence therapy on their cognitive condition and social interactions. They would reminisce for ten minutes before the therapy, and their initial cognitive state was identified before the activity reminiscence therapy and after the activity reminiscence therapy had been completed. It was found that for dementia patients, there had been increased cognition, memory, and attention span. When conferring with family members, it was found that some individuals exhibited a more cheerful demeanor, were more eager to attend the following session, and had improved relationships with their peers in the form of friendships and staff. Therefore, nostalgia administered using reminiscence therapy may have a positive impact on patients with dementia, including AD patients, and may be able to reduce negative feelings surrounding daily tasks that lead to more serious conditions such as depression and anxiety.

Reminiscence therapy may also be effective in producing a positive impact on cognitive function for patients with AD. In a systematic review that examined 3291 articles, it was found that 5 specifically outlined reminiscence therapy with reference to cognitive function and quality of life.[23] In the studies, participants with cognitive deterioration underwent trials that sought to apply methods to improve their cognitive condition. It was found that the moderate cognitive deterioration experienced in AD patients can be reduced or stabilized by reminiscence therapy, further implicating that nostalgia, when induced in an individual with AD, may be able to benefit their cognitive abilities and consequently might be able to impact the rate of memory decline. Utilizing reminiscence therapy to stimulate the neural networks and inadvertently leading to nostalgic recollection may be a beneficial approach to aiding AD patients with moderate cognitive decline or pessimistic attitude.

Stimulus-Induced Nostalgia in the Senses for Alzheimer's:

Stimulus-induced therapy involves stimulating nostalgia in the various senses to elicit a change in memory or psychological state in participants. It has been effective when considering the auditory system and visual system in improving recall of memories and in stimulating positive emotions.

There has been promising information in the auditory system. It has been found that the regions that deteriorate due to AD have a minimal impact on the regions associated with long-term musical memory encoding, such as the pre-supplementary motor area that helps control voluntary actions and the caudal anterior cingulate gyrus that aids in cognitive and emotional function.[24] Since these regions are involved with the encoding of long-term musical memory and are relatively unimpacted by AD, it would be useful to explore the impact of music-evoked nostalgic therapy on the cognitive function of AD patients. In a study involving 63 participants with mild-to-moderate AD, the impact of integrating induced nostalgia into typical activities and into music was tested.[4] To test the impact of the therapy, they relied on the Mini-Mental State Examination (MMSE) and the Montreal Cognitive Assessment Scale (MOCA), which test the cognitive function of individuals. Additionally, the Self-Rating Anxiety Scale (SAS) and the Zung Self-Rating Depression Scale (SDS) were used to examine psychological conditions. Scores from both the control and experimental groups were acquired and compared before and after the experiment to determine the efficacy of treatment. Prior to intervention, scores between both groups had no significant difference, but after the experiment was completed, it was found that the MMSE and MOCA groups testing for cognitive function were higher in the experimental group. This finding demonstrates that stimulating nostalgia in the auditory system may have contributed to an improvement in cognitive function in individuals and may be able to have a role in repairing memory recall after AD has caused it to decline. Moreover, both the SAS and SDS scores of the patients in the treatment group experienced a greater decline when compared to the control group. Therefore, musical therapy inducing nostalgia might have a role in improving the mental status of AD patients and preventing them from undergoing unwanted indirect effects, such as depression and anxiety. By preventing depression and anxiety from harming AD patients, music therapy can change their feelings about themselves and about others, as well as their positive outlook on life, which can prevent further deterioration of their mental condition.

The visual system is connected to areas that have seen degeneration as a result of AD.[25] It has been seen that patients exhibit issues between connections between the visual corticocortical regions, regions that process visual stimuli, in the brain, and thus face problems such as problems with spatial recognition and facial recognition. Despite these findings, it has been seen that induced nostalgia is able to produce a

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positive response in the visual system when involving other systems, such as the auditory system, positively affecting the cognitive function and psychological condition of AD patients after treatment. Specifically, there have been findings involving films that stimulate nostalgia that illustrate the impact of this treatment on individuals. 21 participants with AD, the experimental group, and 22 participants without cognitive impairments, the control group, were further divided into a group that did not watch a nostalgia-inducing film and another group that did watch a nostalgia-inducing film.[26] They first watched nostalgic films and then were tasked to narrate "events that have been important in [their] life" in fifteen minutes. It was found that groups that watched nostalgic films had more episodic specificity, a detailed recall of an event from the past, than did the groups that did not watch the films. The results underline the idea that inducing nostalgia with films can help AD patients remember more details from their past that they were unable to recall prior to watching the film. This finding is further supported by Rasmussen *et al.*, who studied the ability of stimulated nostalgia to stimulate involuntary autobiographical memories (IAMs).[5] The control group involved 22 older adults without cognitive impairment, and the experimental group involved 21 patients with AD. Of these groups, they were further subdivided into a group that recalled memories prior to watching the nostalgic film and a group that did not recall memories before watching the film. The involuntary recall was observed after participants had either been tasked with recalling previous memories before the study or had not been tasked to do so. Biomarkers, such as heart rate and electro-dermal activity, and emotional reactions were recorded while participants watched these nostalgia-inducing films. The study found that AD participants had more emotional responses and experienced more IAMs after watching the films. Within the AD group, it was found that those who reminisced before being instructed to watch the film recalled more memories. Therefore, nostalgia-inducing films may have a beneficial impact on AD patients in both emotional and cognitive aspects. Further, when combined with standard reminiscence therapy administered before watching a film with details that connect with an individual's long-term memories, therapies that target both visual and auditory stimuli can aid AD patients in recalling their memories and face less confusion, one of the main side effects of the neurodegenerative condition.

Caveats to Implementing Nostalgic Therapies:

There may be a few considerations before implementing induced nostalgia as a treatment for AD. Though the results are not specific to AD, it is important to deliberate on nostalgia's impact on loneliness.[27] In a study testing the negative impacts of nostalgia on the psychological condition of individuals, it was found that–when tasked to respond on a 7-point scale with 1 completely disagreeing and 7 completely agreeing with the statement–nostalgia may be able to worsen feelings of loneliness and increase longing for companionship. This research is further supported by a section of the study by Abeyta *et al.*, who observed nostalgia's impact on loneliness and how those feelings impacted social confidence.[28] Participants completed a UCLA questionnaire, answering questions related to their feelings of isolation, support from others, and companionship. Those who felt lower levels of nostalgia felt a negative correlation between loneliness and social-efficacy. However, the study demonstrates how increased levels of nostalgia can reduce the correlation between the two, and that "lonely individuals who report stronger nostalgic feelings, report less of a deficit in social confidence."[28] Nostalgia's ability to increase self-confidence was able to act against the feelings of loneliness to increase social confidence. This finding would further support the notion that the feelings of loneliness experienced by individuals with AD may gradually dissipate as a result of the increased social connection caused by the emotion. Moreover, the increased social connection can lead to more relationships that then decrease isolation and prevent or mitigate the formation of indirect side effects impacting the psychological resources, such as anxiety and depression. Overall, induced nostalgia has been seen to have positive impacts on the mental condition of patients as well as have benefitted cognitive function.

■ Conclusion

The research review explored the various interactions between memory and nostalgia, introducing how nostalgia may serve as an important resource to aid patients with AD by treating inadvertent side effects or by improving the cognitive function of patients, possibly creating a positive impact on their ability to recall memories about themselves. Ultimately, the use of nostalgia for patients with AD may be implemented to alleviate negative feelings associated with the condition, but more research is required to confirm its posited advantages and whether it will have a more important role in supporting the standard of care or be implemented by itself as an alternative treatment.

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■ References

1. *Dementia*. https://www.who.int/news-room/fact-sheets/detail/dementia (accessed 2025-07-23).
2. Yang, Z.; Wildschut, T.; Izuma, K.; Gu, R.; Luo, Y. L. L.; Cai, H.; Sedikides, C. Patterns of Brain Activity Associated with Nostalgia: A Social-Cognitive Neuroscience Perspective. *Soc Cogn Affect Neurosci* **2022**, *17* (12), 1131–1144. https://doi.org/10.1093/scan/nsac036.
3. Umar Ismail, S.; Cheston, R.; Christopher, G.; Meyrick, J. Nostalgia as a Psychological Resource for People with Dementia: A Systematic Review and Meta-Analysis of Evidence of Effectiveness from Experimental Studies. *Dementia* **2020**, *19* (2), 330–351. https://doi.org/10.1177/1471301218774909.

4. Zhang, Y.; Wang, Y.; Liu, Q.; Xiao, J.; Huang, L.; Zhou, L.; Liu, X. Exploring the Effects of Combined Nostalgic Activities and Music Therapy on Alzheimer's Disease Outcomes. *Front. Psychol*. **2025**, *16*. https://doi.org/10.3389/fpsyg.2025.1526761.
5. Rasmussen, K. W.; Salgado, S.; Daustrand, M.; Berntsen, D. Using Nostalgia Films to Stimulate Spontaneous Autobiographical Remembering in Alzheimer's Disease. *Journal of Applied Research in Memory and Cognition* **2021**, *10* (3), 400–411. https://doi.org/10.1016/j.jarmac.2020.11.001.
6. Ismail, S.; Christopher, G.; Dodd, E.; Wildschut, T.; Sedikides, C.; Ingram, T. A.; Jones, R. W.; Noonan, K. A.; Tingley, D.; Cheston, R. Psychological and Mnemonic Benefits of Nostalgia for People with Dementia. *Journal of Alzheimer's Disease* **2018**, *65* (4), 1327–1344. https://doi.org/10.3233/JAD-180075.
7. *How Is Alzheimer's Disease Treated?* National Institute on Aging. https://www.nia.nih.gov/health/alzheimers-treatment/how-alzheimers-disease-treated (accessed 2025-07-30).
8. Nandi, A.; Counts, N.; Bröker, J.; Malik, S.; Chen, S.; Han, R.; Klusty, J.; Seligman, B.; Tortorice, D.; Vigo, D.; Bloom, D. E. Cost of Care for Alzheimer's Disease and Related Dementias in the United States: 2016 to 2060. *npj Aging* **2024**, *10* (1), 13. https://doi.org/10.1038/s41514-024-00136-6.
9. Xiao, D.; Zhang, C. Current Therapeutics for Alzheimer's Disease and Clinical Trials. *Explor Neurosci*. **2024**, *3* (3), 255–271. https://doi.org/10.37349/en.2024.00048.
10. *Autobiographical Memory - an overview | ScienceDirect Topics*. https://www.sciencedirect.com/topics/medicine-and-dentistry/autobiographical-memory (accessed 2025-08-11).
11. Lisman, J. E.; Grace, A. A. The Hippocampal-VTA Loop: Controlling the Entry of Information into Long-Term Memory. *Neuron* **2005**, *46* (5), 703–713. https://doi.org/10.1016/j.neuron.2005.05.002.
12. Oba, K.; Noriuchi, M.; Atomi, T.; Moriguchi, Y.; Kikuchi, Y. Memory and Reward Systems Coproduce 'Nostalgic' Experiences in the Brain. *Soc Cogn Affect Neurosci* **2016**, *11* (7), 1069–1077. https://doi.org/10.1093/scan/nsv073.
13. EL HAJ, M.; Antoine, P.; Nandrino, J.-L.; Kapogiannis, D. Autobiographical Memory Decline in Alzheimer's Disease. *Aging Res Rev* **2016**, *27*, 15–22. https://doi.org/10.1016/j.arr.2016.02.002.
14. Sedikides, C.; Leunissen, J.; Wildschut, T. The Psychological Benefits of Music-Evoked Nostalgia. *Psychology of Music* **2022**, *50* (6), 2044–2062. https://doi.org/10.1177/03057356211064641.
15. Stephan, E.; Wildschut, T.; Sedikides, C.; Zhou, X.; He, W.; Routledge, C.; Cheung, W.-Y.; Vingerhoets, A. J. J. M. The Mnemonic Mover: Nostalgia Regulates Avoidance and Approach Motivation. *Emotion* **2014**, *14* (3), 545–561. https://doi.org/10.1037/a0035673.
16. You, C.; Zhong, Y. The Effect of Nostalgic Contents on Self-Esteem: The Mediating Role of Loneliness. *Psychol Res Behav Manag* **2022**, *15*, 1587–1599. https://doi.org/10.2147/PRBM.S366135.
17. Cheung, W.-Y.; Wildschut, T.; Sedikides, C.; Hepper, E. G.; Arndt, J.; Vingerhoets, A. J. J. M. Back to the Future: Nostalgia Increases Optimism. *Pers Soc Psychol Bull* **2013**, *39* (11), 1484–1496. https://doi.org/10.1177/0146167213499187.
18. *What Happens to the Brain in Alzheimer's Disease?* National Institute on Aging. https://www.nia.nih.gov/health/alzheimers-causes-and-risk-factors/what-happens-brain-alzheimers-disease (accessed 2025-08-10).
19. Kirk, M.; Berntsen, D. The Life Span Distribution of Autobiographical Memory in Alzheimer's Disease. *Neuropsychology* **2018**, *32* (8), 906–919. https://doi.org/10.1037/neu0000486.
20. Rose Addis, D.; Tippett, L. Memory of Myself: Autobiographical Memory and Identity in Alzheimer's Disease. *Memory* **2004**, *12* (1), 56–74. https://doi.org/10.1080/09658210244000423.
21. Oliver, A.; Wildschut, T.; Redhead, E. S.; Parker, M. O.; Sharif, S.; Wood, A. P.; Sedikides, C.; Cheston, R. Benefits of Nostalgic Landmarks for People Living with Alzheimer's Disease. *Journal of Alzheimer's Disease* **2024**, *102* (3), 683–702. https://doi.org/10.1177/13872877241291908.
22. Yamagami, T.; Oosawa, M.; Ito, S.; Yamaguchi, H. *Effect of activity reminiscence therapy as brain-activating rehabilitation for elderly people with and without dementia - YAMAGAMI - 2007 - Psychogeriatrics - Wiley Online Library*. https://onlinelibrary.wiley.com/doi/10.1111/j.1479-8301.2007.00189.x (accessed 2025-08-13).
23. Cammisuli, D. M.; Cipriani, G.; Giusti, E. M.; Castelnuovo, G. Effects of Reminiscence Therapy on Cognition, Depression and Quality of Life in Elderly People with Alzheimer's Disease: A Systematic Review of Randomized Controlled Trials. *Journal of Clinical Medicine* **2022**, *11* (19), 5752. https://doi.org/10.3390/jcm11195752.
24. Jacobsen, J.-H.; Stelzer, J.; Fritz, T. H.; Chételat, G.; La Joie, R.; Turner, R. Why Musical Memory Can Be Preserved in Advanced Alzheimer's Disease. *Brain* **2015**, *138* (Pt 8), 2438–2450. https://doi.org/10.1093/brain/awv135.
25. Cerquera-Jaramillo, M. A.; Nava-Mesa, M. O.; González-Reyes, R. E.; Téllez-Conti, C.; de-la-Torre, A. Visual Features in Alzheimer's Disease: From Basic Mechanisms to Clinical Overview. *Neural Plast* **2018**, *2018*, 2941783. https://doi.org/10.1155/2018/2941783.
26. Rasmussen, K. W.; Berntsen, D. Nostalgia Films Improve the Episodic Richness of the Life Story in Alzheimer's Dementia. *Journal of Applied Research in Memory and Cognition* **2025**. https://doi.org/10.1037/mac0000233.
27. Newman, D. B.; Sachs, M. E. The Negative Interactive Effects of Nostalgia and Loneliness on Affect in Daily Life. *Front Psychol* **2020**, *11*, 2185. https://doi.org/10.3389/fpsyg.2020.02185.
28. Abeyta, A. A.; Routledge, C.; Kaslon, S. Combating Loneliness With Nostalgia: Nostalgic Feelings Attenuate Negative Thoughts and Motivations Associated With Loneliness. *Front Psychol* **2020**, *11*, 1219. https://doi.org/10.3389/fpsyg.2020.01219.

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REVIEW ARTICLE

A Review of Transformer-Based Financial Sentiment Analysis for Online Investor Conversation

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ABSTRACT: Financial sentiment analysis has become an increasingly important tool for understanding market movement, particularly as online platforms and social media play a growing role. Recent advances in transformer-based language models have significantly improved sentiment modeling in formal financial text. However, their application to informal investor conversation introduces distinct challenges. This review surveys recent transformer-based approaches to financial sentiment analysis with a focus on online investor conversations, where language is highly informal and multimodal. We synthesize prior work across datasets, models, and evaluation settings, highlighting how phenomena such as sarcasm, slang, emojis, mixed-content posts, and domain shift complicate sentiment interpretation. The review contrasts lexicon-based methods, recurrent neural models, and transformer architectures to assess both the strengths and limitations of each. Domain-adaptive, multimodal, and prototype-based modeling techniques are also discussed to determine the future direction of financial sentiment analysis. This paper provides a structured analysis of methodological trends, common failure modes, and open research questions in financial sentiment analysis. By clarifying both the capabilities and limitations of current transformer-based systems, this review aims to inform future research on robust, interpretable, and adaptive sentiment models for online investor conversation.

KEYWORDS: Computer Science and Software Engineering, Finance, Artificial Intelligence, Natural Language Processing, Transformer-Based Model, Financial Sentiment, Social Media.

Introduction

Markets now move at the speed of posts, not headlines. A 2025 study found that social media signals can be used to form a trading strategy that yields 4.6% excess returns, as compared to traditional news sentiment models, using real market data from 2013-2021.[1] Traditional sentiment models focus on structured news reports and company filings. Recently, models have been trained to understand financial sentiment in activity on social media platforms—most commonly Reddit.[2-4] The social media posts being examined contain sarcasm, figurative language, slang, and even images that are used to communicate. The transition towards a new type of financial text data presents both an ability to gain valuable information and a challenge for current Natural Language Processing models (NLPs).

Investor sentiment is defined as either the specific or overall opinion of active investors on a particular sector, index, or security. Investor attention, on the other hand, is the volume at which investors are monitoring said investment opportunity, and it is independent from any opinion. This distinction is significant to understand what moves markets. Cookson's team found that positive sentiment was closely correlated with positive short-term returns, and a positive change in attention signaled a reversal in either direction.[1]

While these two metrics were considered abstract before the internet, now researchers and investors alike have concrete methods to measure both sentiment and attention. Through machine learning and web scraping, data can now be collected on both attention and sentiment on social media platforms, and trends can be more accurately studied.

The evidence that these alternative sources can move markets is strong. During the GameStop and AMC short squeeze events in 2021, Reddit's r/WallStreetBets showed large spikes in post volume with sentiment that closely tracked trading activity and volatility.[3] More recent organized and community research into investor chatter from Reddit, StockTwits, and X concluded that social attention and sentiment can drive same-day market movement. In March of 2025, Cookson and colleagues took it a step further and designed a financial strategy using social media sentiment that significantly outperformed traditional models on historical data. The study importantly concluded that attention and sentiment show greater correlation with market lows than with market highs. This aligns with the idea that investors turn to social media when in a state of panic and not elation.[1] These studies show that online conversations are not just noise but signals that matter.

However, there is a fundamental problem: the language of these platforms looks nothing like the financial news articles on which current models were trained. Reddit posts in finance forums often include slang, humor, emojis, and irony. A post by Reddit user wildcat1055 reads: "AMZN green by open. Also, crayons provide many key nutrients your body needs." While it is clear to people that the second sentence has no significant context, models often hallucinate context instead of classifying the text as insignificant. This is because most financial NLPs are trained on news and reports that contain minimal to no figurative language and humor. The study described in the paper "A Large Self-Annotated Corpus for Sarcasm" has shown that sarcasm is extremely challenging to detect, even with large datasets, and that models trained on structured datasets often

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misinterpret tone when faced with figurative language.[5] Transformer models like BERT and FinBERT (fine-tuned for financial text), which have significantly improved sentiment analysis on structured data, struggle when confronted with Reddit's unconventional writing style.[6,7]

This paper explores how current NLP models extract and interpret sentiment from alternative financial text sources, such as Reddit, with unconventional language. This paper will also determine the key challenges and breakthroughs in this domain. If models can reliably interpret sentiment from social platforms, they can be used to improve trading algorithms, risk models, credit evaluations, and policy decisions. Yet, the field is still in its early stages of fully utilizing alternative text data.

It was deduced that while sentiment-based financial strategies have taken a major step forward by using alternative text data from social media, the models used to interpret sentiment in said data still have challenges to overcome before financial sentiment analysis is consistent. Recent research points to possible solutions. Prototype-based models, which classify sarcasm and sentiment into distinct archetypes, can improve performance on noisy social media data.[8] Another solution is multimodal modeling, which combines images and audio with text data to fully capture the message of every user. Finally, domain adaptation methods allow models to adapt to unlabeled Reddit data, which is abundant but difficult to label.[7]

This paper will first discuss the evolution of financial sentiment models from clean, structured datasets. Then, the unique linguistic challenges posed by alternative text data will be examined, along with highlighting recent innovations in NLP that address these issues. Finally, we will look to the future, identifying directions for financial sentiment analysis that can keep pace with ever-changing markets.

Discussion

Evolution of Financial Sentiment Models:

The first models to analyze financial sentiment worked primarily with structured text. These included earnings reports, SEC filings, news articles, and analyst briefings. A common characteristic between these is straightforward language, free from slang and ambiguity. Because of this, early models used rule-based methods and financial dictionaries to classify sentiment. Lexicon-based tools such as the Harvard IV dictionary and Loughran-McDonald sentiment word list were widely used in order to assign "positive" and "negative" labels to words or sentences appearing in financial media.[9] While these tools laid the foundation, they struggled with more nuanced language. For instance, the phrase "performance remained in line with expectations" is technically neutral in the eyes of a sentiment model. However, the statement could signal either confidence or disappointment based on the context from which it was taken.

As researchers began to look into these models, the limitations became clear. Lexicon-based approaches lacked the ability to understand negation, word order, or sentence structure. A phrase such as "not a good outlook" may be interpreted as positive signaling to the model because it identifies the word "good." In a 2019 review, it was concluded that these rule-based methods could not reliably predict market reaction based on textual sentiment alone.[10] Similarly, it was found that dictionary-driven models were consistently outperformed by modern machine-learning methods.[6]

The next major leap in this technology came from the rise of transformer-based models. In 2018, Google released BERT, a pre-trained language model capable of understanding contextual relationships between words.[11] Not long after, FinBERT was introduced, a version of BERT fine-tuned specifically for data such as analyst reports and earnings calls. Unlike the previously used lexicon-based models, FinBERT uses a transformer architecture to create contextual embeddings. These are dynamic mathematical representations of words that depend on the surrounding context.[12]

FinBERT achieved high accuracy and precision on standard financial sentiment benchmarks, such as FiQA and Financial PhraseBank.[12] It was also shown that combining FinBERT with a long short-term memory (LSTM) network improved the prediction of stock price direction in response to sentiment shifts.[13] In 2024, FinBERT performed on par with GPT-4o when dealing with formal financial text.[14]

Yet, these models were never designed to handle user-generated content in blogs and other social media. Transformer-based systems like FinBERT were trained on formal documents, not social media posts full of emojis, slang, and sarcasm. Applying them to Reddit or StockTwits in their current form would not be effective. This is largely due to the problem of domain shift, which is especially common in NLP tasks involving informal versus formal text.[7]

It has been proven that the issue of domain adaptation limits NLP models from analyzing financial sentiment. The ability of large language models (LLMs) to perform sentiment classification on Reddit posts was studied, and it was found that even advanced models struggled without additional fine-tuning or weak supervision.[15] The models, although powerful when it comes to traditional financial text, failed to analyze financial sentiment from social media activity with precision.

In conclusion, financial sentiment models built on structured text, starting with lexicon-based models and now transformer-based models such as FinBERT, are strong when it comes to analyzing the data they are trained on. These models can accurately identify sentiment in financial news and reports, signaling market movement. However, they are not equipped to handle the messy, unpredictable language of online investor communities. As the next section will show, social media platforms like Reddit present challenges that demand a new generation of adaptable NLP models.

Model Development:

Most sentiment analysis tools employ machine learning (ML). Instead of following hard-coded rules, ML models identify and use statistical patterns in data. In supervised learning, the model is trained using labeled examples. In the case of sentiment analysis, the data would consist of words and phrases, labeled with the sentiment, commonly positive, negative, or neutral. Once trained, it can classify new text. Traditional ML methods like logistic regression and support vector machines

(SVMs) worked for simple sentiment tasks, but struggled with the complexity of financial language. Training these models was time-consuming for the performance achieved.[16]

Transformer-based models solved this issue by being able to process all tokens in the data simultaneously, known as parallelization. They are an improvement on recurrent neural networks (RNNs), which process sequences one token at a time. This makes it difficult for RNNs to retain information over larger stretches of data (the vanishing gradient problem). Long Short-Term Memory networks (LSTMs) partially remedy this by selectively forgetting and remembering key tokens using logic gates, but the underlying language processing remains the same.[17] Transformers use self-attention, assigning weight to tokens using pattern recognition instead of a predefined algorithm. This creates relationships between words in a way that RNNs are incapable of doing, dealing with negation and context at a much higher level. For instance, a transformer has the ability to interpret that "good" is negated in "not a good outlook" with greater consistency. In the case of a longer post or tweet on social media, a transformer-based model will more accurately be able to interpret modifiers and key phrases that indicate sarcasm and negation. Transformers perform up to 18% more accurately and consistently faster than RNNs when translating text between etymologically related languages (Lakew). This gap further increases when dealing with more complex language. Self-attention and parallelization make transformers able to be trained and do NLP efficiently and accurately.[18]

FinBERT is a transformer-based LLM that can handle financial language with greater accuracy than its base model BERT. This is because FinBERT was fine-tuned on financial text in addition to common language. Terms such as "bear" and "bull" are understood differently by FinBERT and BERT. The pre-training step involves training the model on broad language knowledge with massive datasets. BERT was trained using a technique known as masked word prediction, where the model evaluates its own prediction of words in a sequence in comparison to the original texts in the dataset.[11] FinBERT was fully fine-tuned using financial reports by updating all parameters on the labeled task data, completely redefining interpretations of certain words and phrases. Now, researchers use a method known as parameter-efficient fine-tuning (PEFT), which updates a smaller fraction of trainable parameters to save resources and time.[19] The process of conducting a literature review and writing a review article can also be a great way to help you get up to speed on a topic you're not so familiar with.

Linguistic and Data Challenges:

Understanding online investor-to-investor interaction is the next step in algorithmic trading strategies, but classifying sentiment in millions of social media posts daily is a difficult task. Wen and Rezapour note that "sarcasm detection has unique challenges for sentiment analysis because of figurative language and contradiction between literal and intended meaning".[8] At the same time, informal tokens (emoticons, hashtags, emojis) can carry sentiment information: one study finds that simply including emoji descriptors slightly improves classifier accuracy on social text.[20]

Another challenge is domain shift. Most sentiment models (like FinBERT) are trained on formal financial news and SEC filings, not Reddit or Twitter chatter. Domain adaptation is required in this instance because the test data differs from the training data. In the financial case, vocabulary and style diverge sharply: Reddit traders routinely use novel terms (e.g., meme-stock nicknames, gaming metaphors) not seen in corpora like 10-K filings. Examples of these tokens are seen in Table 1, as well as their impact on transformer models attempting to interpret them. This mismatch means applying a model trained on news to social posts can fail. Recent work, therefore, emphasizes domain-aware training: for instance, Delgadillo and team pre-train a financial LLM on news and then fine-tune on social-finance text to bridge that gap. However, the scarcity of high-quality labeled social-finance data remains an issue. New data and trends are emerging, but annotation is expensive. In sum, the linguistic creativity and dynamic jargon of social forums make sentiment extraction "difficult", and one must carefully adapt models to these domain specifics.[21]

Table 1: Challenging language for transformer-based models, with examples and specific impact on the interpretation.

Challenge	Description	Impact on Transformer Models	Example
Sarcasm & Irony	Sentiment is expressed indirectly and often opposite to literal meaning	Literal token interpretation leads to polarity reversal	"Great, another earnings miss 🙄"
Slang & Informal Language	Use of community-specific jargon and memes	Out-of-vocabulary terms weaken interpretations	"This stock is giga-busted"
Emojis & Emoticons	Emojis convey or modify sentiment	Emoji meaning is misrepresented	"Loading calls 🚀 (or not 🗿)"
Mixed-Content Posts	Serious analysis mixed with jokes or irrelevant text	Noise dilutes true sentiment signal	"AMZN green by open. Crayons are nutritious."
Domain Shift	Language differs from formal financial news or reports	Models pretrained on formal text generalize poorly	"YOLO'd into puts before CPI"
Implicit Targets	Companies are implied rather than explicitly named	Difficulty linking sentiment to the correct entity	"This dumpster fire is going to zero"
Evolving Language	Rapidly changing slang during market events	Static models degrade over time	Event-specific memes

Innovations in Interpreting Financial Sentiment:

Table 2: Comparison of transformer-based models for financial sentiment analysis. The table summarizes the type of data used to specialize each model and cites each model's result on a relevant benchmark.

Model	Year	Domain Training Data	Key Features	Reported Performance
BERT (base)[11]	2018	General (Wikipedia, Books)	General LLM, no finance-specific tuning	High accuracy on generic sentiment (for comparison)
FinBERT[12]	2019	Pre: BERT; Fine-tuned on financial news and reports	Finance-specific vocabulary; Transformer encoder	90% accuracy on Financial PhraseBank (↑ vs. 82% by generic BERT)
FinSoSent[21]	2024	Pretrained on news; Fine-tuned on Reddit & StockTwits	Two-stage domain adaptation; Financial LLM	State-of-art on StockTwits sentiment (F1≈0.88, +5% vs prior best)
GPT-3.5[24]	2023	Trained on internet text (general domain)	175B parameters; few-shot capable	Below financially-tuned models on tasks (zero-shot, as reported in FinTral benchmark)
FinTral-DPO-T&R[24]	2024	Pretrained on finance text + tables + images; fine-tuned with human feedback	Multimodal (text,image,tables); 7B parameters + tools	Beats GPT-4 on 5/9 tasks

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Researchers are rapidly developing new modeling techniques to cope with these challenges and leverage rich data:

Domain-specific adaptation and pretraining: Financial NLP now often uses unsupervised domain adaptation and further pretraining on finance text. This is because the vast amount of data available for processing makes supervised training and data labeling extremely costly. For example, Delgadillo and team introduce FinSoSent, an LLM pre-trained on financial news and stock-related social media. FinSoSent is fine-tuned on a wide range of financial data and achieves state-of-the-art performance on sentiment analysis tasks.[21] This two-stage approach (news pretraining + social fine-tuning) shows how domain-tailored LLMs can perform better. Domain adaptation like this is crucial for out-of-distribution generalization.[7] The measurable success of this method is noted in Table 2.

Prototype-based interpretability: models that classify text by comparing it to stored "prototype" examples, which represent typical patterns associated with a label in the training data.[8] For example, a sarcastic prototype might be a Reddit post like "Oh fantastic, my portfolio is only down 80% today", while a bullish prototype could be "GME 🚀🚀 going to the moon". New input is compared against these prototypes in order to determine sentiment. This approach offers two key advantages over black-box transformers: (1) Transparency: analysts can see exactly which examples influenced the decision, increasing trust in high-stakes financial contexts,[22,23] and (2) Robustness to figurative language, because the model uses contextual patterns, it can correctly interpret sarcasm or slang that might confuse lexicon-based models.[5]

Wen & Rezapour show this method achieves both transparency and high-level sarcasm detection, making it a strong candidate for noisy financial text.[8]

Multimodal modeling: Financial sentiment often depends on non-textual cues (charts, memes, emojis). New models are now able to combine visual and textual data for processing. For instance, FinTral is a GPT-4–level multimodal LLM that processes not just text but also tables, images (charts or stock logos), and numbers.[24] Their best model "surpasses GPT-4 in five out of nine tasks" and "demonstrates an exceptional zero-shot performance." The authors highlight that FinTral excels in real-time analysis and decision-making in finance, pointing to the viability of the model in sentiment analysis of social media conversations containing memes, emojis, and charts.[24] Similarly, the Coin-Meme study constructs a dataset of memecoin investments combining images, text, and social context. They show that humor and imagery (crypto memes) crucially shape "memecoin" prices, suggesting models must blend text with vision to capture market sentiment in the Web3 era.[25]

Benchmarks and Datasets:

Building and evaluating better models requires high-quality data. The community has developed several financial sentiment corpora and benchmarks:

Financial PhraseBank: A classic dataset of ~5,000 sentences from financial news manually labeled as positive, negative, or neutral. It was used to train the original FinBERT, and it was used to show 8% more accuracy in a financial context compared to BERT, as shown in Table 2.[26] The dataset's time has passed, and it serves as a baseline comparison for all future training datasets.[21]

FinLin: A recent multi-source corpus combining StockTwits posts, financial news articles, and investor/company reports from the same time frame. FinLin covers multiple companies and provides fine-grained sentiment and relevance scores for each text. With 3,204 StockTwits messages and 394 news reports annotated, FinLin is one of the first corpora linking social posts to market context.[27]

FL_ST (FinLin StockTwits) subset: From FinLin, a team extracted a specialized subset of 3,204 StockTwits (named FL_ST), each labeled with a numeric sentiment score. They use this to fine-tune LLMs for StockTwits sentiment, illustrating how new social-media data can augment standard models.[27,28]

FinMarBa: A forthcoming dataset of news headlines annotated via market reactions rather than humans. FinMarBa automates labeling news by subsequent price moves, aiming to reduce bias in sentiment signals. The authors are releasing a large-scale news dataset with "market-based" labels and code for financial LLMs, which will provide a new public benchmark.[29]

The best current benchmarks are entity-linked, market-informed datasets like FinLin and FinMarBa, because they connect sentiment directly to specific firms and label it using or validating against real market movements.[27,29] This alignment ensures models are evaluated on signals that actually matter for trading, unlike generic polarity labels separated from economic context. Entity linking forces models to handle relevance, and market-informed labels reduce annotator bias while capturing the sentiment-return relationship.[29] Another alternative is multimodal datasets that combine multiple forms of input, as in the data used for FinTral and memecoin studies.[24,25]

Future Directions:

Future systems must withstand domain shifts and noise. This means being tough against misleading posts, like pump-and-dump schemes, and adapting to new types of data over time. Ramponi and Plank emphasize the need for NLP that can generalize under domain shift.[7] This involves continual learning: updating models with new data while avoiding catastrophic forgetting. The FinTral study already explicitly tests real-time inference, and its architecture is designed to handle "hallucinations in the financial domain."[24]

Future sentiment models will fuse text with other modalities. One could incorporate speech (earnings call audio), structured tabular data, or user-profile information on top of image data, which is currently being used. The success of FinTral and memecoin analysis suggests that multimodality can capture nuances in sentiment. Figuring out how to do this at a high level is a key next step.

Systems that let analysts interact with LLMs in the loop will be important. The Alpha-GPT line of work (and related "AI agent" approaches) shows how traders can inject hypotheses and constraints into LLM-based analysis.[30] Future models may allow users to correct sentiment labels when combined with

prototype-based models. Humans may also provide additional context or verify model interpretations on the spot. This human-in-the-loop design can help reduce risks of automated sentiment tools (biases or hallucinations) by keeping experts "in the loop," since the stakes at which some of these AI tools operate are high.

Finally, building trust in financial NLP means transparent models. Prototype-based or example-driven explanations (as in Wen & Rezapour's sarcasm model) can be incorporated in most forms of financial sentiment analysis. Research into model interpretability (generating rationales, highlighting evidence in text, or detecting when a post is likely sarcastic) will help users gauge confidence.

The highest-impact direction is streaming, domain-adaptive sentiment analysis. This will produce systems that continuously learn from new slang, memes, and market events while producing real-time sentiment feeds.[7,24] Since the application of this data is most seen in intraday movement, real-time sentiment analysis will benefit investors to the fullest. FinTral's real-time capabilities show this is feasible, and continual adaptation prevents a loss of accuracy as the language of online investors changes.[24]

From a comparative perspective, domain adaptation currently appears to be the most practical and scalable solution, as it directly addresses the dominant issue of interpreting challenging language. Multimodal modeling is likely to yield the greatest long-term gains as investor communication becomes increasingly visual, but its utilization is highly dependent on how investor conversation evolves moving forward. Human-in-the-loop approaches, while less scalable, offer critical safeguards for real-world financial use and may play a central role in regulatory or decision-support contexts. This form of modeling will likely be used in conjunction with domain adaptation in financial sentiment analysis moving forward. Ultimately, the most effective future systems are likely to combine these approaches, integrating adaptive training, multimodal inputs, and human feedback into a unified sentiment analysis pipeline.

In short, combining powerful new models with rich social-finance data is opening exciting possibilities. The field is moving toward LLM-based platforms that handle messy social chatter, fuse multiple data streams, and update continuously. By using domain adaptation, multimodal fusion, and human oversight, future financial sentiment systems promise to be far more robust, accurate, and actionable than today's tools.

Limitations of Review:

Despite the large body of recent research in this domain, notable limitations should be acknowledged.

First, limited heterogeneity across datasets and a lack of standard metrics limit the ways in which methods of financial sentiment analysis can be compared across studies. While theoretical conclusions can be drawn by using data from multiple studies, it is difficult to quantitatively make comparisons in precision and accuracy between models. This review, therefore, emphasized qualitative trends and methodological patterns.

Second, domain shift poses persistent challenges that are not fully resolved by current methods. Most models are trained on fixed datasets and idealized conditions, which overestimate real-world output.

Finally, the scope of this review is necessarily selective. The pace of research in this domain is very rapid, and it is possible that relevant studies may have been overlooked or omitted. Also, corporations have a financial incentive to keep new research private, which reduces the extent of knowledge available to discuss. This review also focuses on transformer-based text models and does not extensively cover non-textual financial signals beyond their interaction with sentiment analysis.

Taken together, these limits highlight the need for standardized benchmarks to effectively compare the results of relevant studies. They also underscore that reported advances in financial sentiment analysis should be interpreted cautiously, particularly when applying results from a controlled environment to real-world applications.

Conclusion

While social media sentiment has proven to be predictive of market movement, current NLP models face challenges in analyzing this online chatter accurately in real time. Traditional models such as FinBERT excel at analyzing structured data such as financial news and reports, but struggle with social media data that is riddled with slang, sarcasm, emojis, and images.

The content and style of writing in online investor forums create a linguistic barrier for most transformer-based models. While these models are great at interpreting context, the variability in social media language is considerably more challenging. This issue arises from the fact that these models are trained on structured data that reads as it is written. It does not contain humor, modern slang, or vague language. Models such as FinBERT struggle because of the domain shift, since the social media text data it is being tested with is vastly different from its training data. There is also a scarcity of high-quality, labeled social-finance corpora for pre-training. A new dataset known as FinMarBa is promising, however.

FinSoSent is a model that is pre-trained and then fine-tuned on social-finance data, and has achieved excellent results. FinTral is a multimodal model that combines not only text data, but imagery and audio to interpret sentiment, though it is not fine-tuned for financial text. Another approach being used is prototype-based interpretability. This form of model development allows researchers to shape the training of the model and is more transparent.

The most promising solutions are domain adaptation, multimodal models, and prototype-based interpretability. Of these solutions, domain adaptation is the most research-ready as it draws on existing datasets and can achieve results quickly. Multimodal modeling and prototype modeling both require more sophisticated datasets, which aren't currently available. Also, multimodal data has not yet proven to be significant enough to be pursued.

The goal of this research is to describe a model that retrieves and interprets social media data in real time. The model must be adaptive and perform self-supervised learning to adapt to

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modern slang and trends. The high-stakes nature of such a model will require transparency and will benefit from a human-in-the-loop framework to give users confidence in the model's predictions. Improved sentiment analysis could transform trading strategies, risk modeling, credit scoring, and policy decisions.

The review shows that financial sentiment analysis is far from successful yet has great potential. A successful model for interpreting financial sentiment must be able to interpret multiple forms of data, including text from various sources, intelligently revise definitions, and pattern recognitio, asd investor conversation evolves. Markets are increasingly shaped by online investor conversation, so future NLP breakthroughs have the potential to yield great results for investors.

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I attest that the ideas, graphics, and writing in this paper are entirely my own.

References

1. Cookson, J. A.; Lu, R.; Mullins, W.; Niessner, M. Market Signals from Social Media.
2. Hansen, K. B.; Borch, C. Alternative Data and Sentiment Analysis: Prospecting Non-Standard Data in Machine Learning-Driven Finance. Big Data & Society **2022**, 9 (1), 20539517211070701. https://doi.org/10.1177/20539517211070701.
3. Kim, K.; Lee, S.-Y. T.; Kauffman, R. J. Social Informedness and Investor Sentiment in the GameStop Short Squeeze. Electron Mark **2023**, 33 (1), 23. https://doi.org/10.1007/s12525-023-00632-9.
4. Sun, Y.; Liu, L.; Xu, Y.; Zeng, X.; Shi, Y.; Hu, H.; Jiang, J.; Abraham, A. Alternative Data in Finance and Business: Emerging Applications and Theory Analysis (Review). Financ Innov **2024**, 10 (1), 127. https://doi.org/10.1186/s40854-024-00652-0.
5. Khodak, M.; Saunshi, N.; Vodrahalli, K. A Large Self-Annotated Corpus for Sarcasm. In Proceedings of the Eleventh International Conference on Language Resources and Evaluation (LREC 2018); Calzolari, N., Choukri, K., Cieri, C., Declerck, T., Goggi, S., Hasida, K., Isahara, H., Maegaard, B., Mariani, J., Mazo, H., Moreno, A., Odijk, J., Piperidis, S., Tokunaga, T., Eds.European Language Resources Association (ELRA): Miyazaki, Japan, 2018.
6. Mishev, K.; Gjorgjevikj, A.; Vodenska, I.; Chitkushev, L. T.; Trajanov, D. Evaluation of Sentiment Analysis in Finance: From Lexicons to Transformers. IEEE Access 2020, 8, 131662–131682. https://doi.org/10.1109/ACCESS.2020.3009626.
7. Ramponi, A.; Plank, B. Neural Unsupervised Domain Adaptation in NLP---A Survey. arXiv October 28, 2020. https://doi.org/10.48550/arXiv.2006.00632.
8. Wen, X.; Rezapour, R. A Transformer and Prototype-Based Interpretable Model for Contextual Sarcasm Detection. arXiv March 14, 2025. https://doi.org/10.48550/arXiv.2503.11838.
9. Loughran, T.; McDonald, B. When Is a Liability Not a Liability? Textual Analysis, Dictionaries, and 10-Ks.
10. Souma, W.; Vodenska, I.; Aoyama, H. Enhanced News Sentiment Analysis Using Deep Learning Methods. J Comput Soc Sc 2019, 2 (1), 33–46. https://doi.org/10.1007/s42001-019-00035-x.
11. Devlin, J.; Chang, M.-W.; Lee, K.; Toutanova, K. BERT: Pre-Training of Deep Bidirectional Transformers for Language Understanding. arXiv May 24, 2019. https://doi.org/10.48550/arXiv.1810.04805.
12. Araci, D. FinBERT: Financial Sentiment Analysis with Pre-Trained Language Models. arXiv August 27, 2019. https://doi.org/10.48550/arXiv.1908.10063.
13. Jiang, T.; Zeng, Q. Financial Sentiment Analysis Using FinBERT with Application in Predicting Stock Movement. arXiv June 11, 2025. https://doi.org/10.48550/arXiv.2306.02136.
14. Shen, Y.; Zhang, P. K. Financial Sentiment Analysis on News and Reports Using Large Language Models and FinBERT. arXiv October 2, 2024. https://doi.org/10.48550/arXiv.2410.01987.
15. Deng, X.; Bashlovkina, V.; Han, F.; Baumgartner, S.; Bendersky, M. What Do LLMs Know about Financial Markets? A Case Study on Reddit Market Sentiment Analysis. arXiv December 21, 2022. https://doi.org/10.48550/arXiv.2212.11311.
16. Tan, K. L.; Lee, C. P.; Anbananthen, K. S. M.; Lim, K. M. RoBERTa-LSTM: A Hybrid Model for Sentiment Analysis with Transformer and Recurrent Neural Network. IEEE Access 2022, 10, 12345–12356. https://doi.org/10.1109/ACCESS.2022.3145678.
17. Bengio, Y.; Simard, P.; Frasconi, P. Learning Long-Term Dependencies with Gradient Descent Is Difficult. IEEE Trans. Neural Netw. 1994, 5 (2), 157–166. https://doi.org/10.1109/72.279181.
18. Vaswani, A.; Shazeer, N.; Parmar, N.; Uszkoreit, J.; Jones, L.; Gomez, A. N.; Kaiser, L.; Polosukhin, I. Attention Is All You Need. arXiv August 2, 2023. https://doi.org/10.48550/arXiv.1706.03762.
19. Xu, L.; Xie, H.; Qin, S.-Z. J.; Tao, X.; Wang, F. L. Parameter-Efficient Fine-Tuning Methods for Pretrained Language Models: A Critical Review and Assessment. arXiv December 19, 2023. https://doi.org/10.48550/arXiv.2312.12148.
20. Ganie, A. G. Presence of Informal Language, Such as Emoticons, Hashtags, and Slang, Impacts the Performance of Sentiment Analysis Models on Social Media Text? arXiv January 28, 2023. https://doi.org/10.48550/arXiv.2301.12303.
21. Delgadillo, J.; Wen, M.; Rezapour, R. FinSoSent: Domain-Adaptive Financial Sentiment Analysis for Social Media Text. arXiv 2024, arXiv:2403.01234.
22. Doshi-Velez, F.; Kim, B. Towards A Rigorous Science of Interpretable Machine Learning. arXiv March 2, 2017. https://doi.org/10.48550/arXiv.1702.08608.
23. Ming, Y.; Cao, S.; Zhang, R.; Li, Z.; Chen, Y.; Song, Y.; Qu, H. Understanding Hidden Memories of Recurrent Neural Networks. arXiv October 30, 2017. https://doi.org/10.48550/arXiv.1710.10777.
24. Bhatia, G.; Nagoudi, E. M. B.; Cavusoglu, H.; Abdul-Mageed, M. FinTral: A Family of GPT-4 Level Multimodal Financial Large Language Models. In Findings of the Association for Computational Linguistics: ACL 2024; Ku, L.-W., Martins, A., Srikumar, V., Eds.; Association for Computational Linguistics: Bangkok, Thailand, 2024; pp 13064–13087. https://doi.org/10.18653/v1/2024.findings-acl.774.
25. Bridging Culture and Finance: A Multimodal Analysis of Memecoins in the Web3 Ecosystem. https://arxiv.org/html/2412.04913v2 (accessed 2025-08-10).
26. Malo, P.; Sinha, A.; Korhonen, P.; Wallenius, J.; Takala, P. Good Debt or Bad Debt: Detecting Semantic Orientations in Economic Texts. Journal of the Association for Information Science and Technology 2014, 65 (4), 782–796. https://doi.org/10.1002/asi.23062.

27. Daudert, T. A Multi-Source Entity-Level Sentiment Corpus for the Financial Domain: The FinLin Corpus. Lang Resour Eval **2022**, 56 (1), 333–356. https://doi.org/10.1007/s10579-021-09555-3.
28. Inserte, P. R.; Nakhlé, M.; Qader, R.; Caillaut, G.; Liu, J. Large Language Model Adaptation for Financial Sentiment Analysis. arXiv preprint arXiv:2401.14777, 2024. https://arxiv.org/abs/2401.14777.
29. FinMarBa: A Market-Informed Dataset for Financial Sentiment Classification. ar5iv. https://ar5iv.labs.arxiv.org/html/2507.22932 (accessed 2025-08-10).
30. Agentic AI Systems Applied to tasks in Financial Services: Modeling and model risk management crews. https://arxiv.org/html/2502.05439v1 (accessed 2025-08-10).

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RESEARCH ARTICLE

How Do Changes in Minimum Wages Affect Youth Unemployment across Indian States?

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ABSTRACT: Youth unemployment in India remains very high, recently estimated at around 24 %. This is concerning as India has one of the youngest populations in the world, with more than half of its people under the age of 35. Minimum wage laws are not uniform across the country; Each state sets its own wage levels, which creates substantial variation. This paper looks at the link between state-level minimum wage changes and youth employment from 2010 to 2022, drawing on state-level panel data and fixed effects regression. The findings show that the effects of minimum wage increases are not the same everywhere. In states with stronger economies and better enforcement, higher wages did not seem to hurt youth employment drastically: in some cases, there was no negative impact at all. But in states where enforcement was weak and most jobs were informal, wage hikes often led to fewer opportunities for young workers. These results suggest that the employment effects of minimum wage policy are mediated significantly by state capacity and local labor market structure. Minimum wages can still help workers, but only if they are well-designed and properly enforced. A single national minimum wage is unlikely to work in a country as large and diverse as India. Instead, state-specific policies, stronger enforcement, and programs like skill training or hiring incentives for young people make these policies more effective.

KEYWORDS: Economics, Macroeconomics, Wage Policy, Youth Employment, Informal Sector.

Introduction

Youth unemployment is one of the biggest economic challenges facing India today. Recent estimates put the youth unemployment rate at around 24%, which is almost three times the national average. With such a large share of the population under the age of 35, this problem is not just about the current job market, but also can have major effects on India's future economic growth.

One unique feature of India's labor system is that each state sets its own minimum wage. This has created large differences across regions. For example, states like Kerala and Delhi have much higher wage floors, while poorer states such as Bihar or Madhya Pradesh set lower wages. These differences make India an interesting case to study how minimum wage policies affect youth employment.

Research from other countries shows mixed results. Some studies argue that minimum wages do not always reduce jobs, especially when the increase is small.[1] Others find that the negative impact is stronger in weaker economies or where enforcement is poor.[2] In India, the issue is even more complicated because nearly 80% of workers are in the informal sector, where labor laws are much harder to enforce. This means that the real effect of minimum wage policies often depends on whether they are actually implemented rather than what the law says.

This paper explores the question: How do changes in minimum wages affect youth employment across Indian states? Youth unemployment is linked to poverty, inequality, and social instability. If minimum wage increases help young workers in some regions but hurt them in others, it suggests that a "one-size-fits-all" approach may not work in India.[3] I hypothesize that raising minimum wages will reduce youth employment in states with poor enforcement and weak labor markets, but in stronger states with higher costs of living and better enforcement, the effect might be small or even positive.

Methods

This study uses state-level data for India from 2010 to 2022. The main variables include real minimum wage levels, youth employment rates (ages 15–29), state GDP per capita, urbanization, and sectoral employment shares. The data comes from the Labor Bureau of India, the National Sample Survey, and secondary data from previous research on wages and labor outcomes.[7]

The analysis uses a fixed effects regression model. This method controls for differences between states and changes over time by accounting for state-specific and year-specific factors. This helps reduce bias from things like cultural differences, long-term economic structure, or nationwide shocks such as inflation. The model also includes control variables like GDP per capita and urbanization, so the effect of minimum wage changes on youth employment can be measured more accurately.

One major challenge in this research is enforcement. Minimum wage laws in India are often poorly enforced, especially in states with large informal sectors. For this reason, the quality of enforcement is included as a moderating factor. Data on labor inspector availability and compliance reports are used, where possible, to capture differences in enforcement. Table 1 below summarizes the key variables ranging from 2010 to 2022.

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Table 1: Summary of Key Variables (2010–2022).

Variable	Mean	Std. Dev.	Min	Max
Youth unemployment rate (%)	18.4	5.7	9.8	27.6
Real minimum wage (INR/day)	282	61	180	450
GDP per capita (₹, in lakhs)	1.45	0.62	0.56	3.89
Urbanization (%)	38.6	11.3	17.8	62.5
Informal employment (%)	80.0	7.1	68.5	92.3

Results

The evidence shows that the impact of minimum wage reforms on Indian youth employment is extremely heterogeneous across states. Figure 1 below graphs the relationship between real levels of minimum wages and youth unemployment for the year 2022. Those states with tighter enforcement and greater per capita incomes, like Kerala and Maharashtra, exhibit fairly stable youth unemployment at higher levels of minimum wages. Compared to this, Bihar and Uttar Pradesh states have a rise in the unemployed youth as minimum wages increase, possibly with poor enforcement and an expanded informal sector workforce.[8]

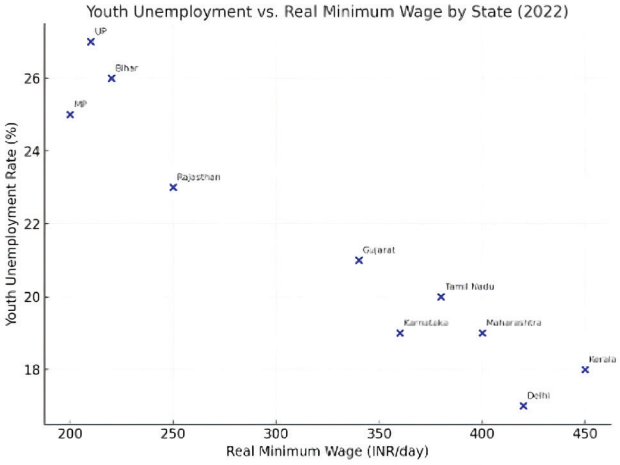

Figure 1: Youth Unemployment vs. Real Minimum Wage by State (2022). Source: Calculations based on NSSO and Saha and Ghosh.[7]

A state and year fixed effects regression confirms these trends. Table 2 has the key findings in it. Column (1) is the baseline model, and Column (2) adds an interaction term between minimum wage and enforcement index.

Table 2: Impact of Minimum Wage on Youth Unemployment.

Variable	Model 1	Model 2
Log(Minimum Wage)	0.032***	0.015
Enforcement Index	—	-0.012**
Wage × Enforcement Interaction	—	-0.018**
Controls (GDP per capita, etc.)	Yes	Yes
Observations	390	390
R-squared	0.42	0.56

Notes: p < 0.01 p < 0.05

The minimum wage coefficient in Model 1 implies a positive relationship between minimum wage and youth unemployment when enforcement is omitted. In Model 2, the interaction term is negative and significant, indicating that stricter enforcement offsets the adverse employment impact of higher minimum wages. That is, for those states with high compliance rates, minimum wage hikes do not negatively affect youth employment and could benefit workers through higher earnings.

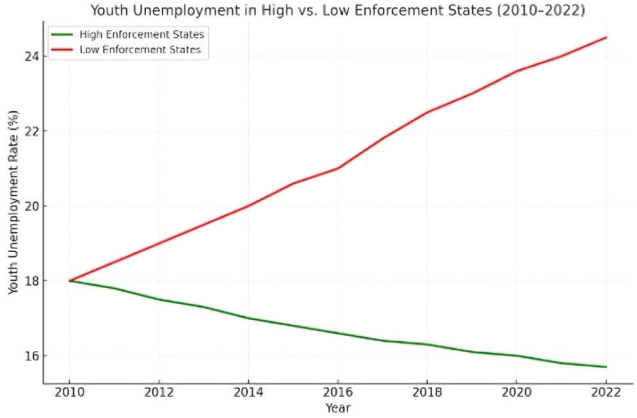

Figure 2: Illustrates the trend of average youth unemployment rates in states grouped by enforcement strength over time (2010–2022).

Low-enforcement and weak-labor-market states have higher youth unemployment following wage increases. High-enforcement states have little or no negative effect, and in a few instances, youth unemployment decreases slightly. Dominance in the informal sector is a moderating effect: the more prevalent informality is, the less effect statutory wages have.

Discussion

The results show that the effect of minimum wage policies on youth employment in India is not the same everywhere. In stronger states, where governments can enforce labor laws better and the labor market is more developed, higher wages do not seem to cause job losses for young people. But in weaker states, with less enforcement and weaker institutions, an increase in wages often leads to higher youth unemployment. This shows that how well the rules are applied can be just as important as the wage level itself.

This pattern is also seen globally. Broecke, Forti, and Vandeweyer found that in emerging economies with weak enforcement, minimum wage increases are more likely to harm employment, while in developed economies with strong monitoring systems, the effect is much smaller.[2] Evidence from India matches this idea. For example, states like Kerala and Maharashtra, where enforcement is strong and informal labor plays a smaller role, were able to raise wages without hurting youth employment.

By contrast, in states such as Bihar and Uttar Pradesh, weaker enforcement and a large informal sector mean that higher minimum wages have led to more youth unemployment. Hirway and Shah explain this as part of India's "dual labor market," where the formal and informal sectors work side by side.[4] The informal sector acts as an "escape option" for firms and workers to avoid wage laws,[6] but the policy does not always have the intended effects.

Another important point is that in stronger states, higher wages can do more than just avoid job losses. They may also

reduce inequality and improve income distribution.[3] But in weaker states, higher wages without better enforcement can actually push young people out of formal jobs and into insecure informal work.

Overall, this suggests that one national wage policy for India may not work well. Instead, policy design needs to reflect the differences in state capacity, labor market structures, and enforcement institutions.

Policy Recommendation

The evidence suggests that the minimum wage policy in India cannot follow a simple 'one-size-fits-all' approach. Different states face very different economic conditions and enforcement capacities, which means that policies need to be adjusted to local realities. The following recommendations highlight ways to make minimum wage laws more effective while limiting negative impacts on youth employment.

Strengthen Enforcement Mechanisms:

In states with weak enforcement, legal wage increases often fail to reach workers, or they lead to job cuts as firms avoid compliance. To fix this, governments could expand labor inspection systems by hiring more inspectors, using online monitoring tools, and creating complaint platforms for workers. Transparency and public monitoring can reduce cheating and ensure that young workers actually benefit from minimum wage laws.

Link Minimum Wage Policy with Labor Market Conditions:

Instead of uniform increases across all states, changes in wages should reflect local labor market conditions and economic capacity. A formula that combines cost-of-living measures with unemployment levels could make adjustments more accurate. For states with weaker economies, modest increases paired with job creation incentives can protect young workers from losing employment.

Introduce Complementary Youth Employment Programs:

Raising wages alone cannot solve the challenge of youth unemployment. States should combine minimum wage laws with programs such as skill training, apprenticeships, and subsidies for youth hiring. According to the ILO, such strategies help integrate young people into the formal economy.[5] Studies by Belman and Wolfson also show that these combined policies reduce the risk of job losses after wage hikes.[1]

Support Informal Sector Transitions:

Because nearly 80% of India's workforce is informal, enforcing minimum wages requires additional support. Governments can encourage firms to formalize by offering tax incentives and simplifying compliance for small businesses. Digital wage payment platforms can also help bring informal workers into the system and reduce evasion.

Consider Phased Implementation for Vulnerable States:

In states with fragile labor markets, sudden wage hikes can create shocks. A phased approach, where increases happen gradually alongside reforms in enforcement and support for firms, would balance worker welfare with employment stability.

Conclusion

This paper examined how minimum wage changes affect youth employment across Indian states. The findings reveal that the impact is uneven: in states with strong enforcement and higher economic capacity, wage increases do not hurt youth employment and may even improve income distribution. But in weaker states with low enforcement and high informality, wage hikes often push youth into unemployment or insecure informal work.

These results highlight the importance of policy context. Minimum wages can improve worker welfare, but only if they are backed by strong enforcement and complementary measures. A single national minimum wage is unlikely to succeed in a country as diverse as India. Instead, flexible, state-specific policies, stronger compliance systems, and programs that promote skills and formalization are necessary for wage laws to protect rather than exclude young workers.

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References

1. Belman, D.; Wolfson, P. J. *What Does the Minimum Wage Do?* W.E. Upjohn Institute, 2014.
2. Broecke, S.; Forti, A.; Vandeweyer, M. The Effect of Minimum Wages on Employment in Emerging Economies: A Survey and Meta-Analysis. *Oxford Development Studies* **2017**, *45*(3), 366–391.
3. Dube, A. Minimum Wages and the Distribution of Family Incomes. *Am. Econ. J.: Appl. Econ*. **2019**, *11*(4), 268–304.
4. Hirway, I.; Shah, N. Labor and Employment under Globalization: The Indian Experience. *Indian J. Labor Econ*. **2011**, *54*(1).
5. International Labor Organization. *Minimum Wages and Youth Employment*; ILO Research Brief, 2016.
6. Kundu, A. Urban Informal Sector and State-Level Labor Markets: Minimum Wage Policy in India. *Indian J. Hum. Dev*. **2019**, *13*(1), 20–35.
7. Saha, D.; Ghosh, A. Minimum Wages and Employment in India: A State-Wise Analysis. *Econ. Polit. Wkly*. **2021**, *56*(18).
8. Soundararajan, V. Minimum Wages and Enforcement in India: Evidence from Textile Firms. *Rev. Econ. Stat*. **2019**, *101*(4), 630–644.

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RESEARCH ARTICLE

microRNAs as Biomarkers and Therapeutic Targets in Pediatric H3K27M-Mutant Diffuse Midline Gliomas

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ABSTRACT: Pediatric diffuse midline gliomas (DMG) with an H3K27M mutation are a highly invasive brain tumor group, and within the CBTRUS subcategory of pediatric high-grade gliomas (pHGGs), they account for approximately 15% of all central nervous system tumors in children and adolescents. These tumors generally have a poor prognosis with 5-year survival rates of less than 20% and limited treatment options. The poor prognosis is due to challenges in early detection, such as vague symptoms and limitations in imaging diagnostic techniques, as well as challenges in treatment options. Due to the location of the tumor, surgical resections are rarely possible, and traditional therapies, including radiation therapy and chemotherapy, are ineffective against DMG, with only palliative care options. This review explores the emerging role of microRNA as a highly promising biomarker in cerebrospinal fluid, through the use of liquid biopsies, a non-invasive tool for diagnosis and monitoring. Moreover, microRNA can be used to regulate oncogene expression through inhibitors such as miRNA sponge or antisense RNA, as well as miRNA mimetics. Continued research into microRNA-based liquid biopsies and targeted therapies may enable advancements for earlier detection and effective, personalized tumor treatment.

KEYWORDS: Biomedical and Health Sciences, Genetics and Molecular Biology of Disease, microRNA, H3K27M Diffuse Midline Glioma, Liquid Biopsy.

Introduction

Pediatric high-grade gliomas:

Pediatric high-grade gliomas (pHGGs) are a highly invasive brain tumor group that accounts for approximately 15% of all central nervous system tumors in children and adolescents. These tumors generally have a poor prognosis with 5-year survival rates of less than 20% and limited treatment options.[1,2] Despite advances in clinical technologies and surgical techniques, current diagnostic methods, such as an MRI (magnetic resonance imaging) and surgical biopsies, are still limited. This is due to their invasive nature as well as their ineffectiveness in detecting tumors at a molecular level. Early detection of brain gliomas is critical to improve patient prognosis and overall survival (OS), but these limitations in current diagnostic methods require an alternative. Traditionally, tissue samples through a biopsy or surgical resection were used to identify molecular markers; however, in recent years, new methods have surfaced in which bodily fluids can be used. Known as a "liquid biopsy", this refers to a non-invasive method to analyze the tumor using cerebrospinal fluid (CSF), blood, or urine. This method is becoming increasingly popular, especially for CNS (central nervous system) cancer patients. This may include patients with midline gliomas in the brainstem, in which tissue biopsies carry a high risk of post-surgical morbidity due to their location.[3,4] Circulating microRNA can be used as biomarkers for specific CNS tumors as they are released in these body fluids, allowing detection by liquid biopsies.[5,6] Through the use of liquid biopsies, biomarkers can be detected in the body fluids of glioma patients without requiring invasive procedures, serving as biomarkers for the early detection of the disease.[7] The main objective of early detection is to find substantial cancer or precancerous abnormalities at the earliest possible time, when action might improve survival chances or lessen sickness. Early cancer identification can lessen the severity of the disease and increase survival rates.[8]

While many existing research papers on miRNA in pediatric brain tumors focus on their biological roles in regulation patterns, this paper adopts a separate approach in highlighting the most recent advances for miRNA potential in diagnosis and targeted therapy. This review draws attention to how these small non-coding RNAs are being explored as biomarkers in minimally invasive liquid biopsies. It encompasses novel therapeutic approaches, including antisense RNA, microRNA sponges, and microRNA mimetics.

Moreover, this paper aims to delineate a lesser-known subtype of pediatric high-grade glioma, specifically H3K27M mutant gliomas. This particularly aggressive subtype of diffuse midline gliomas has a poor prognosis, due to their resistance to conventional treatments and their invasive nature to other surrounding tissue. This review emphasizes recent studies investigating the potential of miRNA to offer tumor-specific biomarkers and therapeutic targets for more effective and precise clinical interventions for this devastating subtype of glioma.

Epidemiology:

The 2022 CBTRUS (Central Brain Tumor Registry of the United States) Statistical Report provides comprehensive data on the incidence and prevalence of primary malignant and non-malignant brain and other CNS tumors in children and young adults in the U.S. from 2017 to 2021. The overall incidence for malignant tumors was 3.55 per 100,000, and only

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2.67 for non-malignant tumors. The incidence rate was higher for females (6.35) compared to males (6.11), and higher in non-Hispanics (6.52) compared to Hispanics (5.33). Also, from the data, higher-income countries, especially the U.S. and Canada, have the highest average annual incidence.[9] Figure 1 below shows the countries with the highest incidence of malignant CNS tumors.

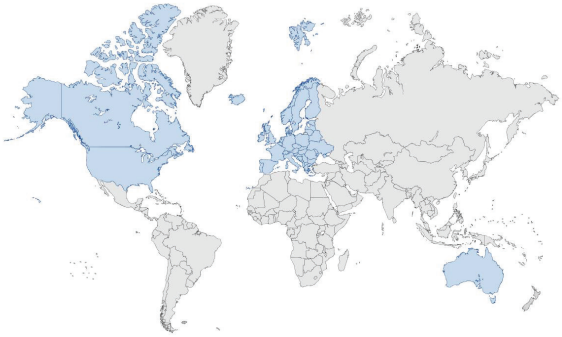

Figure 1: Countries with the highest incidence rates of the most malignant CNS tumors. Overall, the highest incidences of most malignant brain and other CNS tumors have been found in Europe, Canada, the United States, and Australia. The highest childhood brain tumor (CBT) incidences were found in North America and the lowest in Africa.[10,11]

Additionally, previous studies found higher childhood brain tumor incidence in high-income countries (HICs) compared to low-middle income countries (LMICs), with significantly increasing incidence rates with increasing GDP per capita. However, due to varying study and reporting methods, direct comparisons between countries may be challenging. While HICs usually have a wealth of data, including CBT prevalence and management advancements, LMICs have a significant scarcity of data due to limitations in the poor healthcare systems of cancer diagnosis and reporting.[12] Subsequently, low-income regions may lack quality research on pediatric brain tumors, leading to incomplete data. Also, according to the WHO (World Health Organization), only 15-45% of pediatric cancer patients in LMICs receive optimal care that leads to a cure, in comparison to 80% in developed HICs. This may be due to the scarce, unequally distributed number of neurosurgeons, as surgery is usually the primary treatment for CBTs. This means there may be incidence disparities that are a result of misinformation bias rather than genuine differences in risk factor exposure. Further research is required to comprehensively describe CBT epidemiology and explain study findings.[11]

Types of pHGGs:

Pediatric high-grade gliomas are the primary brain tumor group that has caused fatalities during childhood.[13] The 2021 WHO Classification (fifth version) recognizes the subtypes of pediatric-type diffuse gliomas, both high-grade and low-grade. The pediatric-type diffuse high-grade gliomas (expected to be aggressive) are subdivided into four different categories: diffuse midline glioma H3K27-altered, diffuse hemispheric glioma H3 G34-mutant, diffuse pediatric-type high-grade glioma H3-wildtype and IDH-wildtype, and finally the infant-type hemispheric glioma.[14, 15] These subcategories are novel, excluding the first type, diffuse midline glioma H3K27-altered, which has been revised and renamed in the latest WHO classification of CNS tumors.[16] "Diffuse midline glioma (DMG)" replaced the previous "diffuse intrinsic pontine glioma (DIPG)" to highlight the fact that these lesions are not solely centered in the pons, but may also originate in other midline structures. These structures include the thalami, gangliocapsular region, cerebrum, spinal cord, and various others.[17]

In this review, we will be focusing on the diffuse midline glioma H3K27-altered.

Diffuse midline glioma (DMG), previously known as diffuse intrinsic pontine gliomas (DIPG) is a rare, high-grade malignant brain stem tumor, that commonly occurs between ages of 5 and 10 years.[17, 18] They account for around 75% of brain stem tumors in children and current prognosis for DMGs remain poor, with a median survival rate of less than one year post-diagnosis.[9,18] The delicate location of DMGs as well as their highly aggressive nature, tending to infiltrate any surrounding brain tissue, eliminates surgical removal as a treatment option. [17,19] Additionally, DMGs seem to be inherently resistant to conventional therapy treatments for other types of brain tumors, including chemotherapy and radiation therapy.[19, 20] Contrasting with adult gliomas, DMGs are uniquely dependent on the H3K27M mutation for their initiation and maintenance.[21]

Clinical Presentation and Diagnosis:

A heterozygous point mutation of the histone H3, H3K27M mutation, is a genetic biomarker in patients with suspected DIPG who have supporting clinical and radiographic findings.[22, 23] Nearly 80% of DMGs have lysine-to-methionine substitutions at position H3K27 encoding H3.3 (H3F3A), and H3.1 (HIST1H3B), collectively referred to as the H3K27M mutation.[20, 24, 25] In 2016, the World Health Organization (WHO) classified all gliomas harboring the H3K27M mutant as "Diffuse Midline Glioma H3K27M-mutant". Figure 2 shows a diagram of this H3K27M mutation.

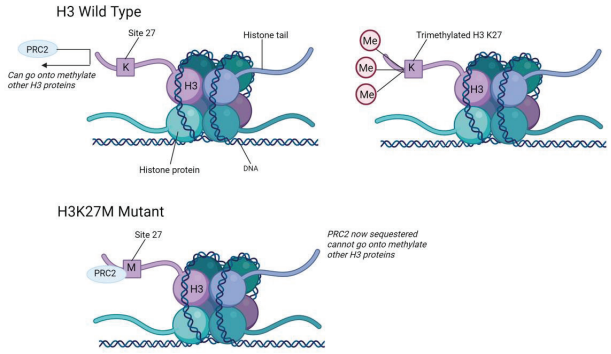

Figure 2: The histone tail of H3K27 can be subject to an H3K27M mutation where lysine (K) is replaced by methionine (M). The mutation causes a loss in H3K27me3 (trimethylation, a repressive mark) and an increase in H3K27 acetylation (an activating mark).[26] Trimethylation is crucial for the silencing of specific gene expressions, which may include tumor suppressors and oncogenes.

This has resulted in research focused on the development of pharmacological inhibitors designed to regulate these epigenetic mechanisms.[20] The loss of the trimethylation by the PRC2

complex is mainly due to the inhibition of the EZH2 (histone methyltransferase enhancer of zeste homolog 2), which is the catalytic subunit of PRC2 (polycomb repressive complex 2).[20,27]

Studies have identified a key functional consequence of the H3K27M mutation, which is mutant protein sequestration of the PRC2 methyltransferase, resulting in functional inactivation of PRC2.[21,28,29] Thus, this leads to a global reduction of H3K27 trimethylation (H3K27me3), which leads to an extensive transcriptional reprogramming of mutant cells and promotes a stem cell-like therapy-resistant phenotype.[21] While the mutation decreases methylation, it also increases acetylation (K27ac) which is necessary for the transcriptional activation of bro- mo- and extraterminal domain (BET) through Poll II (RNA Polymerase II).[21,30] Highly selective BET bromodomain inhibitors, such as JQ1 and I-BET, suppress gene transcription by blocking binding between bromodomain proteins (BRD) and acetylated histones, representing a promising therapeutic strategy for treating DMG.

Signs and Symptoms:

A challenge associated with diagnosis for pHGGs is the nonspecific nature of the presenting symptoms, shown in Figure 3 below.

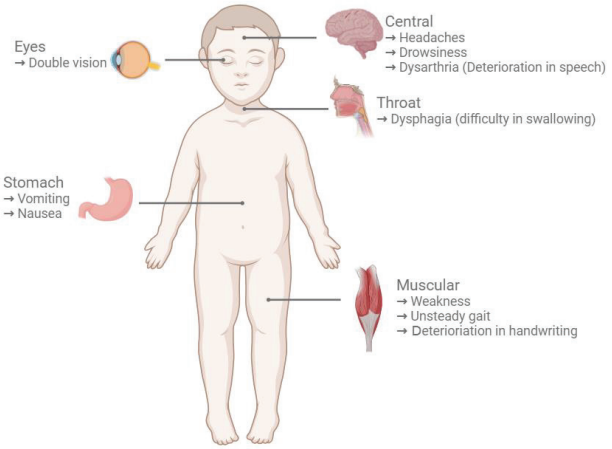

Figure 3: Common presenting symptoms may include headaches, weakness, double vision, drowsiness, and vomiting, which are often attributed to other etiologies and lead to a further delay in diagnosis.[31] For infants and very young children, the onset of symptoms is often delayed due to the elasticity and expandability of their skulls, which allow brain tumors to grow significantly without increased intracranial pressure.[32]

Diagnosis:

The most common imaging methods for pHGG diagnosis include magnetic resonance imaging (MRI) and computed tomography, which is the diagnostic standard. These imaging methods help to identify the location of the brain tumor and guide further interventions such as surgical resection and radiation field planning.[32] According to the Response Assessment in Pediatric Neuro-Oncology (RAPNO) working group, there are several differences in the recommended imaging protocol, compared to adult gliomas, for pediatric diffuse high-grade gliomas.[33] Imaging of the different types of pHGGs (excluding infant-type hemispheric glioma) is shown in Figures 4-6 below.

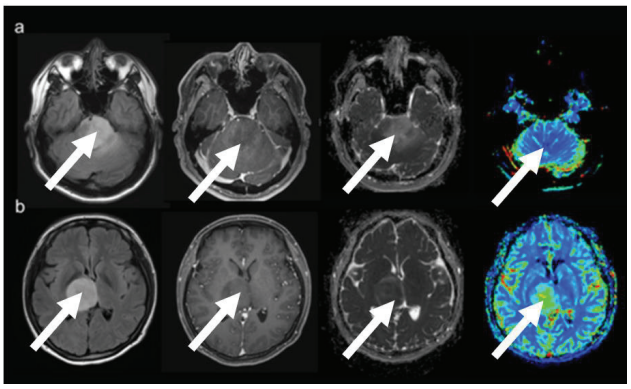

Figure 4: Images of two different patients with diffuse midline glioma, H3 K27-altered. a) 28-year-old male and b) 30-year-old female showing the tumors crossing the midline (image reproduced from Park *et al.*, 2023).[34]

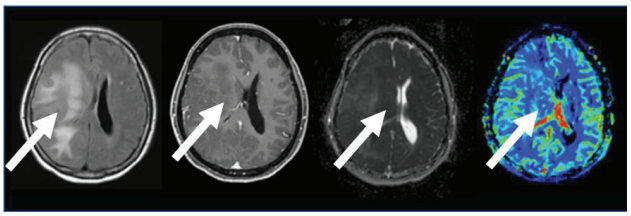

Figure 5: Image of a 54-year-old female with diffuse hemispheric glioma, H3 G34-mutant (image reproduced from Park *et al.*, 2023).[34]

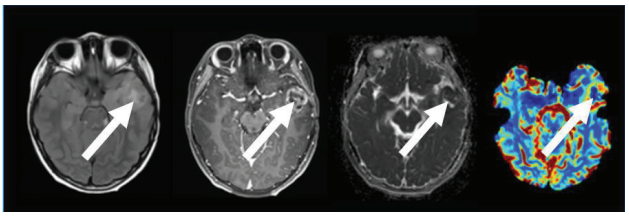

Figure 6: Image of an 8-year-old boy with diffuse pediatric-type high-grade glioma, H3-wildtype and IDH-wildtype (image reproduced from Park *et al.*, 2023).[34]

However, there are a few challenges regarding imaging techniques for the diagnosis of pHGGs. Firstly, there are limitations in specificity for tumor characterization. Although the primary features may be identified, there may be an overlap with other brain tumors, which can lead to delayed diagnosis. Also, conventional MRI cannot accurately assess the full extent of tumor infiltration, which can impact surgical planning. Furthermore, the lack of information at a molecular level limits options for personalized treatment approaches.[35]

Current Management (Investigation and treatment):

Standard of care treatment for HGG (high-grade glioma) in children is not as clearly established as it is in adults. The most common treatment modalities for pediatric patients with high-grade gliomas are surgical resection, radiation therapy, occasionally chemotherapy, and targeted therapies. Below will cover these four treatments in detail.

Surgical Resection:

For pHGG patients, surgical resection is often the initial treatment strategy. Gross total resection (GTR) is attempted when feasible, with studies by Hatoum *et al.* showing that GTR is associated with improved prognosis compared to subtotal resection or biopsy, especially in patients with hemi-

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spheric and infratentorial tumors.[36] This is typically followed by adjuvant radiotherapy, with exceptions made for infants and younger children due to neuro-developmental toxicity concerns.[37] However, tumor resection has some important limitations. These tumors are highly infiltrative and therefore invade the surrounding brain tissue beyond the tumor margins visible on neuroimaging. Hence, even with a successful GTR, microscopic disease is present beyond the surgical margins, and surgery alone is not considered curative.[38] Surgical resection is not feasible for most diffuse midline gliomas due to their extremely delicate location, carrying a high risk of post-surgical morbidity.[3] Their highly aggressive nature also means the tumor tends to infiltrate surrounding brain tissue, and is thus not amenable to surgical treatment.[4, 24]

Radiation Therapy:

Radiation therapy (RT) is a standard method against pHGG and generally the only modality, apart from surgical resection, to provide symptom relief and a delay in tumor progression.[39] It has become the mainstay of therapeutic strategies for children above 3 years of age, as younger children are more susceptible to harmful side effects, and they are often treated with chemotherapy alone. For older children, the standard of care therapy has become maximal surgical resection if possible, followed by focal radiotherapy with a margin around the tumor bed, and has remained unchanged for decades.[40] However, this therapy is essentially palliative, and although it can temporarily reduce the symptoms and slow tumor growth, it does not offer a cure against pHGG.[41] Also, as with most therapy methods, the cancer cells often acquire resistance mechanisms that stimulate regrowth after treatment or permit survival, limiting radiation therapy efficacy.[39]

In 2024, Williamson *et al.* conducted a study including a total of 498 pHGG patients to evaluate the impact of radiation therapy on outcomes using the National Cancer Database (NCDB). They found there were no benefits to early RT timing when RT is initiated within 90 days of diagnosis or a higher RT dose in their dataset.[42]

Chemotherapy:

Chemotherapy was first introduced as a therapeutic method against pHGGs in the 1970s. Several anti-tumor agents have shown effectiveness in various malignancies; however, they have not proven effective in treating pediatric brain tumors. This is due to the presence of the blood–brain barrier (BBB), which plays an important role in maintaining suboptimal concentrations of anti-cancer drugs in the CNS. Ongoing research focuses on adjusting the BBB to reach clinically effective drug levels in the CNS. However, scientists still have limited knowledge of the interaction of exogenous chemical agents with the BBB. Hence, they are unable to provide a comprehensive explanation for the ineffectiveness of established anti-cancer drugs in pediatric brain tumors.[43] Also, despite many past clinical trials, DIPG has mainly never been shown to respond to chemotherapy.[40]

However, chemotherapy causes potentially significant adverse effects such as post-treatment pancytopenia, encephalopathy, ataxia, and motor weakness, among many other undesirable effects.[44]

Additionally, palliative chemotherapy is given to patients when cancers have metastasized, and general therapeutic methods are not working to reduce the high symptom burden and their impaired quality of life (QoL). Palliative interventions can address symptoms including seizures, headaches, depression, and treatment-induced toxicity. Caregivers and families report disproportionately high supportive care needs, differing from other systemic cancers.[43]

Targeted Therapy:

With increasing numbers of pediatric cancer survivors, the long-term complications, such as relapse of cancers at a later stage or during adulthood, of standard therapies, including radiation and chemotherapy, are becoming increasingly apparent. Therefore, in recent years, efforts have been directed toward the use of precision medicine in developing new and innovative treatments.[46]

For pHGGs, targeted therapies are able to be used to target specific oncoproteins that are overexpressed in the tumor to reduce their effects.

Below is Table 1, showing different ongoing, completed, and terminated clinical trials based on specific molecular targets, assessing various drugs for pediatric brain tumors.

Table 1: Table of various clinical trials. Many of these clinical trials are in Phase I or II with unpublished results, indicating they are still in the preliminary stages of estimating the safety of the drug for pediatric patients. Pediatric patients behave differently regarding drug use because many of these young patients cannot tolerate the toxicity at the dose that would work for adults, because their organs are still immature. At this stage of assessing the safety of the drugs, the balance between the toxicity levels and clinical benefit for patients must be considered.

Drug on trial, NCT #	Phase	Cohort	Trial Objective	Results
Gemcitabine, NCT02992015	1	Pediatric DIPG	Determine the presence of gemcitabine in childhood DIPG tissue after systemic treatment with the drug and quantify the intertumoral gemcitabine concentration.	All patients experienced a reduction of tumor-related symptoms. Gemcitabine up to 200mg/m^2/once weekly, added to radiotherapy, is safe and well tolerated in pediatric DIPG.
Pomalidomide, NCT03257631	2	pediatric recurrent or progressive primary brain tumors in 1 of 4 primary brain tumor types: HGG, medulloblastoma. ependymoma and DIPG	Assess efficacy, safety, and tolerability of pomalidomide	Treatment with POM monotherapy did not meet the primary measure of success in any cohort. Future studies are needed to evaluate if POM would show efficacy in tumors with specific molecular signatures or in combination with other anti-cancer agents.
Dordaviprone (ONC201), NCT05580562	3	H3 K27M-mutant diffuse glioma and have completed standard frontline radiotherapy	Assess overall survival with ONC201 treatment following frontline radiotherapy	Estimated study completion: 2026-08
Nivolumab, NCT02960230	1/2	pediatric DIPG or other midline gliomas with H3.3K27M	Assess safety and immune activity of a synthetic peptide vaccine specific for the H3.3K27M epitope given in combination with poly-ICLC and the H3.3K27M epitope given in combination with poly-ICLC and the PD-1 inhibitor, nivolumab.	Administration of the H3.3K27M-specific vaccine was well tolerated. Patients with H3.3K27M-specific CD-8 + immunological responses demonstrated prolonged OS compared with non-responders. However, the outcome of the vaccine used requires/relies on a strong immune response to demonstrate proper therapeutic benefit.
Lorlatinib + BABYPOG/HIT-SKK, NCT06333899	1	pHGG with ALK or ROS1 fusion	Response of loratinib - target genes ALK, TRK receptors	Estimated study completion: 2035-06
ACT001, NCT06838676	2	DIPG and H3K27-altered HGG	Investigate the safety and efficacy of ACT001	Estimated study completion: 2035-07

Berubicin, NCT06838676	1	progressive, refractory, or recurrent pHGG who have completed at least 1 standard line of therapy	Examine safety, tolerability, and PK of Berubicin and estimate its MTD and/or RP2D	No results published
BXQ-350, NCT04771897	1	pediatric DIPG or DMG	Evaluate the safety of BXQ-350 and determine MTD	BXQ-350 was well-tolerated; MTD was not established. Safety profile warranted the investigation of combination studies at the highest dose tested (3.2 mg/kg)
Atovaquone, NCT06624371	1	pHGG/DMG/DIPG	Assess the safety and tolerability of atovaquone in combination with RT	Estimated study completion: 2027-10
GDC-0084, NCT03696355	1	pediatric DIPG or other diffuse midline H3K27M-mutant gliomas	Examine the safety, tolerability, and pharmacokinetics of GDC-0084 and estimate MTD	MTD of 27mg/m^2 has been reported
NEO100, NCT06357377	1	pediatric diffuse HGG	Safety, dosing, and delivery of NEO100	Estimated study completion: 2025-10
rHSC-DIPGVax in combination with BALSTILIMAB and ZALIFRELIMAB, NCT04943848	1	DIPG and DMG	Evaluate the safety and tolerability of rHSC-DIPGVax in combination with BALSTILIMAB and ZALIFRELIMAB.	Estimated study completion: 2025-12
Selinexor, NCT05099003	1/2	pediatric DIPG or pHGG with H3K27M mutation	Test safety, side effects, and the best dose of selinexor given in combination with RT	Estimated study completion: 2027
Abemaciclib, NCT02644460	1	Pediatric relapsed or refractory, or progressive DIPG	Evaluate doses of abemaciclib	The pediatric MTD of abemaciclib was 130 mg/m^2/dose administered orally twice daily on a 28-day cycle. Abemaciclib was well-tolerated with mainly hematologic toxicity. PK and PD will be used to further inform if 130 mg/m^2/dose is the pediatric recommended phase 2 dose.
Indoximod, NCT04049669	2	age 3 to 21 years who have progressive brain cancer (glioblastoma, medulloblastoma, or ependymoma) or DIPG	Test indoximod-based combination chemo-radio-rimmunotherapy for treatment	Estimated study completion: 2027-10
Vorinostat and Temsirolimus, NCT02420613	1	pediatric DIPG	Studies the side effects and best dose of temsirolimus when given together with vorinostat, with or without RT	No results published

Among the promising trials, Dordaviprone (ONC201) is in Phase III clinical trials for newly diagnosed patients with H3 K27M-mutant diffuse glioma and has passed safety evaluations. It is being administered to adult and pediatric patients to assess overall survival (OS) compared to conventional therapy. ONC201, an orally administered small molecule drug, antagonizes the overexpressed dopamine receptor D2 (DRD2) in some tumors and activates ClpP to disrupt energy production, reducing tumor growth. This international trial aims to improve OS following radiotherapy and support regulatory approval globally if effective. This international clinical trial will determine whether ONC201 can improve OS following radiotherapy. If proven effective treatment for this brain glioma type, it intends to support regulatory approval in multiple countries.[47]

Results and Discussion

Liquid biopsy:

In recent years, liquid biopsies have emerged as a potential non-invasive tool for the detection of cancerous tumors in the brain. This is of great clinical need as currently, glioma diagnosis relies on biopsy of tumor tissue and thus, surgical intervention. Studies have shown that gene information for tumors can be detected from the patients' blood, and since then has become the standard liquid biopsy specimen for various types of tumors. However, CSF can circulate in the ventricles and cisterns of the spinal cord and carry tumor metabolites and exfoliated tumor cells, making CSF the ideal sample for CNS tumor liquid biopsies.[48] CSF is mostly collected through lumbar puncture or surgery around the brain area. Currently, liquid biopsy techniques include Enzyme-linked Immunosorbent Assay (ELISA), Polymerase Chain Reaction (PCR), and Next-Generation Sequencing (NGS) for the detection of potential CSF biomarkers.[49] Furthermore, the development of liquid biopsies may be most beneficial for DMG patients, as DMG is resistant to standard cancer therapies, and surgical intervention is not yet accepted.[24] The ability to diagnose patients and assess their response to therapy treatments in a non-invasive manner would become an important clinical advancement in the management of this patient population. Liquid biopsies have been found to confirm diagnosis, identify the presence of the histone H3K27M mutation, and assess response to therapy for pediatric DMG patients.[50] However, despite this, many studies showcase differences in the collection and storage process, making it difficult to make comparisons, particularly as many studies use small patient cohorts.

microRNA:

MicroRNAs (miRNAs) are a type of small, single-stranded non-coding RNA with a length of 19-25 nucleotides, which can be released and detected in biological fluids such as plasma or CSF.[5,6] Recent studies have demonstrated that miRNAs play an important role in posttranscriptional gene regulation.[51] Their main function is to regulate gene expression through silencing or contributing to the degradation of messenger RNA (mRNA).[52] miRNA, which travel outside the cells and enter bodily fluids, are known as circulating miRNAs. This indicates that circulating miRNA is a potential tumor biomarker as well as an important therapeutic target. Below is Figure 7 showing the process of miRNA biogenesis.

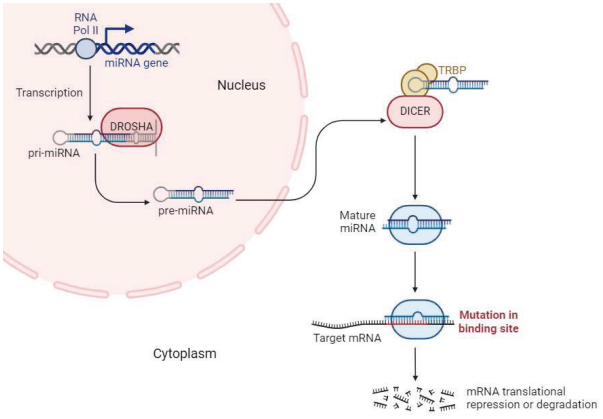

Figure 7: The biogenesis of the miRNA gene begins in the nucleus and finishes in the cytoplasm. First, the RNA Polymerase II enzymes (Pol II) transcribe the miRNA, forming a primary miRNA (pri-miRNA) with one or more hairpin structures.[53] Within the nucleus, the pri-miRNA is then processed by DROSHA, an enzyme that cuts off the redundant tails to then become 70 to 100 nucleotide pre-miRNAs. Furthermore, DICER, another enzyme, dices the pre-miRNA to double-stranded RNA in the cytoplasm, which makes a complementary sequence with the miRNA strand.[54] The now mature miRNA latches onto the mRNA (messenger RNA), and translational repression or degradation can now occur.[52]

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Why is microRNA promising?:

In recent years, microRNAs have emerged as a highly promising class of potential non-invasive biomarkers for early diagnosis and treatment monitoring of brain gliomas, including pHGGs, to indicate tumor presence and progression. Scientists have found that not only is miRNA abundant in tissues, but traces of circulating miRNAs exist in biological fluids.[55,56] Circulating miRNAs are promising biomarkers with beneficial clinical information regarding diagnosis, prognosis, and response to treatment. They originated from difficulties in the diagnosis and monitoring of gliomas without invasive biopsies, as they can be achieved through liquid biopsy analysis, which may replace traditional invasive brain biopsies for diagnosis. This allows for repeatable biopsies for monitoring the progression of the tumor. According to a study by Kopkova *et al.*, these miRNA biomarkers in CSF seem to be a stable and resistant source in even extreme conditions. This allows their possible use to support imaging for CNS tumor diagnosis and monitoring treatment instead of invasive surgical procedures.[56]

Although blood or urine are the most common liquid biopsies for other tumors, due to the BBB, many systemic biomarkers cannot be used for brain gliomas. However, miRNAs have been detected in CSF. CSF is a bodily fluid that is in direct contact with the entire extracellular environment of the CNS, making it an ideal source of CNS disease diagnostic markers, including brain tumors, shown in Figure 8 below.[56,57]

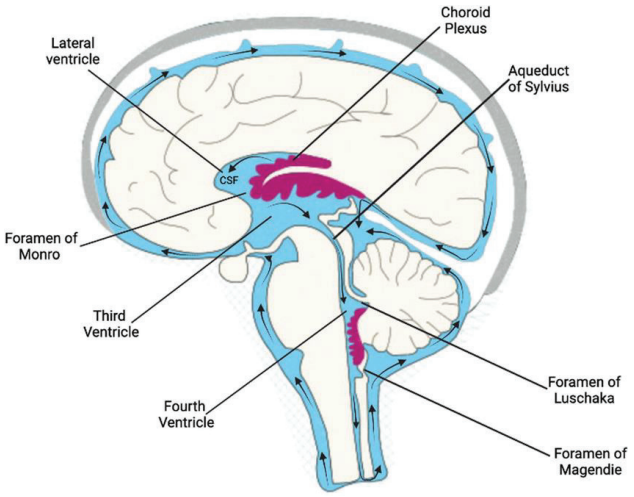

Figure 8: Throughout its circulation pathway, the cerebrospinal fluid is in direct contact with the entire extracellular environment of the central nervous system.[56] Thus, for brain tumors, including DMG, circulating microRNA is released in the CSF and can be extracted for diagnostic testing.

Shi *et al.* compared *miR-21* levels in CSF, blood serum, and exosomes from recurrent glioma patients. While the blood serum-derived exosomal *miR-21* levels did not differ from the control group, the miRNA levels in the CSF significantly increased in the glioma patients, reflecting tumor presence and spinal/ventricle metastasis. Thus, authors suggest that this miRNA may serve as a potential diagnostic and prognostic biomarker for brain gliomas.[58]

A study by Kopkova *et al.* identified specific miRNA signatures for a range of brain tumor types through performing miRNA profiling. qRT-PCR (Quantitative Reverse Transcription Polymerase Chain Reaction) was then used to validate 9 of the candidate miRNAs, successfully resulting in various combination patterns of *miR-30e*, *miR-140*, *miR-10a*, and *miR-21-3p*.[56]

Through the use of the NanoString nCounter assay, a hybridization-based technology enabling direct measurement of the miRNAs, Drusco *et al.* conducted research that suggests that CSF levels of *miR-125b*, *miR-223*, *miR-451*, *miR-711*, and *miR-935* might be efficient diagnostic biomarkers for various CNS malignancies. These include glioblastoma, medulloblastoma, lung metastasis, breast metastasis, and primary CNS lymphoma.[59]

However, microRNA biomarkers in CSF have some limitations. This includes the small sample sizes in current studies, and must be tested on a larger scale to be able to be given out to the public. Moreover, although recent studies have shown the presence of circulating miRNAs in CSF, researchers are facing difficulties in detecting the miRNAs in CSF due to technological difficulties and a lack of standardization. Another important consideration is the biological specificity, as miRNAs are not always tumor-specific, and other processes can alter miRNA expression profiles, which raises concern regarding the accuracy of results and diagnosis.

microRNAs can be used as potential therapeutic targets through specific inhibitors (miRNA sponge and antisense siRNA) or mimetics (increase beneficial miRNA through synthetic oligonucleotides), as shown in Figure 9 below.

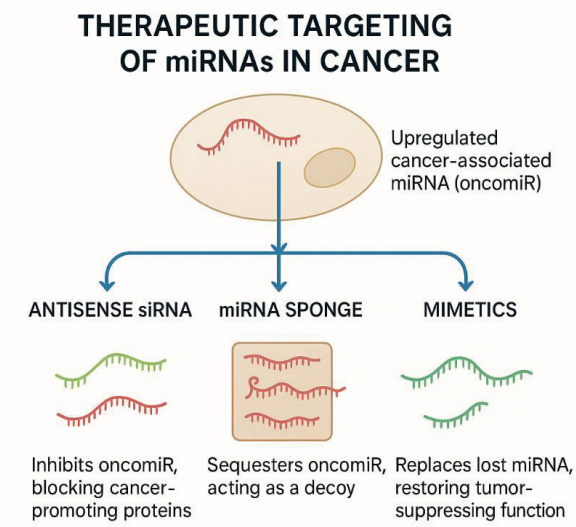

Figure 9: The three main types of miRNA therapeutic targeting strategies include the use of miRNA sponges, antisense siRNA, and miRNA mimetics. These approaches aim to rebalance gene regulation by targeting and blocking oncogenic miRNAs or restoring beneficial miRNAs that suppress the tumor in order to slow tumor growth.

Currently, there are many available delivery vectors of miRNA for the regulation of gene expression to allow access to these therapeutic targets. The two main areas of delivery vectors are viral and non-viral. Viral vectors, for example, lentiviruses, offer high transfection efficiency, whereas non-viral vectors, including lipid and polymer nanoparticles, may have lower transfection efficiency. However, non-viral vectors are

generally safer than viral vectors and are less immunogenic. These methods are outlined in Figure 10 below.

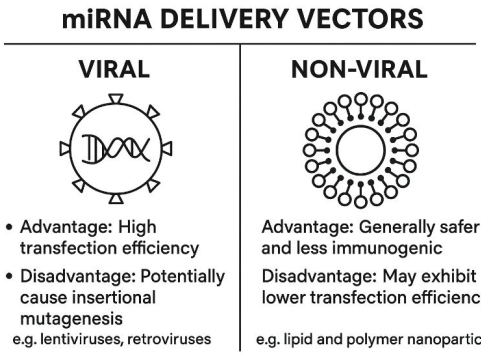

Figure 10: miRNA delivery vectors transport the miRNA into their target cells to allow for regulation of gene expression. Viral vectors generally achieve high transfection efficiency, while non-viral vectors tend to have improved safety profiles for the patient.

Despite advances in delivery techniques, transport of miRNA-based therapies in an effective manner across the BBB continues to be a challenge, with both viral and non-viral vectors causing a trade-off between efficacy and safety for the patient.

miRNA Sponge:

When a miRNA is too active and is causing cancer cells to proliferate, miRNA sponges are used to trap the miRNA. A current example is *miR-10b*. It is typically upregulated in high-grade gliomas as well as other cancers and commonly targets CDKN2A, a crucial cell-cycle regulator responsible for halting cell division when abnormalities are detected. By suppressing CDKN2A, *miR-10b* weakens checkpoint controls, allowing cancer cells to continue dividing. By using this miRNA "anti-*miR-10b* sponge", it acts as a decoy and blocks the oncogenic miRNA, allowing the tumor-suppressing genes to function again, and the tumor growth slows down, and the cancer stops spreading. However, currently, challenges include the delivery of the drug to the brain across the BBB.[60, 61]

Antisense and siRNA:

Antisense RNA and siRNA act as gene silencers to stop cancer-promoting proteins from being made. Antisense RNA, or antisense oligonucleotides, bind to a specific mRNA and block the mRNA from being read by ribosomes, to prevent harmful protein production. For instance, antisense RNA can be synthetically created against *miR-10b*, stopping it from silencing tumor suppressor genes. siRNA (small interfering RNA) binds to a matching mRNA sequence and causes mRNA degradation (permanently silences an overactive oncogene).[60]

A clinical trial for autologous cell immunotherapy (IGV-001) with IGF-2R antisense oligonucleotide (NCT04485949) is currently undergoing assessment of progression-free survival and overall survival in newly diagnosed glioblastoma patients. It has already passed Phase 1 of the trial, demonstrating that IGV-001 is safe in patients with astrocytoma and glioblastoma, and is currently in Phase 2.[62]

miRNA Mimetics:

On the other hand, mimetics can be used as lab replacements for beneficial miRNA that the body is missing. miRNA mimics are synthetic oligonucleotides that can replace the tumor-suppressing function of miRNAs. miRNA *let-7* is a tumor suppressor that is downregulated in certain gliomas. When *let-7* levels are significantly reduced or lost, its inhibitory influence on multiple oncogenes is removed, and these cancer cells proliferate, tilting the balance towards aggressive tumor growth and survival. Scientists inject *let-7* mimics into tumors, which allows replacement of the lost tumor-suppressing miRNAs, and subsequently slows tumor growth, and makes the cancer less aggressive.[60]

Therefore, through these therapeutic strategies of restoring miRNA *let-7* levels or inhibiting *miR-10b*, normal regulation of oncogenes and cell-cycle checkpoints may be able to be restored. Future research can focus on developing specific inhibitors (via miRNA sponge or antisense siRNA) or mimetics (increase miRNA via synthetic oligonucleotides) that modulate these miRNAs for clinical benefit.

Currently, miRNA mimetics have shown signs of success in other conditions such as pleural mesothelioma. In a study by van Zandwijk *et al.* in 2017, they investigated a drug loaded with miR-16-based mimic miRNA to target the unsuppressed tumor growth in adults with a confirmed diagnosis of malignant pleural mesothelioma. The results of suppressing the tumor were successful, and the maximum tolerated dosage amounts were found.

For brain-related tumors, future research of miRNA-based medicine should target the improvement of delivery systems to cross the BBB, minimize off-target effects to avoid unintended gene silencing, and the development of personalized miRNA therapies based on individual tumor profiles (therapeutic potential: exploiting RNA sponges could be a precision oncology strategy, provided we validate their safety, specificity, and efficacy in clinical models).

■ Conclusion

This review highlights the highly promising potential of microRNAs as both biomarkers for diagnosis and therapeutic targets for pediatric H3K27M-mutant diffuse midline gliomas. Within the 2022 CBTRUS Statistical Report Subcategory Pediatric High-Grade Glioma, they account for approximately 15% of all pediatric CNS tumors, and have an extremely poor prognosis worldwide, with overall survival of 5-year survival rates less than 20%.[2,13,17] This is due to the poor early detection methods and limited treatment options. Early detection is a crucial aspect to improve the overall survival of particularly aggressive cancers like DMG; however, currently it is limited by the vagueness of the presenting symptoms, leading to further diagnosis delay and the unreliability of detection through imaging techniques.[31] In specific tumor characterization, there may be limitations in distinguishing between various brain gliomas, as the extent of the tumor infiltration is often not accurately displayed.[35] The current treatment options are also extremely limited, as DMG has been found to be resistant and ineffec-

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tive against traditional therapies, including chemotherapy and radiotherapy, possibly because of the challenges regarding the blood-brain barrier.[40,43] The tumor's delicate location and highly aggressive nature, infiltrating surrounding brain tissue, also eliminates surgical resection as an option.[4,24] Targeted therapies are the most promising option, as they are able to target specific overexpressed oncoproteins. Among the promising trials, Dordaviprone (ONC201) is a drug currently in Phase III and has so far had successful results for H3 K27M-mutant diffuse glioma patients. It is now assessing overall survival compared to conventional therapies.[47] Although ONC201 is showing promise, many of the clinical trials for targeted therapies are in the early stages, still estimating the safety of the drug, and have limited results.

Therefore, an alternative for both early detection and treatment is required. microRNA biomarkers from a liquid biopsy offer significant promise for both. It is a non-invasive method of treatment, only requiring body fluid that has traces of the tumor information. The minimally invasive nature of a liquid biopsy ensures the process can be repeated to track the molecular changes in the tumor through analyzing the circulating microRNAs in the CSF. microRNA has also been found to be a stable source in cerebrospinal fluid, which is easily accessible through the lumbar puncture.[56] This accessibility allows miRNA analysis using CSF to be practical for clinical monitoring protocol integration. The CSF can be analyzed at a molecular level as it bathes the entire central nervous system, and due to this direct contact, early detection and detection of minimal residual disease becomes feasible.[56,57] It will help identify a relapse of the brain tumor before any symptoms emerge. Other body fluids, such as serum and urine, are also being explored but are less promising as they are not in direct contact with the CNS and may contain lower concentrations of the tumor-specific microRNA. MicroRNA also has significant potential as a therapeutic target by regulating gene expression of the oncoproteins post-transcriptionally through inhibitors such as miRNA sponge or antisense RNA and siRNA, as well as miRNA mimetics, which can act as lab replacements for the beneficial tumor-suppressing miRNA that the body is missing.[41,61] However, successful clinical translation will depend on the effectiveness of delivery techniques of the miRNA across the BBB and improvements in minimizing off-target effects. Antisense oligonucleotides are particularly promising, with a clinical trial (NCT04485949) in Phase II, undergoing assessment for progression-free survival and overall survival in glioblastoma patients (also classified as a high-grade glioma).[62]

However, the limitation of this review is the current lack of extensive clinical studies for the use of microRNA as biomarkers or therapeutic targets. With clinical and technological advancements from the growing interest in microRNAs, further exploration of miRNA-based approaches may lead to discoveries for improving the overall survival of pediatric DMG patients. Looking into the future, I believe DMG research will become increasingly focused on non-invasive methods, including liquid biopsies using cerebrospinal fluid, due to its direct contact with the brain. This will allow for earlier detection and diagnosis through biomarkers like microRNA, which offer viable solutions to address the challenges regarding early detection as well as targeted treatment, in a less invasive manner.

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References

1. Ostrom, Q. T., Cioffi, G., Gittleman, H., Patil, N., Waite, K., Kruchko, C., & Barnholtz-Sloan, J. S. (2019). CBTRUS Statistical Report: Primary Brain and Other Central Nervous System Tumors Diagnosed in the United States in 2012–2016. *Neuro-Oncology, 21*(Supplement_5), v1–v100. https://doi.org/10.1093/neuonc/noz150
2. Szychot, E., Giraud, G., Hargrave, D., van Vuurden, D., Grill, J., Biassoni, V., Massimino, M., von Bueren, A. O., Kebudi, R., Gilda-Costa, M. J., van Zanten, S. V., Bailey, S., Karremann, M., Bolle, S., Ajithkumar, T., Krause, M., Lassen-Ramshad, Y., Janssens, G., Morana, G., … Kramm, C. M. (2025). European standard clinical practice recommendations for pediatric high-grade gliomas. *EJC Pediatric Oncology, 5*, 100210. https://doi.org/10.1016/j.ejcped.2024.100210
3. Bounajem, M. T., Karsy, M., & Jensen, R. L. (2020). *Liquid biopsies for the diagnosis and surveillance of primary pediatric central nervous system tumors: A review for practicing neurosurgeons*. https://doi.org/10.3171/2019.9.FOCUS19712
4. Greuter, L., Frank, N., Guzman, R., & Soleman, J. (2022). The Clinical Applications of Liquid Biopsies in Pediatric Brain Tumors: A Systematic Literature Review. *Cancers, 14*(11), Article 11. https://doi.org/10.3390/cancers14112683
5. Petrescu, G. E. D., Sabo, A. A., Torsin, L. I., Calin, G. A., & Dragomir, M. P. (2019). MicroRNA-based theranostics for brain cancer: Basic principles. *Journal of Experimental & Clinical Cancer Research, 38*(1), 231. https://doi.org/10.1186/s13046-019-1180-5
6. Preethi, K. A., Selvakumar, S. C., Ross, K., Jayaraman, S., Tusubira, D., & Sekar, D. (2022). Liquid biopsy: Exosomal microRNAs as novel diagnostic and prognostic biomarkers in cancer. *Molecular Cancer, 21*(1), 54. https://doi.org/10.1186/s12943-022-01525-9
7. Malhotra, S., Miras, M. C. M., Pappolla, A., Montalban, X., & Comabella, M. (2023). Liquid Biopsy in Neurological Diseases. *Cells, 12*(14), Article 14. https://doi.org/10.3390/cells12141911
8. Prasanth, B. K., Alkhowaiter, S., Sawarkar, G., Dharshini, B. D., & R. Baskaran, A. (2023). Unlocking Early Cancer Detection: Exploring Biomarkers, Circulating DNA, and Innovative Technological Approaches. *Cureus, 15*(12), e51090. https://doi.org/10.7759/cureus.51090
9. Ostrom, Q. T., Price, M., Ryan, K., Edelson, J., Neff, C., Cioffi, G., Waite, K. A., Kruchko, C., & Barnholtz-Sloan, J. S. (2022). CBTRUS Statistical Report: Pediatric Brain Tumor Foundation Childhood and Adolescent Primary Brain and Other Central Nervous System Tumors Diagnosed in the United States in 2014–2018. *Neuro-Oncology, 24*(Suppl 3), iii1. https://doi.org/10.1093/neuonc/noac161
10. Leece, R., Xu, J., Ostrom, Q. T., Chen, Y., Kruchko, C., & Barnholtz-Sloan, J. S. (2017). Global incidence of malignant brain and other central nervous system tumors by histology, 2003–2007. *Neuro-Oncology, 19*(11), 1553. https://doi.org/10.1093/neuonc/nox091
11. Raja, N., Hayes, L., Basta, N., & McNally, R. J. Q. (2021). International trends in the incidence of brain tumors in children and young

adults and their association with indicators of economic development. *Cancer Epidemiology, 74*, 102006. https://doi.org/10.1016/j.canep.2021.102006

12. Wireko, A. A., Patel, H., Mehta, A., Jiffry, R., Adebusoye, F. T., & Miteu, G. D. (2023). Pediatric brain tumors in low- and middle-income countries: Available evidence on recent advancements in management, challenges, and recommendations – editorial. *International Journal of Surgery (London, England), 109*(3), 235–238. https://doi.org/10.1097/JS9
13. Mendez, F. M., Núñez, F. J., Garcia-Fabiani, M. B., Haase, S., Carney, S., Gauss, J. C., Becher, O. J., Lowenstein, P. R., & Castro, M. G. (2020). Epigenetic reprogramming and chromatin accessibility in pediatric diffuse intrinsic pontine gliomas: A neural developmental disease. *Neuro-Oncology, 22*(2), 195–206. https://doi.org/10.1093/neuonc/noz218
14. d'Amati, A., Bargiacchi, L., Rossi, S., Carai, A., Bertero, L., Barresi, V., Errico, M. E., Buccoliero, A. M., Asioli, S., Marucci, G., Del Baldo, G., Mastronuzzi, A., Miele, E., D'Antonio, F., Schiavello, E., Biassoni, V., Massimino, M., Gessi, M., Antonelli, M., & Gianno, F. (2024). Pediatric CNS tumors and 2021 WHO classification: What do oncologists need from pathologists? *Frontiers in Molecular Neuroscience, 17*. https://doi.org/10.3389/fnmol.2024.1268038
15. Louis, D. N., Perry, A., Reifenberger, G., von Deimling, A., Figarella-Branger, D., Cavenee, W. K., Ohgaki, H., Wiestler, O. D., Kleihues, P., & Ellison, D. W. (2016). The 2016 World Health Organization Classification of Tumors of the Central Nervous System: A summary. *Acta Neuropathologica, 131*(6), 803–820. https://doi.org/10.1007/s00401-016-1545-1
16. Gianno, F., Giovannoni, I., Cafferata, B., Diomedi-Camassei, F., Minasi, S., Barresi, S., Buttarelli, F. R., Alesi, V., Cardoni, A., Antonelli, M., Puggioni, C., Colafati, G. S., Carai, A., Vinci, M., Mastronuzzi, A., Miele, E., Alaggio, R., Giangaspero, F., & Rossi, S. (2022). Pediatric-type diffuse high-grade gliomas in the 5th CNS WHO Classification. *Pathologica, 114*(6), 422–435. https://doi.org/10.32074/1591-951X-830
17. Di Ruscio, V., Del Baldo, G., Fabozzi, F., Vinci, M., Cacchione, A., de Billy, E., Megaro, G., Carai, A., & Mastronuzzi, A. (2022). Pediatric Diffuse Midline Gliomas: An Unfinished Puzzle. *Diagnostics, 12*(9), Article 9. https://doi.org/10.3390/diagnostics12092064
18. Hoffman, L. M., Veldhuijzen van Zanten, S. E. M., Colditz, N., Baugh, J., Chaney, B., Hoffmann, M., Lane, A., Fuller, C., Miles, L., Hawkins, C., Bartels, U., Bouffet, E., Goldman, S., Leary, S., Foreman, N. K., Packer, R., Warren, K. E., Broniscer, A., Kieran, M. W., … Fouladi, M. (2018). Clinical, Radiologic, Pathologic, and Molecular Characteristics of Long-Term Survivors of Diffuse Intrinsic Pontine Glioma (DIPG): A Collaborative Report From the International and European Society for Pediatric Oncology DIPG Registries. *Journal of Clinical Oncology: Official Journal of the American Society of Clinical Oncology, 36*(19), 1963–1972. https://doi.org/10.1200/JCO.2017.75.9308
19. Buczkowicz, P., Hoeman, C., Rakopoulos, P., Pajovic, S., Letourneau, L., Dzamba, M., Morrison, A., Lewis, P., Bouffet, E., Bartels, U., Zuccaro, J., Agnihotri, S., Ryall, S., Barszczyk, M., Chornenkyy, Y., Bourgey, M., Bourque, G., Montpetit, A., Cordero, F., … Hawkins, C. (2014). Genomic analysis of diffuse intrinsic pontine gliomas identifies three molecular subgroups and recurrent activating ACVR1 mutations. *Nature Genetics, 46*(5), 451–456. https://doi.org/10.1038/ng.2936
20. Hayden, E., Holliday, H., Lehmann, R., Khan, A., Tsoli, M., Rayner, B. S., & Ziegler, D. S. (2021). Therapeutic Targets in Diffuse Midline Gliomas—An Emerging Landscape. *Cancers, 13*(24), Article 24. https://doi.org/10.3390/cancers13246251
21. Watanabe, J., Clutter, M. R., Gullette, M. J., Sasaki, T., Uchida, E., Kaur, S., Mo, Y., Abe, K., Ishi, Y., Takata, N., Natsumeda, M., Gadd, S., Zhang, Z., Becher, O. J., & Hashizume, R. (2024). BET bromodomain inhibition potentiates radiosensitivity in models of H3K27-altered diffuse midline glioma. *The Journal of Clinical Investigation, 134*(13), e174794. https://doi.org/10.1172/JCI174794
22. Lu, V. M., Alvi, M. A., McDonald, K. L., & Daniels, D. J. (2018). *Impact of the H3K27M mutation on survival in pediatric high-grade glioma: A systematic review and meta-analysis*. https://doi.org/10.3171/2018.9.PEDS18419
23. Piunti, A., Hashizume, R., Morgan, M. A., Bartom, E. T., Horbinski, C. M., Marshall, S. A., Rendleman, E. J., Ma, Q., Takahashi, Y., Woodfin, A. R., Misharin, A. V., Abshiru, N. A., Lulla, R. R., Saratsis, A. M., Kelleher, N. L., James, C. D., & Shilatifard, A. (2017). Therapeutic targeting of polycomb and BET bromodomain proteins in diffuse intrinsic pontine gliomas. *Nature Medicine, 23*(4), 493–500. https://doi.org/10.1038/nm.4296
24. Buczkowicz, P., & Hawkins, C. (2015). Pathology, Molecular Genetics, and Epigenetics of Diffuse Intrinsic Pontine Glioma. *Frontiers in Oncology, 5*, 147. https://doi.org/10.3389/fonc.2015.00147
25. Dufour, C., Perbet, R., Leblond, P., Vasseur, R., Stechly, L., Pierache, A., Reyns, N., Touzet, G., Le Rhun, E., Vinchon, M., Maurage, C., Escande, F., & Renaud, F. (2020). Identification of prognostic markers in diffuse midline gliomas H3K27M-mutant. *Brain Pathology, 30*(1), 179–190. https://doi.org/10.1111/bpa.12768
26. Leszczynska, K. B., Jayaprakash, C., Kaminska, B., & Mieczkowski, J. (2021). Emerging Advances in Combinatorial Treatments of Epigenetically Altered Pediatric High-Grade H3K27M Gliomas. *Frontiers in Genetics, 12*. https://doi.org/10.3389/fgene.2021.742561
27. Chammas, P., Mocavini, I., & Di Croce, L. (2020). Engaging chromatin: PRC2 structure meets function. *British Journal of Cancer, 122*(3), 315–328. https://doi.org/10.1038/s41416-019-0615-2
28. Fang, D., Gan, H., Cheng, L., Lee, J.-H., Zhou, H., Sarkaria, J. N., Daniels, D. J., & Zhang, Z. (n.d.). H3.3K27M mutant proteins reprogram the epigenome by sequestering the PRC2 complex to poised enhancers. *eLife, 7*, e36696. https://doi.org/10.7554/eLife.36696
29. Funato, K., Major, T., Lewis, P. W., Allis, C. D., & Tabar, V. (2014). Use of human embryonic stem cells to model pediatric gliomas with H3.3K27M histone mutation. *Science (New York, N.Y.), 346*(6216), 1529–1533. https://doi.org/10.1126/science.1253799
30. Herz, H.-M., Morgan, M., Gao, X., Jackson, J., Rickels, R., Swanson, S. K., Florens, L., Washburn, M. P., Eissenberg, J. C., & Shilatifard, A. (2014). Histone H3 lysine-to-methionine mutants as a paradigm to study chromatin signaling. *Science (New York, N.Y.), 345*(6200), 1065–1070. https://doi.org/10.1126/science.1255104
31. Aggarwal, P., Luo, W., Pehlivan, K. C., Hoang, H., Rajappa, P., Cripe, T. P., Cassady, K. A., Lee, D. A., & Cairo, M. S. (2022). Pediatric versus adult high-grade glioma: Immunotherapeutic and genomic considerations. *Frontiers in Immunology, 13*, 1038096. https://doi.org/10.3389/fimmu.2022.1038096
32. El-Ayadi, M., Ansari, M., Sturm, D., Gielen, G. H., Warmuth-Metz, M., Kramm, C. M., & Bueren, A. O. von. (2017). High-grade glioma in very young children: A rare and particular patient population. *Oncotarget, 8*(38), 64564–64578. https://doi.org/10.18632/oncotarget.18478
33. Fangusaro, J., Witt, O., Hernáiz Driever, P., Bag, A. K., de Blank, P., Kadom, N., Kilburn, L., Lober, R. M., Robison, N. J., Fisher, M. J., Packer, R. J., Young Poussaint, T., Papusha, L., Avula, S., Brandes, A. A., Bouffet, E., Bowers, D., Artemov, A., Chintagumpala, M., … Warren, K. E. (2020). Response assessment in pediatric

DOI: 10.36838/IJHSR811.212

low-grade glioma: Recommendations from the Response Assessment in Pediatric Neuro-Oncology (RAPNO) working group. *The Lancet. Oncology, 21*(6), e305–e316. https://doi.org/10.1016/S1470-2045(20)30064-4

34. Park, Y. W., Vollmuth, P., Foltyn-Dumitru, M., Sahm, F., Ahn, S. S., Chang, J. H., & Kim, S. H. (2023). The 2021 WHO Classification for Gliomas and Implications on Imaging Diagnosis: Part 2—Summary of Imaging Findings on Pediatric-Type Diffuse High-Grade Gliomas, Pediatric-Type Diffuse Low-Grade Gliomas, and Circumscribed Astrocytic Gliomas. *Journal of Magnetic Resonance Imaging, 58*(3), 690–708. https://doi.org/10.1002/jmri.28740
35. Henssen, D., Meijer, F., Verburg, F. A., & Smits, M. (2023). Challenges and opportunities for advanced neuroimaging of glioblastoma. *British Journal of Radiology, 96*(1141), 20211232. https://doi.org/10.1259/bjr.20211232
36. Hatoum, R., Chen, J.-S., Lavergne, P., Shlobin, N. A., Wang, A., Elkaim, L. M., Dodin, P., Couturier, C. P., Ibrahim, G. M., Fallah, A., Venne, D., Perreault, S., Wang, A. C., Jabado, N., Dudley, R. W. R., & Weil, A. G. (2022). Extent of Tumor Resection and Survival in Pediatric Patients With High-Grade Gliomas: A Systematic Review and Meta-analysis. *JAMA Network Open, 5*(8), e2226551. https://doi.org/10.1001/jamanetworkopen.2022.26551
37. Huynh-Le, M.-P., Walker, A. J., Burger, P. C., Jallo, G. I., Cohen, K. J., Wharam, M. D., & Terezakis, S. A. (2016). Management of pediatric intracranial low-grade gliomas: Long-term follow-up after radiation therapy. *Child's Nervous System, 32*(8), 1425–1430. https://doi.org/10.1007/s00381-016-3100-8
38. Vanan, M. I., & Eisenstat, D. D. (2014). Management of high-grade gliomas in the pediatric patient: Past, present, and future. *Neuro-Oncology Practice, 1*(4), 145–157. https://doi.org/10.1093/nop/npu022
39. Metselaar, D. S., du Chatinier, A., Stuiver, I., Kaspers, G. J. L., & Hulleman, E. (2021). Radiosensitization in Pediatric High-Grade Glioma: Targets, Resistance, and Developments. *Frontiers in Oncology, 11*, 662209. https://doi.org/10.3389/fonc.2021.662209
40. Fangusaro, J. (2012). Pediatric High Grade Glioma: A Review and Update on Tumor Clinical Characteristics and Biology. *Frontiers in Oncology, 2*. https://doi.org/10.3389/fonc.2012.00105
41. Staunton, J., Kids Cancer Centre, Sydney Children's Hospital, Randwick, NSW, Australia, Children's Cancer Institute, Lowy Cancer Research Centre, UNSW Sydney, Sydney, NSW, Australia, Ziegler, D. S., Kids Cancer Centre, Sydney Children's Hospital, Randwick, NSW, Australia, Children's Cancer Institute, Lowy Cancer Research Centre, UNSW Sydney, Sydney, NSW, Australia, & School of Clinical Medicine, UNSW Medicine & Health, UNSW Sydney, Sydney, NSW, Australia. (2023). Temozolomide for Pediatric High-Grade Glioma: Time for a Rethink? *Oncology & Haematology, 19*(2), 4. https://doi.org/10.17925/OHR.2023.19.2.4
42. Williamson, C., Williamson, S., Jiang, R., Sudmeier, L., Esiashvili, N., & Eaton, B. R. (2024). The impact of radiation therapy variables on pediatric high-grade glioma outcomes: A National Cancer Database analysis. *Pediatric Blood & Cancer, 71*(1), e30751. https://doi.org/10.1002/pbc.30751
43. Malik, J. R., Podany, A. T., Khan, P., Shaffer, C. L., Siddiqui, J. A., Baranowska-Kortylewicz, J., Le, J., Fletcher, C. V., Ether, S. A., & Avedissian, S. N. (2023). Chemotherapy in pediatric brain tumors and the challenge of the blood–brain barrier. *Cancer Medicine, 12*(23), 21075–21096. https://doi.org/10.1002/cam4.6647
44. Armstrong, C., & Sun, L. R. (2020). Neurological complications of pediatric cancer. *Cancer Metastasis Reviews, 39*(1), 3–23. https://doi.org/10.1007/s10555-020-09847-0
45. Walbert, T., & Stec, N. E. (2023). Chapter 5—Palliative care in brain tumors. In J. M. Miyasaki & B. M. Kluger (Eds.), *Handbook of Clinical Neurology* (Vol. 191, pp. 69–80). Elsevier. https://doi.org/10.1016/B978-0-12-824535-4.00011-2
46. Butler, E., Ludwig, K., Pacenta, H. L., Klesse, L. J., Watt, T. C., & Laetsch, T. W. (2021). Recent progress in the treatment of cancer in children. *CA: A Cancer Journal for Clinicians, 71*(4), 315–332. https://doi.org/10.3322/caac.21665
47. Arrillaga-Romany, I., Lassman, A., McGovern, S. L., Mueller, S., Nabors, B., van den Bent, M., Vogelbaum, M. A., Allen, J. E., Melemed, A. S., Tarapore, R. S., Wen, P. Y., & Cloughesy, T. (2024). ACTION: A randomized phase 3 study of ONC201 (dordaviprone) in patients with newly diagnosed H3 K27M-mutant diffuse glioma. *Neuro-Oncology, 26*(Supplement_2), S173–S181. https://doi.org/10.1093/neuonc/noae031
48. Aili, Y., Maimaitiming, N., Mahemuti, Y., Qin, H., Wang, Y., & Wang, Z. (2020). Liquid biopsy in central nervous system tumors: The potential roles of circulating miRNA and exosomes. *American Journal of Cancer Research, 10*(12), 4134–4150.
49. Xiao, F., Lv, S., Zong, Z., Wu, L., Tang, X., Kuang, W., Zhang, P., Li, X., Fu, J., Xiao, M., Wu, M., Wu, L., Zhu, X., Huang, K., & Guo, H. (2020). Cerebrospinal fluid biomarkers for brain tumor detection: Clinical roles and current progress. *American Journal of Translational Research, 12*(4), 1379–1396.
50. Soffietti, R., Bettegowda, C., Mellinghoff, I. K., Warren, K. E., Ahluwalia, M. S., De Groot, J. F., Galanis, E., Gilbert, M. R., Jaeckle, K. A., Le Rhun, E., Rudà, R., Seoane, J., Thon, N., Umemura, Y., Weller, M., van den Bent, M. J., Vogelbaum, M. A., Chang, S. M., & Wen, P. Y. (2022). Liquid biopsy in gliomas: A RANO review and proposals for clinical applications. *Neuro-Oncology, 24*(6), 855–871. https://doi.org/10.1093/neuonc/noac004
51. Nakamura, K., Sawada, K., Yoshimura, A., Kinose, Y., Nakatsuka, E., & Kimura, T. (2016). Clinical relevance of circulating cell-free microRNAs in ovarian cancer. *Molecular Cancer, 15*(1), 48. https://doi.org/10.1186/s12943-016-0536-0
52. Liu, H., Lei, C., He, Q., Pan, Z., Xiao, D., & Tao, Y. (2018). Nuclear functions of mammalian MicroRNAs in gene regulation, immunity, and cancer. *Molecular Cancer, 17*(1), 64. https://doi.org/10.1186/s12943-018-0765-5
53. Ho, P. T. B., Clark, I. M., & Le, L. T. T. (2022). MicroRNA-Based Diagnosis and Therapy. *International Journal of Molecular Sciences, 23*(13), Article 13. https://doi.org/10.3390/ijms23137167
54. Leitão, A. L., & Enguita, F. J. (2022). A Structural View of miRNA Biogenesis and Function. *Non-Coding RNA, 8*(1), Article 1. https://doi.org/10.3390/ncrna8010010
55. Suárez, B., Solé, C., Márquez, M., Nanetti, F., & Lawrie, C. H. (2022). Circulating MicroRNAs as Cancer Biomarkers in Liquid Biopsies. In U. Schmitz, O. Wolkenhauer, & J. Vera-González (Eds.), *Systems Biology of MicroRNAs in Cancer* (pp. 23–73). Springer International Publishing. https://doi.org/10.1007/978-3-031-08356-3_2
56. Kopkova, A., Sana, J., Fadrus, P., & Slaby, O. (2018). Cerebrospinal fluid microRNAs as diagnostic biomarkers in brain tumors. *Clinical Chemistry and Laboratory Medicine (CCLM), 56*(6), 869–879. https://doi.org/10.1515/cclm-2017-0958
57. Shalaby, T., Achini, F., & Grotzer, M. A. (2016). Targeting cerebrospinal fluid for the discovery of brain cancer biomarkers. *Journal of Cancer Metastasis and Treatment, 2*(0), 176–187. https://doi.org/10.20517/2394-4722.2016.12
58. Shi, R., Wang, P.-Y., Li, X.-Y., Chen, J.-X., Li, Y., Zhang, X.-Z., Zhang, C.-G., Jiang, T., Li, W.-B., Ding, W., & Cheng, S.-J. (2015). Exosomal levels of miRNA-21 from cerebrospinal fluids are associated with poor prognosis and tumor recurrence of glioma patients.

Oncotarget, 6(29), 26971–26981. https://doi.org/10.18632/oncotarget.4699
59. Drusco, A., Bottoni, A., Laganà, A., Acunzo, M., Fassan, M., Cascione, L., Antenucci, A., Kumchala, P., Vicentini, C., Gardiman, M. P., Alder, H., Carosi, M. A., Ammirati, M., Gherardi, S., Luscrì, M., Carapella, C., Zanesi, N., & Croce, C. M. (2015). A differentially expressed set of microRNAs in cerebrospinal fluid (CSF) can diagnose CNS malignancies. *Oncotarget, 6*(25), 20829–20839.
60. Sufianov, A., Begliarzade, S., Ilyasova, T., Liang, Y., & Beylerli, O. (2022). MicroRNAs as prognostic markers and therapeutic targets in gliomas. *Non-Coding RNA Research, 7*(3), 171–177. https://doi.org/10.1016/j.ncrna.2022.07.001
61. Thomson, D. W., & Dinger, M. E. (2016). Endogenous microRNA sponges: Evidence and controversy. *Nature Reviews Genetics, 17*(5), 272–283. https://doi.org/10.1038/nrg.2016.20
62. Lee, I. Y., Hanft, S., Schulder, M., Judy, K. D., Wong, E. T., Elder, J. B., Evans, L. T., Zuccarello, M., Wu, J., Aulakh, S., Agarwal, V., Ramakrishna, R., Gill, B. J., Quiñones-Hinojosa, A., Brennan, C., Zacharia, B. E., Silva Correia, C. E., Diwanji, M., Pennock, G. K., … Boockvar, J. A. (2024). Autologous cell immunotherapy (IGV-001) with IGF-1R antisense oligonucleotide in newly diagnosed glioblastoma patients. *Future Oncology (London, England), 20*(10), 579–591. https://doi.org/10.2217/fon-2023-0702

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RESEARCH ARTICLE

Evaluating the Effectiveness of Japan's 2012 Carbon Tax: Evidence from the Synthetic Control Method

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ABSTRACT: What is the effect of Japan's 2012 carbon tax on CO_2 emissions? This paper analyzes Japan's 2012 carbon tax's efficiency in reducing carbon emissions by using the synthetic control method with data from 1990 to 2023. The synthetic control is made using the weighted average of countries without carbon taxation to replicate Japan's emission patterns in the absence of the policy. Japan's emissions track the synthetic closely before treatment, but diverged upwards largely in 2011–2012 due to the Fukushima nuclear disaster and the resulting surge in fossil fuel use. Even after the Fukushima accident, this paper's results suggest that the carbon emissions were not substantially affected by the carbon tax imposed in 2012. This finding suggests that Japan's low tax rate and its industrial exemptions have been insufficient in altering emission trajectories, emphasizing the need for stronger and complementary climate policies and higher carbon tax rates.

KEYWORDS: Carbon Tax, Synthetic Control Method, Japan, CO_2 Emissions, Climate Policy, Fukushima Nuclear Disaster, Pigouvian Tax, Placebo Tests.

Introduction

Carbon taxation was created based on the Pigouvian theory, where taxing carbon emissions internalizes its negative externalities.[1] Research indicates that well-crafted carbon taxes can reduce emissions, improving general wellfare—consistent with the double dividend hypothesis and the Porter hypothesis of innovation.[2,3]

Statistically, European cases provide convincing evidence of carbon tax effectiveness. Finland's carbon tax, for example, significantly reduced its CO_2 emissions per capita, as shown through the synthetic control method.[4] Sweden's carbon tax has led to great declines in emissions from transportation without hindering GDP growth.[5] In British Columbia, a fiscally neutral tax decreased fuel use without having to decrease competitiveness.[6]

The synthetic control method has surfaced as an effective tool for policy evaluation, especially for the effects of domestic interventions.[7,8] Placebo tests within the synthetic control framework strengthen the validity of the analysis by showing whether the estimated treatment effects are statistically significant relative to the control groups. While there have been many applied studies in Europe regarding carbon taxes, there have not been any studies in Asia using the same method.This paper will contribute to the literature by filling this gap.

Japan's 2012 carbon tax (Named the Tax for Climate Change Mitigation) was implemented as a levy under Japan's already existing Oil and Coal Tax system.[9] The tax is targeted upstream, meaning it is charged to fossil fuel importers and distributors, and not directly to consumers or emitting companies. So petroleum, natural gas, and coal importers are taxed on the carbon content of their fuels. Due to this tax structure, the burden is partially passed downstream via increased fuel prices, however it does not directly charge emitters.

Japan, one of the first Asian countries to implement a carbon tax in 2012, offers an important case. The tax rate was set at around ¥289 per ton of CO_2 (about USD $2.60) and was intended to gradually increase, but it has stayed constant and remained modest compared to its European counterparts. Studies emphasize that Japan's carbon tax is one of the lowest in developed economies, which limits its ability to substantially change carbon emissions.[10,11] Japan's heavy dependence on fossil fuels during the period after the Fukushima nuclear incident, along with widespread exemptions for energy-intensive industries, increasingly constrains the policy's effectiveness. Current assessments for the tax remain mostly descriptive or based on computable general equilibrium (CGE) models, leaving space for empirical evaluations such as the synthetic control method to determine whether the tax has had a measurable impact on emissions.

Modeling studies confirm that Japan's carbon tax has only a limited impact at its current level. Takeda estimate that the tax alone would achieve only small reductions unless combined with other complementary energy and emission policies.[12] Similarly, Inoue stated that the carbon tax's effect is diluted by exemptions and its low price compared to international standards.[11] These studies suggest that Japan's carbon tax effectiveness depends heavily on raising its rate and integrating it with broader energy transition measures.

Evidence from the United States suggests that fuel and energy taxes often shift consumer and firm behaviors more effectively when combined with revenue recycling systems (transfers to households that are more affected by these policies).[13] Likewise, studies from the OECD also highlight how carbon tax outcomes are variable depending on sectoral exemptions.[14] Poorly designed frameworks risk efficiency loss when their coverage is narrow or the policy's enforcement is weak.[15]

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In a theoretical sense, models of optimal tax illustrate that carbon taxation can be welfare- improving even under uncertainty.[16] Further extensions later underline the political economy trade-offs in actual carbon tax adoptions.[17]

France's fuel tax protests provide evidence suggesting that equity and distributional considerations affect a policy's durability greatly.[18] Relatedly, climate damage disproportionately affects lower-income regions, further enforcing the need for redistributive policy design in carbon taxation.[19]

Empirical macroeconomic evaluations propose that carbon taxation does not always need to reduce economic growth. Using panel data, researchers found that there was no systematic negative impact of carbon taxation on GDP across the OECD countries.[20]

Micro-level evidence also shows behavioral adjustments. Vehicle fuel taxation leads to significant decreases in gasoline demand, showing the responsiveness of consumption to carbon-pricing signals.[21] Meanwhile, policy review experiences conclude that the political feasibility and institutional stability determine effectiveness more than the theoretical efficiency proposed by pure economics by itself.[22]

In environmental economics, reductions in emission intensity are consistently linked to the effects of innovation. Higher carbon prices incentivize clean innovation, particularly in automotive and transport technologies.[23] Likewise directed technical change models argue that carbon taxation can accelerate the transition to green economic growth if applied consistently over time.[24]

Regional studies highlight policy effect variation. For example, Japan's carbon tax had a limited impact due to its low rate and overlapping regulations, while Ireland's showed substantial emission reductions despite its political turnover.[12,24] Together, these studies show that carbon tax effectiveness depends not only on tax level, but also on the supporting or overlapping policies, as well as enforcement quality —how effectively the government can actually tax subjects. This study provides new insight by utilizing the synthetic control method and placebo tests to assess whether Japan's carbon tax has measurably reduced Carbon dioxide emissions, and how its structure compares to successful carbon taxation examples such as Sweden's.

The rest of the paper will proceed as follows: Section 2 will contain the methodology of the research and the data used, Section 3 will present the results of the study and analyze the implications behind it, and Section 4 will have a conclusion.

■ Empirical Method and Data

Within this section, the synthetic control method is briefly presented, followed by a description of the data utilized in the analysis. A more formal description of the model can be found in previous studies.

2.1. Empirical method:

The synthetic control method (SCM) is made to evaluate the effect of a policy intervention at the comprehensive level when the number of units is limited.[8] In this paper, the units are countries, observed during T periods indexed by t. Let T_0 represent the number of pre-treatment years and T_1 represent the amount of post-treatment years, with $T = T_0 + T_1$.

Among J+1 countries, only one (Japan) is exposed to the policy intervention (the 2012 carbon tax). The remaining J countries create the donor pool. It is assumed that Japan is only affected by the policy from T_0+1,…,T, and that no spillovers occur across units.

Let $Y_{\{jt\}}$ represent the result (CO_2 emissions per capita) of the country j in period t. The treatment effect for Japan in period t, a_{1t}, is defined as:

$a_{1t} = Y^1 1t - Y^N 1t$,

where $Y^I 1t$ is the observed outcome under treatment and $Y^N 1t$ is the (unobserved) counterfactual outcome in the absence of treatment. Due to the unobserved untreated outcome for Japan after 2012, a counterfactual must be constructed.

The synthetic control is the weighted average of the untreated countries that best reproduces the pre-treatment characteristics of Japan. Specifically, let $W = (W_2,,W_{J+1})'$ represent a vector of weights, where $W_J \geq 0$ *and* $\Sigma\, W_J = 1$. For a set of predictors X, SCM chooses W^* to minimize the distance between Japan's predictors (X_1) and those of the donor pool (X_0W):

$min_W (X_1 - X_0W)'\, V(X_1 - X_0W)$,

where V is a diagonal matrix that assigns importance to each predictor. Effectively, V and W are chosen to minimize the mean squared prediction error (MSPE) of the outcome variable during the pre-treatment period.[5]

The treatment effect in period t is then obtained through the equation:

The treatment effect in period t is then obtained through the equation:

$$a_{1t} = Y_{1t} - \sum_{j=2}^{J+1} w^*_j Y_{jt}.$$

2.2. Data:

All the data was originally compiled from *Our World in Data*, which is a compilation of data sets. Data like CO_2 emissions originate from the *Global Carbon Project* and the *Carbon Dioxide Information Analysis Center*. Data on GDP per capita and merchandise trade come from the *World Bank's World Development Indicators*, and employment shares are taken from the International Labor Organization. Urbanization data is taken from the *United Nations World Urbanization*.

Data:	Description:
GDP Per Capita	GDP per capita is calculated as the value of all final goods and services produced each year in a country (the gross domestic product), divided by the population. It represents the average economic output per person. Represented in PPP—purhasing power parity— at constant 2021 international dollars. GDP per capita generally increases as economies transition from agriculture towards industry and services.
Emissions per capita	Carbon dioxide (CO_2) emissions from burning fossil fuels and industrial processes. This includes emissions from transport, electricity generation, and heating, but not land-use change. Measured in metric tons. Land-use change, like deforestation and urban expansion, releases stored carbon and contributes to about 10–15% of global CO_2 emissions. It is omitted due to data uncertainty and differing estimation methods from other energy related emissions. Emissions per capita increase with industrialization and income, then stabilize or decline at higher GDP per capita.

Share of the population living in urban areas	Urban population refers to people living in urban areas as defined by national statistical offices. The data are collected and smoothed by the United Nations Population Division. Urbanization increases with economic development and generally demands higher energy usage and emissions.
Employment in services as a percent of population	Distribution of total employment between the services sector. This includes employment in the informal economy. The share of employment services generally increases as GDP per capita rises.
Employment in industry as a percent of population	Distribution of total employment between the industry sectors. This includes employment in the informal economy. Industrial employment generally rises in early stages of development, declining as economies become service-dominated.
Employment in agriculture as a percent of population	Distribution of total employment in the agriculture sector. This includes employment in the informal economy. Agricultural employment generally declines with a country's urbanization and increasing income.
Merchandise trade as a share of GDP	the proportion of a country's economic output (Gross Domestic Product) that is accounted for by the international trade of physical goods (exports and imports). Merchandise trade generally accounts for a larger share of GDP as countries industrialize.

Model Application:

The outcome variable is total CO_2 emissions per capita—measured in metric tons. The predictors include a series of lagged values of CO_2 emissions per capita (1991–2010), GDP per capita (PPP, constant 2021 international dollars), the percentage of the urban population, the employment shares in services, industry, and agriculture, as well as all merchandise trade as a share of GDP. These predictors were selected to capture both the emissions trajectory and the economic-demographic structure of Japan relative to the donor pool.

The panel covers 1991 to 2023, with 22 pre-treatment years (1991–2011) and 12 post-treatment years (2012–2023). All countries with carbon taxes were removed from the list of potential donor countries to avoid spillover effects. The most important contributors to synthetic control based on their unit weights are: the United States (0.272), Zimbabwe (0.244), South Korea (0.177), and Romania (0.097). Additional contributors include Hong Kong (0.060), Libya (0.049), Russia (0.043), Bulgaria (0.027), Oman (0.015), Singapore (0.008), and Saudi Arabia (0.007).

To strengthen the credibility of the analysis, placebo tests are also implemented. These include reassigning the treatment to donor pool countries that did not introduce carbon taxes in 2012. If the placebo countries show no large post-treatment gaps compared to Japan, it supports the interpretation that any divergence observed for Japan is due to its carbon tax rather than random variation

Results

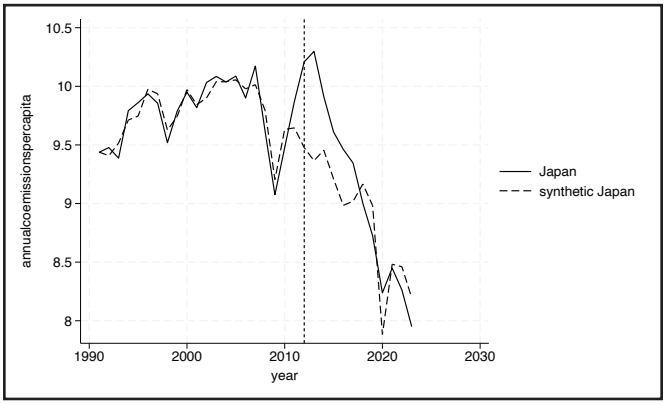

Figure 1: Figure 1 shows the trajectory of Japan's per capita CO_2 emissions compared to its synthetic control between the years 1990 and 2023. The pre-treatment period (1990–2011) shows a tight fit, suggesting that the synthetic control offers a credible counterfactual. From 2011 onward however, Japan's emissions diverge upward greatly from the synthetic. This spike corresponds to the Fukushima nuclear disaster, which forced the closing of nuclear power plants driving a large increase in fossil fuel demand and use. The divergence closes in through the post-treatment period, but never reaches a significant negative value, suggesting that the 2012 carbon tax has had limited impact in reducing emissions.

The placebo tests reinforce this interpretation. Table 1 reports p-values for each year after the carbon tax was introduced. If the p-values are low, the divergence between Japan and its synthetic control is unlikely to be due to random chance; higher values imply that the divergence could have occurred by coincidence.

Year	P-Value
2012	0.083
2013	0.066
2014	0.23
2015	0.28
2016	0.25
2017	0.39
2018	0.61
2019	0.5
2020	0.45
2021	0.91
2022	0.6
2023	0.54

Placebo test results show that only the first two post-treatment years (2012–2013) show relatively low p-values (~0.08 & ~0.07), indicating that Japan's divergence from its synthetic control was somewhat unusual immediately after the tax introduction—most likely due to the Fukushima incident abruptly increasing demand for fossil fuels for the next two years after 2011. However, from 2014 onward, the p-values rise, staying above 0.20 every year, even surpassing 0.90 by 2023. This suggests that most of the observed differences are statistically indiscernible from the placebo.

The findings indicate that Japan's carbon tax has not generated a strong or consistent reduction in CO_2 emissions per capita. The persistent reliance on fossil fuels after Fukushima, along with the tax's low rate and broad exemptions, appears to be the reason for its ineffectiveness, which is consistent with

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current research on Japan's carbon tax (Even though different methods were used by them).

Discussion

This study utilized the synthetic control method to evaluate the effectiveness of Japan's 2012 carbon tax in reducing CO_2 emissions per capita. The results show that Japan's emissions diverged upward from its synthetic control immediately after the tax's introduction, but mainly due to the 2011 Fukushima nuclear disaster and the resulting increase in fossil fuel use. After 2013, however, the difference between Japan and its synthetic counterpart became statistically insignificant.

The synthetic control was built by combining data from countries without carbon taxation to replicate Japan's pre-treatment emissions trend. Control variables included GDP per capita, employment shares by sector, trade share of GDP, and urban population percentage. This model created a "synthetic Japan" that closely mirrored Japan's economic and demographic structure before 2012, isolating the policy's post-treatment effects. In accordance with existing research on carbon taxation these controls effectively represent the economic and structural factors that are highly linked to national emission levels.[4,5] This study improves upon several of the previous papers by adding a larger set of socio-economic indicators and broadening the donor pool.

The findings indicate that Japan's carbon tax has not achieved a measurable reduction in emissions. The main reasons are its low rate, broad industrial exemptions, and introduction during an energy crisis. Large industries—such as manufacturing steel, cement, and energy production—face partial or complete exemptions, undermining the price signal. At ¥289 per ton (USD $2.60), Japan's carbon tax is much lower than that of other countries. For example, Finland and Canada charge USD $70-90 per ton, and Sweden's rate is above USD $130 per ton— making its price signal too weak to significantly alter behavior. Japan's reliance on imported fuels as it turned to fossil fuels, natural gases, and coal, after the Fukushima incident, offset its potential emission gains.

Ultimately, this analysis suggests that Japan's carbon tax serves more as a symbolic measure than a significant emission control tool.

Conclusion

The results emphasize that carbon tax effectiveness requires proper rates, coverage, and integration with other policies. Japan's low rate and small scope provide little incentive for decarbonization. To improve effectiveness, Japan should gradually increase the tax and narrow industrial exemptions.

The Fukushima disaster continues to confound the policy evaluation, making it difficult to purely isolate the tax's impact. As new data becomes available, replicating this analysis will reveal whether Japan's emissions eventually diverge from its synthetic control or continue to follow the same path. Future research could refine this model by including energy mix (e.g ... share of coal, LNG, oil, renewable energy) and sector-specific emissions (power generation, transportation, manufacturing), to better capture these effects.

Japan's case shows carbon tax adoption is only the starting point. Without strong price signals, enforcement, and compatible policies, carbon taxation can become purely symbolic rather than effective.

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References

1. Pigou, A. C. (1920). *The Economics of Welfare*. Macmillan.
2. Pearce, D. (1991). "The role of carbon taxes in adjusting to global warming." *Economic Journal*, 101(407), 938–948. https://doi.org/10.2307/2233865
3. Porter, M. E., & van der Linde, C. (1995). "Toward a new conception of the environment–competitiveness relationship." *Journal of Economic Perspectives*, 9(4), 97–118. https://doi.org/10.1257/jep.9.4.97
4. Elbaum, J. D. (2021). "The effect of a carbon tax on per capita carbon dioxide emissions: Evidence from Finland." *Environmental and Resource Economics*, 80(3), 553–576. https://doi.org/10.1007/s10640-021-00545-9
5. Andersson, J. J. (2019). "Carbon taxes and CO_2 emissions: Sweden as a case study." *American Economic Journal: Economic Policy*, 11(4), 1–30. https://doi.org/10.1257/pol.20170144
6. Murray, B., & Rivers, N. (2015). "British Columbia's revenue-neutral carbon tax: A review of the latest 'grand experiment' in environmental policy." *Energy Policy*, 86, 674–683. https://doi.org/10.1016/j.enpol.2015.08.011
7. Abadie, A., & Gardeazabal, J. (2003). "The economic costs of conflict: A case study of the Basque Country." *American Economic Review*, 93(1), 113–132. https://doi.org/10.1257/000282803321455188
8. Abadie, A., Diamond, A., & Hainmueller, J. (2010). "Synthetic control methods for comparative case studies: Estimating the effect of California's tobacco control program." *Journal of the American Statistical Association*, 105(490), 493–505. https://doi.org/10.1198/jasa.2009.ap08746
9. Takeda, S., & Arimura, T. H. (2020). "A computable general equilibrium analysis of environmental tax reform in Japan." Discussion Paper, Waseda University. https://ideas.repec.org/p/was/dpaper/2002.html
10. Gokhale, K. (2021). "Japan's carbon tax: A small step or a missed opportunity?" *Journal of Environmental Studies and Sciences*, 11(2), 1–10. https://doi.org/10.1007/s13412-021-00673-5
11. Inoue, E., Kimura, F., & Yamaguchi, S. (2020). "Japan's carbon tax: Is it effective?" *Energy Policy*, 145, 111765. https://doi.org/10.1016/j.enpol.2020.111765
12. Takeda, S., Arimura, T. H., & Momoe, A. (2019). "The effectiveness of Japan's carbon tax in reducing CO_2 emissions." *Energy Policy*, 133, 110832. https://doi.org/10.1016/j.enpol.2019.110832
13. Metcalf, G. E. (2009). "Designing a carbon tax to reduce U.S. greenhouse gas emissions." *Review of Environmental Economics and Policy*, 3(1), 63–83. https://doi.org/10.1093/reep/ren015
14. OECD. (2018). *Effective Carbon Rates 2018: Pricing Carbon Emissions through Taxes and Emissions Trading*. OECD Publishing. https://doi.org/10.1787/9789264305304-en
15. Parry, I. W. H., Heine, D., Lis, E., & Li, S. (2014). *Getting Energy Prices Right: From Principle to Practice*. IMF Working Paper 14/152. International Monetary Fund.
16. Weitzman, M. L. (1974). "Prices vs. quantities." *Review of Economic Studies*, 41(4), 477–491. https://doi.org/10.2307/2296698

17. Goulder, L. H., & Schein, A. R. (2013). "Carbon taxes vs. cap and trade: A critical review." *Journal of Economic Literature*, 51(3), 675–704. https://doi.org/10.1257/jel.51.3.675
18. Douenne, T., & Fabre, A. (2020). "French attitudes on climate change, carbon taxation, and other climate policies." *Journal of Public Economics*, 191, 104265. https://doi.org/10.1016/j.jpubeco.2020.104265
19. Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., … Houser, T. (2017). "Estimating economic damage from climate change in the United States." *Quarterly Journal of Economics*, 132(2), 1–56. https://doi.org/10.1093/qje/qjx005
20. Metcalf, G. E., & Stock, J. H. (2020). "The macroeconomic impact of Europe's carbon taxes." *Brookings Papers on Economic Activity*, 2020(Spring), 405–456. https://doi.org/10.1353/eca.2020.0005
21. Davis, L. W., & Kilian, L. (2011). "Estimating the effect of a gasoline tax on carbon emissions." *American Economic Review: Papers & Proceedings*, 101(3), 1–7. https://doi.org/10.1257/aer.101.3.1
22. Aldy, J. E., & Stavins, R. N. (2012). "The promise and problems of pricing carbon: Theory and experience." *Journal of Economic Perspectives*, 26(4), 79–106. https://doi.org/10.1257/jep.26.4.79
23. Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., & Van Reenen, J. (2016). "Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry." *American Economic Review*, 106(11), 3869–3896. https://doi.org/10.1257/aer.20150807
24. Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). "The environment and directed technical change." *Econometrica*, 80(2), 601–643. https://doi.org/10.3982/ECTA8828
25. Callan, T., Lyons, S., Scott, S., Tol, R. S. J., & Verde, S. (2009). *The Distributional Implications of a Carbon Tax in Ireland*. ESRI Research Series 10. Economic and Social Research Institute (ESRI).
26. Abadie, A., Diamond, A., & Hainmueller, J. (2015). "Comparative politics and the synthetic control method." *American Journal of Political Science*, 59(2), 495–510. https://doi.org/10.1111/ajps.12116
27. Ritchie, H., Roser, M., & Rosado, P. (2023). *Our World in Data: CO_2 and Greenhouse Gas Emissions; GDP; Trade and Globalization; Urbanization; Employment.* https://ourworldindata.org

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REVIEW ARTICLE

A Comprehensive Review of AI Regulations and Their Effects on Innovation and Adoption

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ABSTRACT: Society stands on the precipice of a new technological era with Artificial Intelligence (AI) transforming numerous industries and becoming increasingly integral to society. Generative AI, defined as models that can produce human-like content (e.g., text or images) by learning from large datasets, has significantly expanded the capabilities of AI. In response to this development, legacy legal doctrines are being reinterpreted and applied to the unique challenges posed by generative AI systems. Simultaneously, regulatory bodies have introduced governance frameworks that seek to align innovation with ethical, legal, and societal safeguards. This paper aims to provide a detailed synthesis of both legacy and emerging governance frameworks, evaluating their influence on the pace and direction of innovation in generative AI. First, I examine how legacy doctrines such as Data Protection, Intellectual Property, Liability, and Intermediary Liability apply to generative AI. Then, I consider regulatory proposals for AI from various governments. Finally, I evaluate the impact that regulation could have on the innovation and adoption of AI. This paper aims to provide a reference for policymakers and researchers, while also encouraging more discussion on how to sensibly approach AI regulation..

KEYWORDS: Systems Software, Algorithms, Generative AI, Governance, AI Innovation.

Introduction

The rise of Generative Artificial Intelligence marks an inflection point where computational creativity has begun to match human ingenuity. Unlike earlier predictive models that simply classify or rank existing data, generative systems produce new text, images, code, and audio, expanding the scope of automation and challenging the rationale that served as the foundation for current AI policy.[1] These generative AI tools, such as ChatGPT, Claude, or Gemini, are the product of the substantial investment in recent years that has accelerated progress in machine learning and deep learning. For instance, venture capital funding for generative AI start-ups has increased by more than 74 percent since 2017, signaling strong confidence in a technology that now reaches millions of users globally.[2] With this rapid growth, generative AI can have a profound impact on our global economy in the long term, potentially adding between 2.6 and 7.9 trillion US dollars to global output each year.[2] At the same time, nearly forty percent of jobs are vulnerable to automation, with inequality likely to intensify without large-scale programs for reskilling and social protection.[3-5] Beyond economic consequences, it is important to discuss the widening spectrum of societal risks surrounding realistic deepfakes, intellectual property rights, algorithmic bias, and the spread of misinformation.[6-8] These risks raise concerns for national and individual security, as manipulated media can distort democratic processes and incite violence, while biased algorithms may entrench discrimination in employment, financial systems, or law enforcement. Moreover, there are concerns that without proper guardrails, generative AI can enable pervasive state-run surveillance, concentrate power in a few firms, or give rise to highly autonomous systems that escape human oversight.[9]

Given the scale of these risks, policymakers increasingly acknowledge that current regulatory frameworks are no longer sufficient. Designing effective rules for AI has therefore become both essential and unusually complex because the underlying technologies evolve rapidly while their harms and benefits cut across many domains.[10] As a result, courts and legislatures have begun to apply legacy doctrines, including Section 230, liability, and copyright law, to cover autonomous content creation.[11-14] However, debates persist over whether incremental regulation can keep pace or whether entirely new legal frameworks are required. Alongside these debates, governments and international bodies have introduced dedicated frameworks such as the European Union's Artificial Intelligence Act, China's Interim Measures for Generative AI Services, and the United States' AI Action Plan.[13-15,17] Additionally, international organizations such as the OECD, UNESCO, the G7, and the Council of Europe have also developed frameworks for AI regulation.[15-17] However, despite the rapid proliferation of regulatory initiatives across jurisdictions, substantial gaps remain, with current scholarly frameworks collectively addressing only about thirty-four percent of the risks identified by bodies such as NIST, the European Union, and ISO.[18] To address these gaps, scholars over the past few years have proposed a range of regulatory approaches, with some outlining their own frameworks, and others synthesizing global policies into one harmonized plan intended to capture the full spectrum of risks and opportunities presented by generative AI.[19-21] However, a clear gap in the literature remains regarding how current legal doctrine and emerging global regulation affect technological development and innovation. Thus, this paper evaluates the current state of generative AI governance by surveying research on legacy frameworks, newly developed generative AI policies,

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and empirical analyses of innovation. By reviewing these studies, this paper aims to guide future policymaking that balances innovation with safeguards, promoting further dialogue surrounding how to ensure the proper regulation of generative AI. Considering the economic promise of generative AI alongside its potential to deepen inequality and heighten security risks, it is essential to design regulations that mitigate harm without stifling progress. In the next sections, this paper will first review how foundational legal doctrines, including data protection, copyright, liability, and intermediary liability, are being reinterpreted to govern generative AI models. Then this paper will survey the statutes, regulations, and policies introduced by national governments. Finally, this paper reviews how regulations influence innovation, investment, and adoption of AI.

Discussion

1. Legacy Legal Doctrines:

Legacy legal doctrines are increasingly being applied to the challenges posed by generative AI, raising important questions about whether AI falls within the scope of these doctrines and whether they remain effective in practice. Although many of these doctrines are not AI-specific, they are still extremely influential on the trajectory of AI development and deployment, as both insufficient regulation and overregulation of these legacy doctrines could have profound consequences for innovation and individual rights.[9] This section reviews the literature surrounding how different jurisdictions are applying legacy doctrines to AI, with a primary focus on the United States and the European Union, as well as China, for areas where its framework is especially relevant, such as data protection and intellectual property. To reflect the different structures of these countries, the review will be organized by country for data protection, liability, and intermediary liability, while intellectual property will be broken down thematically, given its two distinct questions of training and authorship.

1.1. Privacy and Data Protection:

One of the most impactful and controversial issues in generative AI is how AI training interacts with privacy and data-protection laws. Generative AI models are typically trained on three types of data: (1) information that is publicly available on the internet, (2) data that the developer licenses from third parties, and (3) the data provided by human trainers or users.[22,23] Information being publicly available does not remove its status as personal data, since all major definitions of personal data in the U.S., EU, and Chinese law agree that such data remains protected.[23-25] In this section, we will be discussing how comprehensive current data-protection laws are addressing AI, focusing on the approaches of the United States, the European Union, and China. It should be noted, however, that this section focuses on overall regulatory frameworks or environments, rather than sector-specific rules, which can impose even stricter regulations in industries such as healthcare.[26]

1.1.1. United States

The United States lacks a comprehensive federal privacy and data protection law, with protections being sector and state-specific.[22,26,27] The most prominent state statute is California's CCPA, which requires businesses to inform consumers of the categories of data collected, the purposes for collection, and how that data will be managed.[22,26,27] Consumers may request information about their data, seek correction or deletion, know what information is shared and with whom it is shared, and opt out of storage, retention, or transfer of their data.[26] Although the statute does not explicitly state AI, it applies to organizations that develop or use AI trained on large consumer datasets, and recent revisions add duties to disclose appropriate uses of automated decision systems to users, to conduct risk assessments that describe safeguards to ensure appropriate use, and to refrain from processing data when privacy risks outweigh benefits to society.[22,26] At the federal level, the Federal Trade Commission (FTC) uses Section 5 to police unfair or deceptive data practices and has brought hundreds of these cases to court, though critics have argued that this policing is overreach in certain cases (e.g., *FTC v. Wyndham Worldwide*).[26] For instance, in the cases of Rite Aid and Alexa, the FTC ordered the deletion of unlawfully obtained data along with the algorithms and models built from it.[22] Across the AI lifecycle, Fair Information Practice Principles such as data minimization and purpose limitation restrict repurposing data collected for one use to train models for another without a new legal basis or a documented compatibility analysis.[22] Overall, despite opt-outs and other rights in state and sector rules, there is a large burden placed on individuals to protect their data.[22] Individuals often do not know when their data has been scraped, brokered, or repurposed for training. Moreover, because federal proposals such as the American Data Privacy Protection Act have stalled, the U.S. landscape for data-protection and privacy remains extremely fragmented, leaving AI developers to navigate overlapping state, sectoral, and federal rules without a single national standard.[22]

1.1.2. European Union's General Data Protection Regulation:

The European Union regulates privacy and data protection through the General Data Protection Regulation (GDPR), which has been applied since 2018 to harmonize national rules and strengthen individual rights.[13,22-24] The GDPR defines personal data broadly as information relating to an identified or identifiable person and gives data subjects rights regarding their personal data. For data collection, there are 6 legal bases outlined in Article 6.[23,24] Many AI providers rely on the legitimate-interests basis, which requires three conditions for processing large amounts of data: (1) a legitimate interest, (2) processing data must be necessary for that interest, and (3) that the interest is not outweighed by the rights and freedoms of the data subject.[23] Many providers' legitimate interest is commercial, which can qualify as legitimate, but even if providers prove that they have a legitimate interest, Article 5 requires that data collection be limited to only what is strictly necessary (i.e., not the entire internet), and that information gathered cannot later be repurposed for objectives beyond those originally specified at the time of collection.[23] Then, in accordance with Article 14, a provider must notify all individuals when their data is collected directly; however, due to the amount of

data collected, providers usually invoke the "disproportionate effort" exception and publish general notices.[23] In principle, if a provider could effectively and permanently anonymize the data (i.e., you cannot reconstruct the original data from the model), the trained model could fall outside of the definition of "personal data" under the GDPR.[23] In practice, however, advanced attacks (e.g., model inversion) can still reconstruct elements of the original non-anonymized training data, which makes achieving anonymization that meets the GDPR's strict standards very difficult.[23,28] Regarding data subject rights, the GDPR provides individuals the right to request access to, information about, and deletion of their data.[22-24] Despite this, those rights are very difficult to enforce because while users could request that their information be deleted from the training dataset, it would be very difficult to trace the data in question, and deletion from the dataset does not remove its imprint from the model's weights, so the information can persist and reappear in outputs.[23]

1.1.3. China:

China's privacy and data-protection policy seeks to protect individual data rights while also safeguarding national security and the public interest.[24,25] China took influence from the EU's GDPR, defining personal data mainly with two doctrines: the Personal Information Protection Law (PIPL), which defines personal data as information that is related to an identified or identifiable natural person, and the Civil Code of the People's Republic of China (CCPRC), which defines it as any information that can identify a person by itself or combined with other information.[24,25,29-31] To connect these older doctrines to the new challenges posed by AI, China passed the AI Measures, which requires high quality training data, and protection of data subjects' rights and interests during development and deployment.[25,32] The AI measures mainly function as a bridge between the older legal system and AI, acting as high-level guidance that mainly tells AI to comply with existing data-protection and privacy laws such as PIPL and CCPRC.[25,32] Similar to the EU, individuals enjoy rights such as to be informed, to give or refuse consent, to access their data, and to seek correction and erasure.[24,25] Specifically, providers must obtain consent from data subjects; explain the scope, purpose, and methods of processing; cooperate with requests to inquire about, copy, or delete data; and safeguard data against breaches.[24,25] Publicly available personal information, however, may be processed without consent within a reasonable scope.[24,25] Moreover, providers are limited to only collecting data that is essential for stated purposes and may not repurpose it for incompatible uses.[24,25] To ensure data is safe, providers are required to encrypt and de-identify data, appoint personal information protection officers, record and keep audits, and allow for external supervision by the government.[25] While there is a heavy priority on the safety of data, victims face difficulties obtaining relief for harms from data leaks due to how vague Article 69 of PIPL is on determining non-material damage.[25]

1.2. Intellectual Property:

Intellectual Property (IP) law protects an author's creative work (e.g., inventions, literary or artistic works, and designs) by granting creators exclusive rights to their works, incentivizing more innovation and creativity.[7,33-35] The introduction of generative AI challenges IP laws, as the training data for generative AI models often includes copyrighted works, and the outputs of generative AI partially contain human contributions.[7,33-35] Unlike the other legal doctrines analyzed in this paper, IP law raises two very distinct questions in the context of AI: training and authorship.[7,33-35] Thus, this section will be organized thematically around these two issues rather than by country, examining whether the use of protected works for AI training is lawful under global IP law frameworks, and whether the outputs of AI systems contain protectable human authorship and, if so, who owns them.

1.2.1. Training Data:

The central issue surrounding IP law and generative AI is whether developers are allowed to use copyrighted works to aid the training of generative AI models without permission from the rights-holder.[13,33-35] Globally, there have been varying levels of regulation and approaches. In the United States, rights-holders challenge the use of these works as unlawful, arguing that using huge numbers of copyrighted works to train models is illegal and not "fair use" because it requires making completely new copies. In response, developers argue that copying is used only to analyze patterns for training and not to replace the works themselves, so therefore it is "fair use."[33,35] Amidst these debates, the US has yet to develop a standardized framework for regulation, relying on the courts to rule on a case-by-case basis.[7,35] To do this, the courts have been relying on the four fair-use factors (purpose, nature, amount, and market effect), and have focused on whether or not the AI is a substitute for the original for its own market.[34] For instance, if the AI output could compete directly with the original work (e.g., stock photos, artwork), then it violates IP law; however, if the copies are just part of the training process and do not have the potential to substitute the originals, the justification for fair use could be stronger.[34,35] Unlike the United States, the European Union has specific legislation addressing the use of copyrighted data for training generative AI models called the "Text and Data Mining Exceptions" from the "Directive on Copyright in the Digital Single Market."[7] Under these rules, as long as the works have been obtained lawfully, developers are allowed to train models with copyrighted works without permission for research uses; however, for commercial uses, it can only occur if rights-holders have not opted out.[7] If the rights-holders have opted out, then the developers must obtain a license to use the work as training data. In China, developers have a larger duty to respect third-party IP. For instance, if copyrighted works are taken to train a model without permission, that is treated as unauthorized copying.[34] Moreover, if the model's output is close to an existing protected work, courts categorize it as a derivative work (i.e., a new work based on or adapted from the original), and require the developer to obtain a license.[34] In the *Ultraman* decision, the Guangzhou Internet

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Court ruled that because the AI-generated image resembled a copyright-protected character, it was deemed a derivative work, and therefore, the developer is expected to remove or license the character for both training and generation.[34]

1.2.2. AI-assisted Authorship:

Across major countries, copyright doctrine continues to revolve around human creativity and authorship. In the United States, fully machine-generated material is not protectable, while AI-assisted works can be protected to the extent of identifiable human creative contribution, with the disclosure of AI's role.[33,34] In the case of the AI-generated comic book *Zarya of the Dawn*, the United States Copyright Office (USCO) protected the human contributions only (e.g., text of the work, the selection, and the arrangement of the images), and required the disclosure of what was made by generative AI, which were the images in this case. In US patent law, the USCO ruled in *Thaler v. Vidal* that an inventor must be human and cannot be AI. In both the European Union and thus the U.K., since they largely follow EU copyright law, works are only recognized as original if the author makes "free and creative choices" and adds a "personal touch."[36] However, unlike the rest of the regulatory regimes, in the UK, there is an exception that allows copyright protection for purely computer-generated works (Section 178 of the UK Copyright Designs and Patents Act), where the "author" is the person making the necessary arrangements for creation; however, this exception has not yet been tested with generative AI.[36]

1.3. Tort Liability:

Tort liability is the body of law that assigns civil responsibility for injuries or harm caused by activities and products, setting the conditions under which victims are compensated and wrongdoers are held liable.[37] Generative AI complicates this framework because many systems function as complex "black boxes," making foreseeability difficult.[38] Thus, the introduction of generative AI raises questions about who should bear responsibility for harmful outputs, whether AI should be treated as a product or a service, and how to evaluate fault when systems appear to act autonomously.[37-42] This section reviews how these challenges are being addressed by existing Tort liability doctrines in the United States and the European Union.

1.3.1. United States' Liability Law:

In the United States, Tort liability is determined on a case-by-case basis, with plaintiffs typically proceeding under one of three main doctrines: negligence, product liability, or strict liability.[37] For negligence, judges evaluate whether a developer has used reasonable care to avoid foreseeable harms to people or property.[37,38,43] Specifically for AI, when deciding if the developer should be held liable, other factors such as a model's societal benefits are considered, as well as if industry standard regulations were followed and if rigorous pre-release testing occurred.[37] In defense, a developer could claim that their model was used by a third-party in an unintended way that resulted in harm.[37,44] However, this defense often does not hold up, because the harm that occurred is usually foreseeable, and thus there should have been safeguards to prevent it from happening.[37] A developer could be shielded, however, if a user substantially alters an AI model or uses it for general advice, and that advice is used for harmful practices (e.g., asking for coding advice that is later used for a cybercrime).[37] Product liability revolves around the manufacture, design, or warnings of a product.[37,42] Whether or not an AI system should be treated as a product is still debated over because software is sometimes treated as a service; however, courts are more willing to treat software embedded in physical devices (e.g., an autonomous car) or certain platform functionalities as products, and the FDA's treatment of software as a medical device supports product characterization in health care.[37,42,45] If an AI system is treated as a product, design-defect claims utilize two tests[37,42,45] First is the risk-utility test, which evaluates whether feasible safeguards or alternative designs would have reduced foreseeable risks without unduly impairing the beneficial uses of the system.[37,42,45] Second is the consumer-expectations test, which holds the developer liable if the product fails to perform as safely as an ordinary customer would expect, and thus causes harm.[37,42,45] This test offers a more specific, plaintiff-friendly path, as plaintiffs using consumer expectations do not have to prove negligence, but this test is overruled by adequate warnings from the developer.[37,42,45] However, while adequate warnings can defeat consumer-expectations claims, failure-to-warn can support the plaintiff without proof that a better warning would have changed user behavior.[37] If a developer releases a system as open-source without warning that fine-tuning can disable built-in safeguards, and a user fine-tunes it, inadvertently removing those safeguards, the developer could be held liable for the resulting harms due to a failure to warn.[37] Some developers argue that open-source systems are a distinct product category that limits design-defect exposure, but ordinary negligence analysis still applies regardless of that classification.[37] Strict liability applies when an actor engages in an abnormally dangerous or ultrahazardous activity (e.g., use of explosives) and causes harm to another person's body or property, regardless of whether the actor exercised all due care or not.[37,46] In the context of AI, it is a possibility that releasing very powerful AI systems could impose risks of a different kind and greater magnitude than seen before, and thus a court could, in principle, treat the development or release of such models as abnormally dangerous or ultrahazardous.[37,42,46] For instance, strict liability could and may apply to fully autonomous vehicles.[42] In practice, however, whether or not courts will actually apply strict liability to AI is extremely unclear.[37,42] Courts are hesitant to expand the set of activities subject to strict liability: they rarely impose strict liability on sellers or distributors rather than owners or possessors (channeling most claims into product liability), and they consider net societal value, which for AI is usually high, meaning it is unlikely to be subject to strict liability.[37,42] However, a developer could face strict liability if a powerful model escapes the developer's possession and causes widespread, catastrophic harm, even after sale or distribution.[37] Overall, there is very little precedent currently applying strict

liability to AI, so any use of this doctrine is likely to be limited and highly specific to the case.[37,42]

1.3.2. European Union's Product Liability Directive:

In the European Union, the doctrine outlining Tort Liability laws is the Product Liability Directive of 1985 (PLD), which imposes no-fault liability on the producer when a defective product causes death, personal injury, or qualifying property damage.[39,41,47] The Directive defines "producer" broadly to include the manufacturer of a finished product, the manufacturer of any component, a producer of raw materials, any person who presents itself as the product's producer, or the importer of an imported product.[41] Moreover, multiple producers can be jointly and severally liable, which is the case for many technology products.[41,47] A product is deemed "defective" if it fails to provide the safety a person is entitled reasonably to expect, assessed in light of the product's presentation (including advertising), its reasonably expected use, and the time it was put into circulation.[41,47] With the emergence of AI, many important definitions in the PLD were directly challenged. For instance, debates emerged over whether AI systems were "products" at all, since many of these systems functioned as services or hybrids, pushing harms caused by AI outside the PLD's scope.[41] In response, a revision to the PLD was proposed and passed to try to account for the new challenges posed by AI.[39,40] The revision answers these challenges by explicitly including software within the definition of a "product," specifically recognizing AI systems as products for the PLD's purposes, and treating AI system providers as manufacturers.[40] It also redefines "component," broadening the definition's scope to include any AI service that is within or related to a product.[40] Moreover, the revision addressed defectiveness in AI contexts, with judges now considering factors specifically tailored to digital systems.[40,47] These factors include the quality of instructions for installation, use, and maintenance; the effect of any ability of continued learning after deployment; the effect of other products reasonably expected to be used alongside it; compliance with safety requirements, including cybersecurity; and the specific expectations of intended users. Lastly, because AI systems are usually complex and opaque, it is often difficult for a victim to provide evidence of a defect and evidence that the defect caused the harms experienced.[39,40,47] To address this burden-of-proof asymmetry, two mechanisms were added: courts may order the disclosure of relevant evidence by the provider, and in certain circumstances, the claim that the AI is defective will be held as true, unless the provider could prove otherwise.[39,40,47] Finally, because AI products are data-dependent, continuously updated, and open-ended, providers could argue that malfunctions stemmed from defective information that influenced the AI after the initial sale. However, the revision addresses this defense: if a manufacturer still had control when defectiveness from services or updates occurred, the original manufacturer is held liable.[40]

1.4. Intermediary Liability:

Intermediary-liability rules distinguish the party that states a message from the platform that it is stated on, protecting the latter.[48] These rules were embedded in early technology policy and enabled both search engines and social media platforms to grow by shielding them from liability for potentially unlawful content posted by third-party users on their platforms.[48] However, the growth of generative AI systems has complicated these rules because generative AI produces new content in accordance with the provider's training rather than solely relaying third-party content.[49,50] As a result, there are ongoing debates about whether and how intermediary-liability frameworks apply to generative AI models. In this section, I examine two very influential frameworks at the core of these debates: Section 230 of the U.S. Communications Decency Act and the European Union's Digital Services Act.

1.4.1. Section 230 of the U.S. Communications Decency Act:

Congress adopted Section 230 in 1996 to promote a competitive online marketplace by protecting online platforms from publisher liability for content supplied by third parties.[11,51] The statute defines an "interactive computer service" (i.e., any platform that enables multiple users to access a computer server), and specifies that such a service may not be treated as the publisher or speaker of information provided by a third-party "information content provider."[49,51] On a literal interpretation, this statute could extend to generative-AI systems, which deliver online information services, accept user prompts, and return responses that might be characterized as pure transformations of user input.[11] In principle, the argument therefore could be made that the safe harbor could apply whenever an output remains sufficiently tied to the user's prompt rather than to independent creative decisions by the model. In practice, however, courts do not apply Section 230 immunity when a service creates or develops the disputed content, even in part. For example, in the cases of *Roommates.com* and Accusearch, the Ninth and Tenth Circuits ruled that even without modifying third-party content, services that contributed partially to its "development" (i.e. adding to or shaping the part of the content that gave rise to the legal claim), are considered "information content providor(s)" rather than neutral intermediaries and therefore were not entitled to Section 230 immunity.[11] This scope includes generative AI systems, since generative AI creates original text rather than merely transmitting third-party speech.[51-53] In addition, generative AI often hallucinates, generating confident but false assertions that do not originate from any third-party speaker, making the provider look less like a conduit and more like a content creator.[11,49-52] Even if it were technically possible to constrain output to be only verbatim quotes from training data, the process of generating output based on probabilities is still distinct from transmitting user-generated content.[54] Moreover, while quotes-only models may technically resemble search functions, most systems still synthesize or edit content in ways that go beyond what a neutral intermediary that simply hosts third-party content would do.[49]

1.4.2. European Union's Digital Services Act:

The applicability of the European Union's Digital Services Act (DSA) is similar to Section 230, in that generative AI is

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not an intermediary; however, the DSA is more complex and contains other regulations that can still apply to generative AI systems. The European Union adopted the DSA in 2022, providing a comprehensive framework for many types of online services that host user-generated content, aiming to tackle illegal content and protect user rights.[55] Similar to Section 230, the DSA sought to promote the growth and innovation of intermediary digital services (i.e., "mere conduit," "hosting," or "caching" services) by shielding them from legal liability for third-party content posted on their platforms.[50,55,56] In this aspect, generative-AI systems do not qualify because their content is produced by the model itself (Arcila, 2023; Novelli *et al.*, 2024).[50,56] However, unlike Section 230, the DSA goes beyond shielding intermediaries, setting responsibilities for online services that aim to strengthen user protections.[50,55,56] If a generative-AI service is used to search the internet, it can reasonably be treated as a search engine, and thus an intermediary, within the DSA framework.[50] In practice, this classification process is case-by-case, relying on how the product functions and is offered to users.[56] For example, if generative AI is embedded in a search engine service, the host service's DSA obligations apply to the embedded service as well.[56] This is the case for Bing Chat, which is integrated in Bing's search engine system and can therefore be treated either as part of the search engine, thus falling under the same regulations that Bing would fall under.[56] For these generative-AI-related search engines, once they are designated a "very large online search engine" (i.e., approximately 45 million monthly active users in the EU), they are required to conduct risk assessments annually and before launching new "high-impact" features.[55] These assessments are extremely comprehensive, covering a plethora of risks arising from the design and use of the embedded generative tool, such as the potential spread of illegal content, effects on natural rights, impacts on minors, and risks to democracy.[50,55,56] The provider must then implement effective mitigations (such as model adjustments, risk disclosures, and watermarking), undergo annual audits, and grant regulators access to data needed to evaluate both risks and mitigations.[50,55,56]

2. Emerging Global Frameworks for Generative AI:

In addition to legacy doctrines, emerging global regulatory frameworks and environments have been developed to address the unique challenges of generative AI, reflecting the growing global consensus that legacy doctrines alone are no longer sufficient to manage generative AI.[13,15] While these frameworks vary in scope and design, they share a common goal of balancing innovation with the protection of individual rights, safety, and security.[17] This section reviews the literature on emerging approaches to AI governance, focusing on the three most prominent regulatory environments, the United States, the European Union, and China, while also examining other influential frameworks that illustrate the diversity of global regulatory responses.

2.1. EU's AI Act:

The EU AI Act is the first comprehensive statute for AI in Europe, adopted to harmonize national regulation, safeguard fundamental rights and safety, and give developers a single set of binding obligations to follow.[13,15,16,57] The EU adopted a rights-based approach, with most duties falling on upstream providers that place systems on the market, while downstream users generally face lighter obligations unless they substantially modify a system, such as fine-tuning, in which case they can be treated as a new provider.[13,15,16,57] The scope of the act is deliberately broad, applying to AI systems in EU markets and to models whose outputs are used in the EU, giving the act practically global reach.[13,16,57] Structurally, the act organizes regulations by four levels of risk: unacceptable risk, high risk, limited risk, and minimal risk.[13,16,57] A narrow set of uses is banned outright if they are deemed an unacceptable risk because they threaten rights or safety, such as systems that assign people a government score to decide access to public services or algorithms that are used to manipulate and exploit vulnerabilities of individuals.[15,57] High-risk AI systems are highly regulated; however, they are not deemed so dangerous that they should be banned, such as in education, migration, employment, or law enforcement.[15,57] Limited-risk (e.g., chatbots or video generation) and Minimal-risk (e.g., video games or email-sending) systems face much lighter rules, such as informing people when they interact with AI or when content is artificially generated.[15,57] Regardless of risk level, however, any developer or provider of AI must comply with Article 4, which requires all staff and agents interacting with an AI system to have adequate AI literacy (i.e., understanding the technicalities, limitations, and regulations of AI).[13] Under the EU Act, there are specific regulations for general-purpose and generative models.[13,15,57] In accordance with Article 53, developers of general-purpose systems must give core technical information on performance, training data, and energy usage to a European regulator, the AI office within the European Commission and any downstream professional users that implement the AI system.[13] Article 53 also extends existing laws regarding data collection and copyright discussed in the previous sections onto AI systems, such as the Text and Data Mining provisions, requiring any developer whose system is used in the EU, regardless if it was trained outside the EU, to comply with these laws and requiring a detailed disclosure of training data sources.[13] Particularly powerful general-purpose systems, or systems deemed to have "systemic risk" face more oversight under Article 55 and Article 14 which require including standardized safety tests, incident reporting, appropriate cybersecurity, as well as requiring a qualified natural person to oversee the development and usage of the high-risk system.[13,57] Lastly, after the system reaches the market providers are required to create a post-market monitoring system to track user interactions and must inform the relevant Market Surveillance Authority for their country within 15 days of any malfunction.[57]

2.2. The United States Regulatory Landscape & AI Action Plan:

The United States recently passed the AI Action Plan under the Trump administration, which guides the U.S. regulatory landscape, aiming to remove regulatory barriers and reduce fragmentation, and setting three priorities: accelerating innova-

tion, building AI infrastructure, and leading internationally.[58,59] However, before reviewing the literature surrounding the AI Action Plan, it is important to first understand the current complex regulatory landscape of the U.S. for AI. Rather than a single set of binding obligations across all industries, such as the EU's AI Act, the U.S. governs AI through a decentralized, market-driven, sector-specific system.[13,60,61] However, the regulatory landscape of the United States does align with many of the principles from international initiatives such as the G7 Hiroshima Process and OECD AI Principles.[60] Moreover, unlike the EU's rights-driven approach and China's state-run model, the U.S. prioritizes innovation and development the most, minimizing state intervention and relying on existing laws, agencies, and voluntary standards.[60,61] While there have been several national policies regarding AI, such as former president Biden's Executive Order on Safe, Secure, and Trustworthy AI, which directed agencies to set safety guardrails for the development and use of AI in their respective sectors, the primary function of most federal policies has been to organize federal practice and standards, avoiding a single cross-sector framework for all private actors.[13,60] Bills that would impose cross-sector duties have been proposed but not yet enacted (e.g., the Algorithmic Accountability Act, which, if passed, would require impact assessments and disclosures to improve transparency and address bias).[60] Thus, the majority of federal regulations affecting AI result from applying existing laws within each domain. For example, the FTC has pursued unfair or deceptive AI practices and moved against AI-enabled impersonation, while the Equal Employment Opportunity Commission has pursued initiatives that enforce equality in employment decisions made by AI.[60] The U.S. also utilizes self-regulatory approaches, including voluntary commitments from major AI developers and frameworks such as NIST's AI Risk Management Framework, a nonbinding framework that provides developers with a comprehensive guide for creating and managing responsible AI systems.[60] Taken together, these elements create a vertical federal layer in which the sector regulator that already oversees important industries like healthcare, finance, transportation, or communications addresses AI uses in that domain, rather than a single horizontal authority. Historically, however, federal action has been slow due to a lack of congressional consensus, resulting in significant regulatory action by state legislatures.[62] In 2024, states proposed 700 AI-related bills, but only a fraction were enacted and, of those, most were conventional or narrow measures such as deepfake protections or the creation of state committees to study AI.[59,62] Notable exceptions to this trend were an AI-transparency bill in California that requires the disclosure of training data, and a civil-rights-based bill in Colorado that protects consumers from algorithmic discrimination.[59] This state-led landscape does have notable advantages. Regulation often responds faster than federal lawmaking, can adapt to emerging use cases, and allows for tailoring to the local priorities of each state.[62] However, at the same time, divergent statutes could create a regulatory patchwork that can increase compliance costs for firms or result in certain states passing overly burdensome regulations, potentially hurting innovation and development.[59,62] This fragmentation and the concern about hurting innovation are among the main incentives for the recent "AI Action Plan" announced by the Trump administration.[58,62,63] To achieve the aforementioned goals delineated by the AI Action Plan, federal agencies will consider a state's "AI regulatory climate" when awarding AI-related funds, examining whether state AI rules conflict with the national priorities.[58,59] These measures are purely advisory, as they guide states through funding choices but do not override any state laws.[63] If the U.S. wanted to truly enforce the priorities of the plan, it would need to pursue broad preemption, which would require Congress or clear delegated authority, but courts generally presume against preemption.[62] Both the level of enforcement and effectiveness of the AI Action Plan are extremely uncertain as details for implementation are vague due to a lack of timelines, lead agencies, or budgeting.[63] However, from this plan, the U.S. has made it clear that its priority is to accelerate AI innovation and maintain global leadership, even if that means loosening domestic guardrails (e.g., supporting broad 'fair use' claims for training data).

2.3. China:

China has one of the world's most developed AI regulatory systems, regulating AI through a sector-specific and state-driven system.[64-66] Its regulatory landscape consists of many different laws and government agencies enforcing them for their respective sector.[64-66] This section will go over the main policies passed over the years, both nationwide and application-specific, as well as explaining how China enforces these laws. The foundation of the regulatory landscape is the New Generation AI Development Plan passed in 2017, which sets a three-phase roadmap until 2030 for AI development and global leadership, while also appointing "national champions" (i.e. specific companies tasked to lead the development of AI in their industry), such as Baidu for autonomous driving, Alibaba for smart cities, and Tencent for medical AI.[64-66] In 2021, China passed the Algorithmic Recommendation Provisions, which introduced the world's first algorithm registry that required companies to disclose information about each algorithm used in their services.[65,66] For example, a single application might have to disclose information for its AI personalized recommendation algorithm and for its AI content filtration algorithm. In 2022, the Provisions on the Administration of Deep Synthesis Internet Information Services were passed, mandating that AI-generated images and videos must be labeled and requiring companies that offer deepfake tools to register algorithms and provide security assessments on their systems.[63,64] In addition to these provisions, to regulate systems that are accessible to the general public, such as chatbots, text-to-image tools for the public, and video generators, China passed the Interim Measures for the Management of Generative AI Services.[65] These measures cover a large portion of AI regulation, mainly updating definitions of existing law and acting as a bridge between legacy doctrines (e.g., IP infringement, data security/collection, and privacy) and AI.[32,65] However, the scope of these measures is restricted to only publicly available systems and excludes systems used privately for research or enterprises.[32,65] These publicly accessible systems must set up a complaint channel

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for users that regulators can use for investigations, undergo a security self-assessment (i.e., disclosing how an algorithm was trained, which datasets it used, what functions it performs), and register their algorithms under the Cyberspace Administration of China (CAC).[32,65] The CAC is one of seven ministries or administrations that enforce the laws that regulate AI. Ministries such as the Ministry of Industry and Information Technology, the Ministry of Public Security, and others coordinate enforcement in their respective domains.[65]

2.4. Other Global Actors:

Alongside the developments of complex regulatory environments in the U.S. and EU, other countries have developed very similar, but not as comprehensive, regulatory frameworks for generative AI.[13,60]

2.4.1. United Kingdom:

The U.K. does not have a single AI Act that regulates all industries; instead, under the White Paper's "pro-innovation approach to AI," it governs generative AI through a sector-specific approach guided by 5 principles that heavily align with the OECD's principles of safety, transparency, fairness, accountability, and contestation.[13,16,67] While the core definition of AI remains the same throughout all industries, how that definition gets applied will differ depending on the domain.[16,67] Moreover, the White Paper puts legal responsibility on the people or organizations in the AI supply chain who are actually in the best position to manage the risk.[16,67] For instance, developers of a model may be required to handle risks related to training data, while the company integrating the AI would be held liable for the impact on end users.

2.4.2. India:

India's approach to generative AI focuses on soft law and standards rather than binding regulation.[3,15] For instance, NITI Aayog, India's prominent policy think tank, played a big role in developing the National Strategy for AI, which aims to align AI development to AI's needs in industries such as healthcare, agriculture, and education, as well as releasing the Responsible AI documents of 2021, which provide both ethical and operational guidance.[3,60] Furthermore, the Ministry of Electronics and Information Technology led implementation programs such as "India AI," which aim to promote innovation and guide workforce deployment.[15] This regulatory environment reflects India's strategy of fostering innovation while adopting safeguards that align with the best international standards.[3,15]

2.4.3. Brazil:

Brazil is advancing a comprehensive framework through Bill No. 2,338/2023, which has passed the Senate and awaits review in the Chamber of Deputies, and attempts to balance innovation with individual rights.[13,68] The bill adopts a risk-based approach modeled after the EU's AI Act. It bans "excessive-risk" applications outright and imposes obligations on high-risk systems, including algorithmic impact assessments, required human oversight, and protections against algorithmic discrimination.[13,68] Generative AI is included within the scope, especially when used in consequential settings such as finance or employment.[13,68]

3. Innovation & Adoption:

In addition to regulation, a central question is how regulation affects the innovation and adoption of generative AI. Because these systems are extremely economically significant, as well as potentially dangerous to society, any policy that regulates AI must balance safeguards with incentives to sustain adoption and promote innovation. Thus, this section will analyze the two most prominent regulatory trends shaping AI governance globally: centralized risk-based frameworks and fragmented decentralized approaches. This section will examine how both regulatory systems pose challenges to sustained innovation despite their differences. Centralized, risk-based regulatory frameworks impose substantial direct costs on innovation through compliance burdens and restrictive constraints. Under the EU's AI Act, compliance is projected to increase operational overhead by about 17 percent and reduce the productivity gains of AI technologies by nearly 30 percent due to strict data-protection laws, with small and medium enterprises disproportionately affected.[69,70] For high-risk AI systems (e.g., those used in medical devices, credit scoring, or educational assessment), a small business with €10 million in turnover could lose 40 percent of its profits due to the EU AI Act.[69] Across the EU, these compliance burdens are projected to reduce AI investments by almost 20 percent.[69] This can also be seen in the United States, where more stringent, risk-based AI regulation (e.g., Colorado's) could reduce the probability of startup fundraising by 2-3 percent annually.[71] This trend of stringent regulation hurting innovation and adoption is not isolated to the EU and U.S. When China allowed AI firms access to government "data-rich" contracts (effectively the opposite of restricting data access through privacy regulation), they were able to build about 20 percent more commercial products and nearly 50 percent more government-facing products within 3 years.[72] Overall, this regulatory environment has constrained European AI development. Over the past two decades, the European Union has produced only three notable AI models compared to the United States' forty and China's fifteen notable models.[73] On adoption, European organizations lag behind their U.S. counterparts by 45 to 70 percent in both AI spending and implementation of technologies.[74]

However, the issue of compliance is not solved in the fragmented system of the US. States have proposed over 700 AI-related bills, and the differing requirements can create substantial complexity for firms operating nationally.[59,62] For example, the varying state privacy laws could impose $98-112 billion annually in out-of-state compliance costs.[75] Colorado's AI Act alone imposes penalties up to $20,000 per violation, exemplifying the escalating compliance burden.[76] For example, a firm adopting AI would have to comply with conflicting standards (e.g., California's data transparency requirements, New York's bias audit mandates, and Colorado's algorithmic discrimination protections) simultaneously.[77] Overall, these compliance costs disproportionately burden smaller firms lacking resources, with one-quarter of small businesses not using

AI citing concerns relating to compliance costs as the main reason for not adopting AI.[76] In this light, the approach of overarching regulation could provide mechanisms that support innovation, as the harmonization of standards under the AI Act and Brazil's Bill 2,338/2023 reduces the negative effects that the U.S. patchwork of state and sector regulations results in, streamlining processes by reducing compliance uncertainty.[17,78] This would be highly beneficial to innovation, as compliance uncertainty is often seen as one of the primary barriers to innovation, especially to smaller firms, as it results in them devoting a higher cost to trying to figure out the convoluted regulations of multiple states or sectors.[78] Ultimately, due to the robust nature of generative AI, it is difficult to attribute the discrepancies between the EU's and the US's AI development solely to regulatory choices. In this section, we have analyzed two prominent regulatory environments and their effects on innovation. Clearly, many countries are trending toward one of two options: either fragmented decentralized regulation or an overarching risk-based framework. While the choice of regulatory approach influences adoption and innovation, factors such as a culture more open to risk-taking (on the entrepreneurial and investor side), greater access to diverse global talent, and the advantage of a large unified home market play an equally or more important role in shaping innovation and adoption.[79]

Conclusion

This paper has examined the governance of generative AI through legacy doctrines, national regulatory environments, and the effect of regulation on innovation. Within legacy doctrines, comparative analysis was essential to identify three fundamental challenges that persist: (1) protecting privacy in the training and outcomes of AI systems, (2) determining whether AI can or should be treated as a legal or creative entity capable of holding rights or responsibilities, and (3) addressing how the autonomy of AI systems complicates the attribution of intention and decision-making in areas such as authorship and liability. Across all three challenges, it is increasingly evident that current frameworks being applied are not up to date on the technical challenges of AI, such as the persistence of data in model parameters and the opacity of the decision-making process of AI systems. While some existing frameworks have been updated or revised to address AI directly (e.g., the EU's reform of the Product Liability Directive), in most cases, adoption has been left to courts to decide on a case-by-case basis, such as the U.S. fair use disputes in copyright, resulting in an inconsistent and inadequate response to an ever-growing challenge.[37,40]

Countries have also begun to develop national frameworks and regulatory environments to specifically address the new challenges posed by AI.[13,15] These emerging national regulations fall into four main approaches: (1) risk-based approach, such as the EU AI Act and Brazil's Bill 2,338/2023; (2) innovation-first systems, such as in the U.S. which rely on sectoral agencies; (3) state-directed systems like China's regulatory environment; (4) and voluntary or soft-law approaches in India and the U.K., which emphasize guidelines over binding rules. Although these approaches share common elements, such as prohibiting unacceptable uses, requiring some level of transparency, and trying to protect individual rights, through comparative analysis, it is evident that the regulation of AI is too fragmented. Attempting to harmonize the approaches reviewed in this paper would be highly beneficial, as harmonization could provide global consistency, establish universal ethical standards, address transnational challenges, and allow for enhanced public trust and global cooperation.[17] Nevertheless, this study has limitations. Its reliance on comparative legal analysis constrains its ability to evaluate the real-world impact of these frameworks on innovation. Moreover, the relative novelty of generative AI means that robust empirical data remains limited, making it difficult to measure how specific regulatory approaches affect innovation, startup formation, and investment. Future research should therefore focus on developing empirical methods to assess these impacts and explore how regulation can ensure accountability and protection of human rights without impeding technological progress.

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References

1. Takale, D.; Mahalle, P.; Sule, B. (PDF) Advancements and Applications of Generative Artificial Intelligence. *J. Inf. Technol. Sci.* **2024**, *10* (1).
2. Chui, M.; Hazan, E.; Roberts, R.; Singla, A.; Smaje, K.; Sukharevsky, A.; Yee, L.; Zemmel, R. The Economic Potential of Generative AI. The next Productivity Frontier. **2023**.
3. Joshi, S. Generative AI: Mitigating Workforce and Economic Disruptions While Strategizing Policy Responses for Governments and Companies. Social Science Research Network: Rochester, NY, February 12, 2025. https://doi.org/10.2139/ssrn.5135229.
4. Salari, N.; Beiromvand, M.; Hosseinian-Far, A.; Habibi, J.; Babajani, F.; Mohammadi, M. Impacts of Generative Artificial Intelligence on the Future of the Labor Market: A Systematic Review. *Comput. Hum. Behav. Rep*. **2025**, *18*, 100652. https://doi.org/10.1016/j.chbr.2025.100652.
5. Oder, N.; Béland, D. Artificial Intelligence, Emotional Labor, and the Quest for Sociological and Political Imagination among Low-Skilled Workers. *Policy Soc.* **2025**, *44* (1), 116–128. https://doi.org/10.1093/polsoc/puae034.
6. Babaei, R.; Cheng, S.; Duan, R.; Zhao, S. Generative Artificial Intelligence and the Evolving Challenge of Deepfake Detection: A Systematic Analysis. *J. Sens. Actuator Netw*. **2025**, *14* (1), 17. https://doi.org/10.3390/jsan14010017.
7. Chesterman, S. Good Models Borrow, Great Models Steal: Intellectual Property Rights and Generative AI. *Policy Soc*. **2024**, *44* (1), 23–37. https://doi.org/10.1093/polsoc/puae006.
8. Jaidka, K.; Chen, T.; Chesterman, S.; Hsu, W. *Misinformation, Disinformation, and Generative AI: Implications for Perception and Policy | Digital Government: Research and Practice*. https://dl.acm.org/doi/10.1145/3689372 (accessed 2025-07-30).

DOI: 10.36838/IJHSR811.228

9. Judge, B.; Nitzberg, M.; Russell, S. When Code Isn't Law: Rethinking Regulation for Artificial Intelligence. *Policy Soc*. **2025**, *44* (1), 85–97. https://doi.org/10.1093/polsoc/puae020.
10. Zaidan, E.; Ibrahim, I. A. AI Governance in a Complex and Rapidly Changing Regulatory Landscape: A Global Perspective. *Humanit. Soc. Sci. Commun*. **2024**, 11 (1), 1121. https://doi.org/10.1057/s41599-024-03560-x.
11. Ryan, G. Generative AI Will Break the Internet: Beyond Section 230. Social Science Research Network: Rochester, NY, May 10, 2024. https://doi.org/10.2139/ssrn.5337202.
12. Buiten, M.; de Streel, A.; Peitz, M. The Law and Economics of AI Liability. *Comput. Law Secur. Rev*. **2023**, *48*, 105794. https://doi.org/10.1016/j.clsr.2023.105794.
13. Hacker, P.; Engel, A.; Hammer, S.; Mittelstadt, B. Introduction to the Foundations and Regulation of Generative AI. Social Science Research Network: Rochester, NY, February 14, 2025. https://doi.org/10.2139/ssrn.5137750.
14. Atkinson, D.; Morrison, J. A Legal Risk Taxonomy for Generative Artificial Intelligence. arXiv May 23, 2024. https://doi.org/10.48550/arXiv.2404.09479.
15. Davtyan, T. An Overview of Global Efforts Towards AI Regulation. *Bull. Yerevan Univ. C Jurisprud*. **2024**, *15* (2 (41)), 158–174. https://doi.org/10.46991/BYSU.C/2024.15.2.158.
16. Cole, M. *AI Regulation and Governance on a Global Scale: An Overview of International, Regional and National Instruments*. https://doi.org/10.21552/aire/2024/1/16.
17. Kashefi, P.; Kashefi, Y.; Ghafouri Mirsaraei, A. Shaping the Future of AI: Balancing Innovation and Ethics in Global Regulation. *Unif. Law Rev*. **2024**, *29* (3), 524–548. https://doi.org/10.1093/ulr/unae040.
18. Raza, S.; Qureshi, R.; Zahid, A.; Fioresi, J.; Sadak, F.; Saeed, M.; Sapkota, R.; Jain, A.; Zafar, A.; Hassan, M. U.; Zafar, A.; Maqbool, H.; Vayani, A.; Wu, J.; Shoman, M. Who Is Responsible? The Data, Models, Users, or Regulations? A Comprehensive Survey on Responsible Generative AI for a Sustainable Future. arXiv April 28, 2025. https://doi.org/10.48550/arXiv.2502.08650.
19. Taeihagh, A. Governance of Generative AI. *Policy Soc*. **2025**, *44* (1), 1–22. https://doi.org/10.1093/polsoc/puaf001.
20. Janssen, M. Responsible Governance of Generative AI: Conceptualizing GenAI as Complex Adaptive Systems. *Policy Soc*. **2025**, *44* (1), 38–51. https://doi.org/10.1093/polsoc/puae040.
21. Luna, J.; Tan, I.; Xie, X.; Jiang, L. Navigating Governance Paradigms: A Cross-Regional Comparative Study of Generative AI Governance Processes & Principles. Proc. AAAIACM Conf. *AI Ethics Soc*. **2024**, *7* (1), 917–931. https://doi.org/10.1609/aies.v7i1.31692.
22. King, J.; Meinhardt, C. *Rethinking Privacy in the AI Era: Policy Provocations for a Data-Centric World | Stanford HAI*. https://hai.stanford.edu/policy/white-paper-rethinking-privacy-ai-era-policy-provocations-data-centric-world (accessed 2025-09-04).
23. Ruschemeier, H. Generative AI and Data Protection. *Camb. Forum AI Law Gov*. **2025**, *1*, e6. https://doi.org/10.1017/cfl.2024.2.
24. de Jonge, A. Data Privacy in China and Europe: Individual, Collective, Subjective, and Objective Perspectives. *Int. J. Law Inf. Technol*. **2024**, *32*, eaae025. https://doi.org/10.1093/ijlit/eaae025.
25. Ye, X.; Yan, Y.; Li, J.; Jiang, B. Privacy and Personal Data Risk Governance for Generative Artificial Intelligence: A Chinese Perspective. *Telecommun. Policy* **2024**, *48* (10), 102851. https://doi.org/10.1016/j.telpol.2024.102851.
26. Arokun, E. Complexities of AI Trends: Threats to Data Privacy Legal Compliance. Social Science Research Network: Rochester, NY, May 6, 2024. https://doi.org/10.2139/ssrn.4943466.
27. Haile, A.; Ashraf, M. *(PDF) Data Protection and AI: Navigating Regulatory Compliance in AI- Driven Systems*. ResearchGate. https://doi.org/10.13140/RG.2.2.13639.92328.
28. Qiu, Y.; Yu, H.; Fang, H.; Zhuang, T.; Yu, W.; Chen, B.; Wang, X.; Xia, S.-T.; Xu, K. MIBench: A Comprehensive Framework for Benchmarking Model Inversion Attack and Defense. arXiv March 10, 2025. https://doi.org/10.48550/arXiv.2410.05159.
29. Calzada, I. Citizens' Data Privacy in China: The State of the Art of the Personal Information Protection Law (PIPL). Social Science Research Network: Rochester, N, Y September 8, 2022. https://papers.ssrn.com/abstract=4214011 (accessed 2025-09-04).
30. Shao, G.; Huang, Q.; Xiang, Q.; Peng, C. Assessing the Implementation of China's Personal Information Protection Law: A Two-Year Review. *Int. Data Priv. Law* **2025**, *15* (1), 18–31. https://doi.org/10.1093/idpl/ipae022.
31. Gao, R. Y. Personal Information Protection Under Chinese Civil Code: A Newly Established Private Right in the Digital Era. Social Science Research Network: Rochester, NY 2020. https://papers.ssrn.com/abstract=3934721 (accessed 2025-09-04).
32. Zou, M.; Zhang, L. Navigating China's Regulatory Approach to Generative Artificial Intelligence and Large Language Models. Camb. *Forum AI Law Gov*. **2025**, *1*, e8. https://doi.org/10.1017/cfl.2024.4.
33. Poland, C. M. Generative AI and US Intellectual Property Law. arXiv November 27, 2023. https://doi.org/10.48550/arXiv.2311.16023.
34. Okoro, D. C. An Intellectual Property Approach to the Use of Generative AI. *World J. Innov. Mod. Technol*. **2025**, *9* (4), 97–116.
35. Oladele, O. K. *(PDF) Generative AI and Intellectual Property: Ownership, Copyright, and Creative Rights*. ResearchGate. https://www.researchgate.net/publication/390033354_Generative_AI_and_Intellectual_Property_Ownership_Copyright_and_Creative_Rights (accessed 2025-09-04).
36. Mammen, C.; Collyer, M.; Dolin, R. A.; Gangjee, D. S.; Melham, T.; Mustaklem, M.; Sundaralingam, P.; Wang, V. Creativity, Artificial Intelligence, and the Requirement of Human Authors and Inventors in Copyright and Patent Law. Social Science Research Network: Rochester, NY, July 5, 2024. https://doi.org/10.2139/ssrn.4892973.
37. Ramakrishnan, K.; Smith, G.; Downey, C. *U.S. Tort Liability for Large-Scale Artificial Intelligence Damages: A Primer for Developers and Policymakers*; 2024. https://www.rand.org/pubs/research_reports/RRA3084-1.html (accessed 2025-08-27).
38. Lior, A. *Holding AI Accountable: Addressing AI-Related Harms Through Existing Tort Doctrines | The University of Chicago Law Review*. https://lawreview.uchicago.edu/online-archive/holding-ai-accountable-addressing-ai-related-harms-through-existing-tort-doctrines (accessed 2025-08-27).
39. Noto La Diega, G.; Bezerra, L. C. T. Can There Be Responsible AI without AI Liability? Incentivizing Generative AI Safety through Ex-Post Tort Liability under the EU AI Liability Directive. *Int. J. Law Inf. Technol*. **2024**, *32*, eaae021. https://doi.org/10.1093/ijlit/eaae021.
40. Rodríguez de las Heras Ballell, T. The Revision of the Product Liability Directive: A Key Piece in the Artificial Intelligence Liability Puzzle. *ERA Forum* **2023**, *24* (2), 247–259. https://doi.org/10.1007/s12027-023-00751-y.
41. Cabral, T. S. Liability and Artificial Intelligence in the EU: Assessing the Adequacy of the Current Product Liability Directive. *Maastricht J. Eur. Comp. Law* **2020**, *27* (5), 615–635. https://doi.org/10.1177/1023263X20948689.

42. Herbosch, M. Liability for AI Agents. Social Science Research Network: Rochester, NY April 28, 2025. https://doi.org/10.2139/ssrn.5236649.
43. Selbst, A. D. Negligence and AI's Human Users. Social Science Research Network: Rochester, NY, March 11, 2019. https://papers.ssrn.com/abstract=3350508 (accessed 2025-09-04).
44. Fraser, H. L.; Suzor, N. Locating Fault for AI Harms: A Systems Theory of Foreseeability, Reasonable Care and Causal Responsibility in the AI Value Chain. Social Science Research Network: Rochester, NY April 26, 2024. https://doi.org/10.2139/ssrn.5190797.
45. Chagal-Feferkorn, K. Am I an Algorithm or a Product? When Products Liability Should Apply to Algorithmic Decision-Makers. Social Science Research Network: Rochester, NY August 14, 2018. https://papers.ssrn.com/abstract=3241200 (accessed 2025-09-04).
46. Henson, R. "I Am Become Death, the Destroyer of Worlds": Applying Strict Liability to Artificial Intelligence as an Abnormally Dangerous Activity. Social Science Research Network: Rochester, N, Y July 15, 2024. https://doi.org/10.2139/ssrn.4894986.
47. Karanikić Mirić, M. Product Liability Reform in the EU. Social Science Research Network: Rochester, NY, November 7, 2023. https://papers.ssrn.com/abstract=4626103 (accessed 2025-09-04).
48. Grimmelmann, J.; Zhang, P. An Economic Model of Intermediary Liability. Social Science Research Network: Rochester, NY April 19, 2023. https://papers.ssrn.com/abstract=4422819 (accessed 2025-08-11).
49. Lemley, M. A.; Henderson, P.; Hashimoto, T. Where's the Liability in Harmful AI Speech? Social Science Research Network: Rochester, NY, August 3, 2023. https://doi.org/10.2139/ssrn.4531029.
50. Arcila, B. Is It a Platform? Is It a Search Engine? It's Chat GPT! The European Liability Regime for Large Language Models. Social Science Research Network: Rochester, NY August 12, 2023. https://papers.ssrn.com/abstract=4539452 (accessed 2025-08-12).
51. Ariyaratne, H. ChatGPT and Intermediary Liability: Why Section 230 Does Not and Should Not Protect Generative Algorithms. Social Science Research Network: Rochester, NY, May 16, 2023. https://doi.org/10.2139/ssrn.4422583.
52. Volokh, E. Large Libel Models? Liability for AI Output. Social Science Research Network: Rochester, NY August 19, 2023. https://papers.ssrn.com/abstract=4546063. (accessed 2025-08-11).
53. Davidson, J.; Buttrick, H. *(PDF) SAY WHAT?! When ChatGPT Gets it Wrong: EXAMINING GENERATIVE AI, SECTION 230 OF THE COMMUNICATIONS DECENCY ACT, AND THE ESSENCE OF CREATIVITY*. ResearchGate. https://www.researchgate.net/publication/376953148_SAY_WHAT_When_ChatGPT_Gets_it_Wrong_EXAMINING_GENERATIVE_AI_SECTION_230_OF_THE_COMMUNICATIONS_DECENCY_ACT_AND_THE_ESSENCE_OF_CREATIVITY (accessed 2025-09-04).
54. Cheong, I.; Caliskan, A.; Kohno, T. Safeguarding Human Values: Rethinking US Law for Generative AI's Societal Impacts. *AI Ethics* **2025**, *5* (2), 1433–1459. https://doi.org/10.1007/s43681-024-00451-4.
55. Wilman, F. The Digital Services Act (DSA) - An Overview. Social Science Research Network: Rochester, NY December 16, 2022. https://doi.org/10.2139/ssrn.4304586.
56. Novelli, C.; Casolari, F.; Hacker, P.; Spedicato, G.; Floridi, L. Generative AI in EU Law: Liability, Privacy, Intellectual Property, and Cybersecurity. Computer Law & Security Review 2024, 55, 106066. https://doi.org/10.1016/j.clsr.2024.106066.
57. Edwards, L. The EU AI Act: A Summary of Its Significance and Scope, 2022. https://www.adalovelaceinstitute.org/wp-content/uploads/2022/04/Expert-explainer-The-EU-AI-Act-11-April-2022.pdf (accessed 2025-09-08).
58. Schildkraut, P.; Curtis, D.; Choi, E.; Magnani, T.; Lee, R.; Annatoyn, T.; Rhea, S.-M.; Magnani, T. *America's AI Action Plan: What Full Steam Ahead Means for Your Company | Advisories.* Arnold & Porter. https://www.arnoldporter.com/en/perspectives/advisories/2025/07/americas-ai-action-plan (accessed 2025-09-06).
59. Ball, D. W. *The Coming Year of AI Regulation in the States | TechPolicy.Press.* Tech Policy Press. https://techpolicy.press/the-coming-year-of-ai-regulation-in-the-states (accessed 2025-09-06).
60. Davtyan, T. The U.S. Approach to AI Regulation: Federal Laws, Policies, and Strategies Explained. *J. Law Technol. Internet* **2025**, *16* (2), 223.
61. Roberts, H.; Cowls, J.; Hine, E.; Mazzi, F.; Tsamados, A.; Taddeo, M.; Floridi, L. Achieving a 'Good AI Society': Comparing the Aims and Progress of the EU and the US. *Sci. Eng. Ethics* **2021**, *27* (6), 68. https://doi.org/10.1007/s11948-021-00340-7.
62. Novelli, C.; Gaur, A.; Floridi, L. Two Futures of AI Regulation under the Trump Administration. Social Science Research Network: Rochester, NY, March 31, 2025. https://doi.org/10.2139/ssrn.5198926.
63. Meinhardt, C.; Zhang, D.; King, J.; Haupt, A.; Cryst, E. *Inside Trump's Ambitious AI Action Plan | Stanford HAI*. https://hai.stanford.edu/news/inside-trumps-ambitious-ai-action-plan (accessed 2025-09-06).
64. Roberts, H.; Cowls, J.; Morley, J.; Taddeo, M.; Wang, V.; Floridi, L. The Chinese Approach to Artificial Intelligence: An Analysis of Policy, Ethics, and Regulation. Social Science Research Network: Rochester, NY, September 1, 2019. https://doi.org/10.2139/ssrn.3469784.
65. Zhang, A. H. The Promise and Perils of China's Regulation of Artificial Intelligence. Social Science Research Network: Rochester, NY January 28, 2024. https://doi.org/10.2139/ssrn.4708676.
66. Sheehan, M. China's AI Regulations and How They Get Made. *Horiz. J. Int. Relat. Sustain. Dev*. **2023**, No. 24, 108–125.
67. Gikay, A. A. Risks, Innovation, and Adaptability in the UK's Incrementalism versus the European Union's Comprehensive Artificial Intelligence Regulation. *Int. J. Law Inf. Technol.* **2024**, *32*, eaae013. https://doi.org/10.1093/ijlit/eaae013.
68. Ziosi, M.; Hwu, R.; Guedes, P.; Freiman, O.; Yeo, H. *A Comparative Framework for AI Regulatory Policy: Phase* 2; 2024. https://ceimia.org/wp-content/uploads/2024/06/a-comparative-framework-for-ai-regulatory-policy_-phase-2-report.pdf.
69. Mueller, B. How Much Will the Artificial Intelligence Act Cost Europe?, 2021. https://www2.datainnovation.org/2021-aia-costs.pdf.
70. Misch, F.; Sher, G.; Park, B.; Pizzinelli, C. *AI and Productivity in Europe*. IMF. https://www.imf.org/en/Publications/WP/Issues/2025/04/04/AI-and-Productivity-in-Europe-565924 (accessed 2025-09-08).
71. Mulla, J. AI Regulation and Entrepreneurship. Social Science Research Network: Rochester, NY, October 11, 2024. https://doi.org/10.2139/ssrn.4986041.
72. Beraja, M.; Yang, D. Y.; Yuchtman, N. Data-Intensive Innovation and the State: Evidence from AI Firms in China. *Rev. Econ. Stud.* **2023**, *90* (4), 1701–1723. https://doi.org/10.1093/restud/rdac056.
73. Maslej, N.; Fattorini, L.; Cortez, E. K.; Lotufo, J. B.; Reuel, A.; Rome, A.; Salatino, A.; Santarlasci, L.; Brynjolfsson, E.; Clark, J.; Etchemendy, J.; Ligett, K.; Lyons, T.; Chase, Jpm.; Manyika, J.; Niebles, J. C.; Parli, V.; Shoham, Y.; Wald, R.; Capstick, E.; Kariuki, N.; Glismann, M. van D.; Hamrah, A.; Oak, S.; Paintsil, N. F.; Shi, A. Artificial Intelligence Index Report 2025 Policy Highlights. Stanford University Human-Centered Artificial Intelligence 2025.

DOI: 10.36838/IJHSR811.228

74. Sukharevsky, A.; Hazan, E.; Smit, S.; Dagorret, G.; Mischke, J.; Hieronimus, S.; de Jong, M.; de la Chevasnerie, M.-A. AI in Europe: A new opportunity for growth | McKinsey. https://www.mckinsey.com/capabilities/quantumblack/our-insights/time-to-place-our-bets-europes-ai-opportunity (accessed 2025-11-07).
75. Castro, D.; Diebold, G.; Dascoli, L. The Looming Cost of a Patchwork of State Privacy Laws; 2022. https://itif.org/publications/2022/01/24/looming-cost-patchwork-state-privacy-laws/ (accessed 2025-11-07).
76. Stevens, M. State of Confusion: How a Patchwork of AI Laws Hurts Small Businesses and U.S. Competitiveness. ACT | The App Association. https://actonline.org/2025/10/10/state-of-confusion-how-a-patchwork-of-ai-laws-hurts-small-businesses-and-u-s-competitiveness/ (accessed 2025-11-07).
77. Shields, T. The AI Regulation Nightmare: Why State-by-State Rules are Crushing Your Business Innovation. Kelley Kronenberg. https://www.kelleykronenberg.com/blog/the-ai-regulation-nightmare-why-state-by-state-rules-are-crushing-your-business-innovation/ (accessed 2025-11-07).
78. Wu, W.; Liu, S. Compliance Costs of AI Technology Commercialization: A Field Deployment Perspective. arXiv January 31, 2023. https://doi.org/10.48550/arXiv.2301.13454.
79. Bradford, A. The False Choice Between Digital Regulation and Innovation. Social Science Research Network: Rochester, NY, March 7, 2024. https://doi.org/10.2139/ssrn.4753107.

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REVIEW ARTICLE

A Review of the Biomechanics of ACL Injuries in Ballet, Bharatanatyam, and Modern Dance

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ABSTRACT: Anterior cruciate ligament (ACL) injuries are a significant concern in various physical activities, particularly for dancers. The forces placed on the knee during dance put dancers at a high risk for knee-related injuries. Developing injury-reduction strategies that can be readily incorporated into an existing dance training program is highly desirable but challenging. It requires understanding the biomechanics of dance movements and their relationship to knee anatomy. In addition, newly developed strategies need to allow dancers the freedom to maintain essential aspects of their current training regimens. In this review, we use a combination of biomechanical research and anatomical understanding to elucidate how forces incurred during dance affect the knee joint. We also discuss how dancers can optimize their training to reduce incidents of ACL injuries. For this study, ballet, Bharatanatyam, and modern dance were chosen as representative styles. We review the available literature, analyze relevant data, and present strategies that dancers can use to reduce the risk of ACL injury.

KEYWORDS: Biomedical Engineering, Biomechanics, Injury Prevention, ACL, Dance EMG.

Introduction

Dancing, like many sports, is associated with various types of injuries, and more often, lower limb injuries. [1-6] The prevalence of sudden changes in direction, deep knee flexion, and high-impact landings in dance makes knee injuries a particularly common type of injury for dancers. In fact, among all types of injuries sustained by dancers, knee injuries typically account for 14-20%, and within those knee injuries, tearing of the anterior cruciate ligament (ACL) is particularly common.[7] For example, in a study monitoring classical dancers over 10 years, the risk of rupturing the left ACL was approximately 7%. [8] An ACL injury can have severe consequences for a dancer's career. ACL injuries in dancers have most likely been studied less than in athletes because dance is often viewed as an art form rather than a sport, leading to fewer biomechanical studies within this population. Additionally, standardized performance conditions and injury reporting systems, which are common in sports, are often lacking in dance. ACL tears typically require surgery and a lengthy rehabilitation period post-surgery.[9] Moreover, even after recovery, many people exhibit a reduced range of motion and a higher risk of re-injury. Despite these commonalities among all ACL injuries, two features specific to dance make ACL injuries particularly intriguing. First, in most sports, the incidence of ACL tears in women is significantly higher than that occurring in men. However, this gender disparity of ACL injuries does not seem to hold for dancers.[10] seconds, the risk of an ACL injury in dance depends on a complex interplay of intrinsic and extrinsic factors that are often difficult to distinguish. For example, the type of flooring, footwear, and variable training loads are examples of extrinsic factors that can often affect the propensity for injury.[8]

The collection of biomechanical data in dancers can be used to identify muscle fatigue, muscle imbalances, or inefficient activation patterns that may contribute to injury. A large body of literature exists that reports biomechanical data on dancers. However, little focus is placed on how dancers can use that data. These limitations have prompted us to review existing biomechanical data on dancers and their training to identify methods for reducing injury risk. In particular, we examine ACL injuries in dancers through the lens of five common movement culprits: knee valgus, lack of lower limb strength, hip immobility, and faulty landing mechanics. We hope dancers can use this information to adjust their training programs in ways that improve strength, flexibility, and coordination– ultimately enhancing performance while minimizing the likelihood of injury.

Discussion

Methodology:

A comprehensive literature search was conducted to identify studies on ACL injuries in dancers. Databases including PubMed and Scopus were systematically searched using the following keywords: "ACL injury", "dance", "modern dance", "ballet", "bharatantyam", "biomechanics", "training", and "prevention". The choice of papers included in our review was limited to peer-reviewed articles published in English. Additionally, we aimed to review studies that had at least 15 participants, when applicable. For this study, ballet, Bharatanatyam, and modern dance were chosen because of the availability of biomechanical data in each style. For instance, we have found a large body of literature comparing the prevalence of ACL injuries in ballet and modern dance, in addition to the large amount of data found in each dance style individually. Moreover, to demonstrate the generality of our analysis, a well-established and traditional dance style, Bharatanatyam, was selected. Although Bharatanatyam is a dance that dates back centuries and changes to the dance style itself are not plausible, we show that it can

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benefit from additions to the training program. Finally, whenever data for a specific dance style was unavailable, we chose to use biomechanical data for other non-contact ACL injuries and drew conclusions based on what was found.

Knee Anatomy:

ACL injuries are among the most common injuries impacting the knee, often resulting from movements such as pivoting or landing from a jump. The ACL plays a large part in controlling the forward motion of the tibia relative to the femur, preventing excessive rotation of the knee.[11] When the ACL is injured, either by tear or rupture, the stability of the knee is compromised, leading to pain, swelling, and instability of the joint. This can lead to further injuries, including tears of the menisci and increased wear on the cartilage structures. Treatment often includes surgery followed by extensive rehabilitation. However, even with treatment, returning to physical activities can be extremely difficult, often taking between six and nine months to fully heal. Therefore, taking preventative measures is crucial in protecting the knee for any athlete.[12]

The knee is a compound joint that connects the three bones: the femur (thigh bone), tibia (shin bone), and the patella (kneecap), as shown in Figure 1. Because of its geometric complexity, the nature of forces that can be incurred on the knee can be very complicated. The knee consists of three main joints: the tibiofemoral joint (between the tibia and femur), the tibiofibular joint (between the tibia and fibula), and the patellofemoral joint (between the patella and femur). These joints allow for flexion and extension. This joint is then strengthened by a combination of ligaments – the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), and the lateral collateral ligament (LCL) – that provide resistance to abnormal movement of the joint. Additionally, the knee consists of two cartilage structures, the medial and lateral menisci, which act as shock absorbers for the knee, reducing friction as well. Synovial fluid in the joint cavity lubricates the structures, enhancing smooth movements. The quadriceps and hamstrings are muscles surrounding the knee, and they play a crucial part in the stability and movement of the joint, contributing to the functionality.[13]

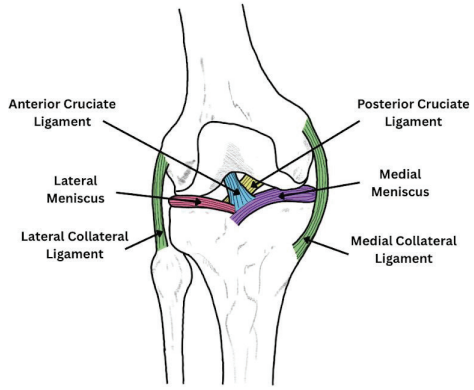

Figure 1: Adapted from.[43] Schematic of the knee joint

Bharatanatyam:

Bharatanatyam is one of the eight classical dances that originated in the subcontinent of India. The dance form focuses on abhinaya, facial expressions, and adavus, the basic steps. One of the fundamental postures in Bharatanatyam is called 'aramandi', in which a dancer stands with heels together and toes pointing outwards, squatting halfway to form a diamond shape with their legs, as illustrated in Figure 2(a).[14] In this position, the hip joints are externally rotated and abducted, while the knees are under significant flexion. This combined loading pattern on the lower limb joints places increased stress on the ACL, due to the rotational and shear forces involved. This becomes particularly concerning when dancers transition into and out of aramandi without adequate muscular support or optimal joint alignment.[15] Another of the three main postures in Bharatanatyam is "mandi," which is like a grand plié in ballet. In this position, the dancer transitions from aramandi and fully squats down, lowering until the thighs are parallel to the floor, with their heels lifting off the ground, as illustrated in Figure 2(b). The flexion of the knees required in mandi, coupled with the external rotation at the knee joint, increases the strain on the joint and may elevate the risk of ACL injury. When these movements are performed repetitively, especially with light misalignments or under muscular fatigue, the cumulative stress can contribute to injury over time. A study on Bharatanatyam dancers found that poor aramandi technique was the cause of 28.57% of ligament-related injuries. The authors also discuss how improving a dancer's flexibility can reduce the risk of knee injuries. They concluded that lower levels of flexibility in the dancers were a leading cause for knee-related injuries and that incorporating yogic stretches and warmups can help reduce injury risk.[16] While several studies have examined the prevalence of ACL injuries during aramandi, there is comparatively less data on mandi. We attribute this difference to the biomechanics of ACL loading during knee flexion. Specifically, the ACL is most mechanically engaged between 0° and 30 knee flexion and becomes progressively less loaded as the knee moves into deeper flexion.[17]

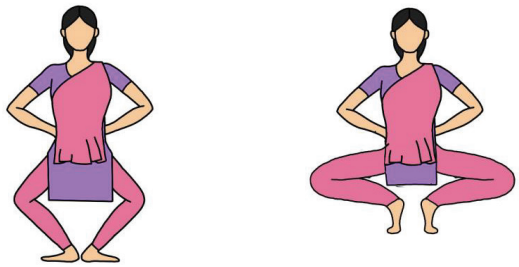

Figure 2: Dancer in Bharathanatyam postures (a) Dancer in aramandi (b) Dancer in mandi

Ballet:

Ballet is a classical dance form that originated during the Italian Renaissance and evolved in France and Russia, known for its emphasis on precision, posture, and technique. A foundational aspect of ballet technique is the five basic positions of the feet. In "first position", the dancer's heels touch with the toes pointed outwards, forming a straight line. "Second position" is similar in how the feet are turned out, but the dancer's heels are shoulder-width apart. In "third position", one foot is placed in front of the other with the heel of the front foot

touching the arch of the other foot. "Fourth position" is similar, but the dancer moves the front foot in third position in front of the other foot, still angled the same way. "Fifth position", the most turned-out and closed of all, has one foot directly in front of the other so that the toes and heel of each foot are touching.[18] These positions not only help train turnout and alignment but also create the clean lines and elegant shapes that define ballet's aesthetic. These positions rely heavily on external rotation of the hip, often referred to as turnout. While turnout is aesthetically central to ballet, it can be biomechanically problematic if the rotation is forced at the knees or ankles rather than initiated from the hips. Improper or excessive turnout places significant stress on the ACL, particularly during landing, pivoting, or directional changes. A study done using electromyography analyzed which of the five positions causes the most strain on a dancer's body. They found that the fourth position was the most demanding, requiring the greatest pelvic anterior tilt. The repetitive jumping, landing, and directional shifts in ballet, especially from turned-out positions, can exacerbate instability in the knee joint, increasing the likelihood of ACL strain or tear. According to a study by Fotaki et al., the grand plie, a key movement in ballet, mimics the mechanism of meniscus injuries because it leads to the knee experiencing a strong impact from the ground and excessive forward movement at the knee joint.[19] Moreover, the demand for hyperextension and rigid alignment may reduce natural shock absorption, compounding the risk of joint injury.

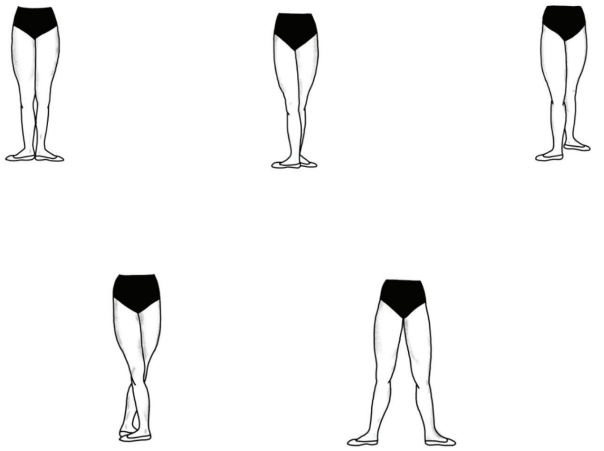

Figure 3: Adapted from.[42] Dancer in ballet postures (a) Dancer in first position (b) Dancer in second position (c) Dancer in third position (d) Dancer in fourth position (e) Dancer in fifth position

Modern Dance

Modern Dance is a broad genre of dance that was formed in the 20th century as a reaction against the structure found in classical ballet. Unlike other forms of dance, modern dance does not rely on a codified set of positions but instead explores the body's natural lines and movement patterns. Modern dancers use positions like parallel feet (where the toes point forward and the feet are hip-width apart) instead of turned-out feet, emphasizing a more natural stance. These forms reflect modern dance's focus on individual interpretation over formal structure. This alignment is generally more anatomically neutral and can reduce strain on the knee joint. However, modern dance also frequently incorporates unpredictable or improvisational movements, floor work, and off-axis balance, which may challenge knee stability.[20] While the parallel stance may offer better baseline support for ACL safety, the dynamic shifts, sudden directional changes, and non-linear choreography of modern dance can still pose a risk, especially if a dancer has insufficient control or strength. Modern dance presents several unique biomechanical challenges that may increase susceptibility to ACL injury. One concern is the lack of consistent turnout or structured alignment training, which can lead to variation in lower limb mechanics during high-demand movements. This can result in inconsistencies in knee alignment, such as increased dynamic knee valgus or internal tibial rotation during landings, leaps, or floor recoveries, known contributors to ACL stress.[8]

Biomechanical data and its limitations in dance:

The degree of muscle activation in a dancer can be assessed using electromyography (EMG).[21] In an EMG, electrodes are placed on the skin, above a specific muscle, or inserted into the skin through a needle. As a muscle contracts, it generates electrical signals, whose amplitude correlates with the intensity of the contraction. By placing electrodes over several muscles, researchers can determine the activity of each of those muscles during a specific movement.[22] It is often the inactivation of certain muscles that is of primary interest in ACL injuries. For example, reduced or delayed gluteus medius activation is associated with an increased incidence of ACL injuries. Incorporating EMG into dance research can therefore explain why certain movements can increase the risk of ACL injuries. However, its application in dance has many limitations.

One limitation in EMG research is the impact of sweat on signal quality. As dancers exert themselves, perspiration can reduce electrode adhesion and increase skin impedance. In turn, this decreases the reliability of recorded muscle activity.[23] This presents a challenge in dance studies, where continuous, high-intensity movement can lead to dancers perspiring. Another limitation stems from how EMG protocols are applied in research studies. Dancers are typically asked to repeat the same movement multiple times for data collection, not aligning with how they would typically train or perform choreography. This methodological choice, often necessary to average EMG signals, may limit validity and restrict the applicability of findings to real dance settings. To mitigate this limitation, researchers will often specify that dancers do not perform the same movement more than a set number of times without a break in between, to create a closer simulation of how dancers realistically train. Furthermore, EMG interpretation in dance is complicated by the fact that many muscles are activated simultaneously during complex movements. This leads to overlapping electrical signals and cross-talk between electrodes.[24] These technical challenges highlight the difficulty of using EMG as a stand-alone tool to understand ACL injury mechanisms in dancers and suggest that training programs informed by biomechanical data must carefully account for the unique conditions of dance performance. Nevertheless, EMG

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can still be used to uncover general trends that dancers can follow to mitigate injury risk.

Injury Mechanisms in Dance

Knee valgus:

Knee valgus, or medial collapse of the knee joint during movement, is a well-established biomechanical risk factor for non-contact ACL injuries.[25] It typically occurs when the knee falls inward relative to the hip and foot. This misalignment is most commonly observed during dynamic activities, such as landing, cutting, or squatting. When excessive knee valgus occurs, large rotational forces are generated across the joint, which increases strain on the ACL. This mechanism was studied by Withrow et al., who used cadaveric knee specimens to investigate the effect of knee valgus angle on peak ACL strain. In the first trial, the force was directed posterior to the knee joint center in the sagittal plane. In the second trial, the force was directed 15 degrees lateral to the knee sagittal plane. A differential variable reluctance transducer was used to measure the relative ACL strain. The study found that when impulsive compression was applied to a knee in flexion and valgus, the strain on the ACL increased by 30% compared to flexion alone. They concluded that reducing the knee valgus of the joint will lower ACL strain during a jump landing and therefore reduce the risk of ACL injury.[26] These forces that cause strain can gradually weaken the ligament or cause a sudden ACL tear.

To better understand the biomechanical factors contributing to knee valgus, Turner et al. conducted a study examining the relationship between knee valgus angle, hip strength, joint mobility, and muscle activation.[27] The researchers used three methods to collect data regarding muscles and range of motion: a dynamometer to measure hip muscle strength, a goniometer to measure the hip external range of motion, and an EMG system to measure gluteus maximus and gluteus medius activation. They assessed how dancers and non-dancers landed from a jump, both naturally and when instructed to prevent knee contact and to land with toe-first foot placement before the heels. They found that after being given instructions, non-dancers saw a greater increase in the measured knee valgus angle, while the value in dancers did not show a significant change. These results are compelling because they offer insight into movement training and how that relates to injury prevention. For instance, the study recruited participants with a mixed background of ballet and modern dance. This may bias the results in favor of dancers as a whole because of variations in training approaches and emphasis. For instance, in ballet dance, every position (Figure 3) has dancers point their toes outwards, creating "turnout." This technique is heavily enforced in classical ballet and is a part of most movements in ballet. Consequently, the knees of a ballet dancer do not fall inward when they land. This pattern of landing is so deeply ingrained in a ballet dancer's motor memory that even when given instructions to land with their feet in a neutral position, it is difficult for them to do so. This consistent method of landing leads to less variation in knee valgus angle, ultimately reducing the risk of ACL injuries. Notably, this preventative mechanism is not seen in other physical activities. For example, female soccer players show a higher rate of ACL injuries compared to female dancers.[28] In another study, video analysis showed that female soccer players tended to place their knees in increased knee valgus angles when making sudden changes of direction. This significantly increases the stress placed on the knee and can explain the large incidence, approximately 80,000, of ACL injuries among female high school soccer players alone. Compared to their male counterparts, instances of ACL injuries are 2-10 times higher in female soccer players.[29] This discrepancy in frequency of ACL tears between female and male soccer players is not as prevalent in dancers. For instance, Karl Orishimo et al. analyzed 40 professional dancers, 20 men and 20 women of similar backgrounds, and their knee valgus angle when performing single-leg drop-landings from a platform. The data indicated that in dancers, there was no discrepancy in ACL injuries in females vs males, contrasting most other sports.[10]

Lack of lower-body strength:

Insufficient lower-body strength is a well-recognized biomechanical risk factor for non-contact ACL injuries.[30] Weakness or an improper distribution of muscle strength in key muscle groups, such as the quadriceps, hamstrings, glutes, and calves, can impair joint stability and neuromuscular control during dynamic movements. This lack of strength often becomes evident during high-impact activities like jumping, landing, or cutting, where the muscles are unable to adequately absorb forces or maintain proper alignment. As a result, the knee may experience abnormal movement patterns, such as excessive valgus or rotational stresses, which significantly increase the strain on the ACL. Over time or during a single high-load event, this can lead to ligament rupture. This issue is particularly critical in athletes, where muscle imbalances or inadequate strength training can leave the knee vulnerable to injury.[31]

There are several techniques that researchers can use to measure lower-body strength. In a wall sit test, for example, participants lean their back against a wall with their knees in line with their ankles and thighs parallel to the floor. A researcher then measures the time during which the position is held. Longer times are typically associated with greater lower-body strength. Another test involves participants performing hops on a single leg for six meters, followed by the same hops with the other leg. The time taken to perform the action is also correlated with lower-body strength, where decreasing times are associated with greater lower-body strength. A study used those tests to compare the lower-body strength of Bharatanatyam dancers and non-dancers.[32] The data show that Bharatanatyam dancers were able to hold a wall sit position for approximately 2.5 times longer than non-dancers, revealing increased quadricep, glute, and hamstring strength relative to non-dancers. In addition, Bharatanatyam dancers were able to hop 6 meters at relatively the same speed with their right and left legs, while non-dancers showed a preference for one leg. Those findings were explained by the dance training profile of Bharatanatyam dancers. Those findings were attributed to the time Bharatanatyam dancers spent in the aramandi posi-

tion (Figure 2a). For example, in a typical 60-minute training session, a Bharatanatyam dancer spends 30-40 minutes in the aramandi position, which seems to greatly improve their lower body strength. This empirical observation is consistent with biomechanical findings on the quadriceps and hamstring muscle activation during the aramandi position.[15] Although the scope of the study by Jyothi and Sujaya did not include ACL injuries, one can infer from biomechanical data the protective benefit the aramandi position can have for a Bharatanatyam dancer. It is well known that a larger degree of lower-body muscle activation is associated with a lower incidence of ACL injury.[33,34] The findings we discussed corroborate the idea that prevention efforts should focus not only on alignment cues but also on strengthening the stabilizing muscles.[32] This prolonged muscular engagement, in addition to repetitive movements like adavus, functions similarly to isometric strength training and builds endurance in the hamstrings and hip stabilizers over time.

The emphasis on static holds observed in the training program of Bharatanatyam dancers is in stark contrast to other forms of dance, such as ballet. In ballet, for example, more focus is put on increasing flexibility and developing aesthetic lines rather than improving muscular load or endurance. Due to this difference in dance training, ballet dancers may not consistently engage the lower body in ways that develop strength sufficient to withstand high biomechanical stress. This lower-body strength deficiency can make them more vulnerable to ACL injury. This hypothesis is consistent with the study of Jeffery A. Russell, where the addition of targeted physical conditioning in female dancers was associated with a drop in injury rates from 4.14 to 1.81 per 1,000 hours over 3 years.[5] This suggests that injury risk can be mitigated by addressing muscular deficiencies directly. Moreover, it demonstrates that dancers in disciplines with less emphasis on lower limb strength—such as ballet and modern dance—would especially benefit from supplemental strength training outside of traditional technique classes.

Hip immobility:

While limited data is investigating the effects of hip immobility on risk of ACL injury in the ballet, modern, and Bharatanatyam dancers, there is ample data on the biomechanical link between hip immobility and ACL injuries. A study done by Tainaka et al. has linked poor hip mobility, especially in extension and external rotation, to an increased risk of ACL injuries.[35] Limited range of motion or poor neuromuscular control at the hip, particularly in hip extension, abduction, and external rotation, can alter lower limb alignment and movement patterns. When the hips are restricted in motion or lack stability, the body compensates for the increased movement and stress at the knee. This compensation often presents as excessive knee valgus, internal femoral rotation, or lateral trunk lean, biomechanical patterns consistently associated with non-contact ACL injuries. Because knee valgus can be caused by hip immobility, many of our conclusions and recommendations in section 3.1 are relevant to hip immobility-related ACL injuries.

There are a couple of reasons to conclude that the risk of hip immobility-induced ACL injuries for dancers may not be so high. First, the data reporting such injuries is very limited. Second, consider the discrepancy mentioned earlier about ACL injuries in male versus female athletes. Female athletes experience ACL injuries at a rate 3.5 times greater in basketball and 2.8 times greater in soccer than male athletes.[36] One proposed explanation is that many female athletes display lower hip strength and mobility relative to male athletes, and without targeted training to address these deficits, the knee becomes the point of compensation during rapid movement. Remarkably, this discrepancy does not hold between male and female dancers. Therefore, it is likely that the training of external rotation and controlled hip abduction that is present in Bharatanatyam and ballet dancers could reduce the risk of ACL injury.

Ground Reactive Forces:

Ground reaction forces (GRFs) represent the load transferred from the ground into the body during movements like landings. In dance styles like ballet, peak vertical GRFs can reach 2.8-3.8 times a dancer's body weight during landings in leaps like a grand jete.[37] These elevated forces place great amounts of mechanical stress on the knee joint and surrounding soft tissues. When coupled with limited joint flexion, stiff landing technique, or poor shock absorption strategies, high GRFs can significantly elevate the strain on the ACL, increasing the risk of non-contact injuries. Understanding the magnitude and dynamics of GRFs in dance-specific movements thus informs targeted training interventions to improve force attenuation, optimize landing mechanics, and thereby mitigate ACL injury risk.

Ballet dancers may be especially vulnerable to GRF-related injury risks due to the aesthetic demands of the discipline. Frequent jumps and directional changes, combined with stylistic requirements like external rotation and an upright torso, alter natural force absorption strategies. These biomechanical constraints often reduce the contribution of stabilizing muscles in the lower limbs, leaving the ACL to absorb a larger share of the force.[38] A study done by Yayoi Jones shows that certain leaps, like a calypso, lead to higher GRFs, meaning there is more force applied from the ground when a dancer lands, leading to a higher risk of ACL injury. In the study, different leaps had significant differences in the resulting GRFs, with the most basic leaps having the lowest GRF and the most advanced leaps having the highest.[39] It can be concluded that as dancers become more advanced, the emphasis on the aesthetics of the jumps is prioritized, leading to the high GRFs as dancers choose to focus on hip rotation and upright posture instead of engaging hamstrings, quadriceps, and glutes. There was a lack of biomechanical data found regarding Bharatanatyam dancers, but we can conclude that since they possessed higher lower-body strength, they would be more likely to engage their muscles. This would lead to a decreased load being placed on the ACL. Similarly, a lack of biomechanical data regarding ground reactive forces during landings was found in modern dancers. However, we can assume that because modern danc-

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ers focus less on the precision and aesthetics of their jumps, they would also activate their muscles more than ballet dancers. This increased muscle activation would remove strain from the ACL and reduce the risk of injury.

Additionally, the number of jumps expected from ballet dancers is higher than that of modern dancers. In a study analyzing the landing mechanics of dancers, 6 dancers in a classical company had ACL injuries, while no dancers in the 2 modern dance companies' studies had ACL injuries. Outside factors such as floor type and dancing hours have been ruled out as they were very similar between the two companies. In a classical dance company, the number of jumps is far greater than in a more modern company, and these landings will be in the classical turned-out position of the leg. Due to this, the amount of strain on the ACL in ballet dancers will be higher over an extended period, leading to an increased risk of ACL injuries.[8] For example, during a sudden change of direction or landing from a jump, inadequate muscle activation may prevent proper absorption of forces and lead to faulty joint alignment, dramatically increasing ACL strain. While a lack of data was found comparing Bharatanatyam to the other dance styles, we can conclude that, because, like modern dance, the frequency of jumps is minimal in Bharatanatyam compared to ballet, the high ground reactive forces would be lower, leading to less strain on the ACL. Further research should be done to collect data regarding ground reactive forces in certain adavus in Bharatanatyam to conclude if there is less strain on the ACL in Bharatanatyam.

Discussion and recommendations

The data we have analyzed (summarized in Tables 1 and 2) shows that every dance style form offers unique protective mechanisms, but no single style provides complete coverage of all the necessary elements for ACL injury prevention. By integrating elements from other dance styles and physical conditioning protocols, dancers can strengthen vulnerable areas, enhance joint control, and reduce the likelihood of ACL injuries. For example, classical ballet emphasizes elevation, flexibility, and aesthetic alignment but often neglects strength development. This lack of strength is most notable in the posterior chain and stabilizing muscles around the knee. Therefore, ballet dancers will benefit from integrating lower limb strength training into their routine. Ballet dancers also spend significant time on turnout (Figure 3a) and line formation, which often comes at the expense of muscular conditioning. To counter this, ballet dancers would benefit from borrowing strength-focused additions from other dance styles to help reduce their injury risk. For example, our analysis shows that the prolonged time Bharatanatyam dancers spend in aramandi (Figure 2a) leads to increased hamstring strength. This type of isometric strength development is particularly effective in stabilizing the knee joint and absorbing ground reaction forces during dynamic movement. Studies have shown that a lack of strength in the hamstrings compared to the strength of the glutes significantly increases the risk of ACL tears.[40]

Modern dancers, in contrast to ballet dancers, often prioritize fluidity, improvisation, and natural movement. Our review of the data shows that modern dancers have a greater change in knee valgus angle during landings, compared to ballet dancers. This variance in knee valgus angle makes modern dancers more susceptible to ACL injuries. Consequently, modern dancers would benefit from training consistent joint alignment, particularly to address variability in the knee valgus angle. Unlike ballet or Bharatanatyam, modern dance does not rely on fixed positions or turnout, which means dancers often lack a standardized reference for joint alignment. This variability can lead to inconsistent joint movements during landing or changing directions, where uncontrolled knee valgus is a well-established risk factor for ACL injury. Ballet dancers, by comparison, train in consistent external rotation and often land with similar lower limb alignment across movements, resulting in less variation in the knee valgus angle. Adopting a similar focus on alignment, through exercises that develop consistent hip-to-knee-to-foot coordination, would help modern dancers reduce valgus-related injury risk.

Another key factor in injury prevention we reviewed is hip mobility. Ballet places heavy emphasis on external rotation of the hip and deep hip abduction. This emphasis trains dancers to initiate movements from the hip rather than compensating them through the knee or ankle. This consistent use of the hip joint not only enhances performance but also protects the knee from absorbing excessive rotational or valgus stress. In contrast, Bharatanatyam dancers, and especially athletes in non-dance sports, often neglect structured hip mobility training. Data collected comparing the range of hip motion in ballet and modern dancers to Bharatanatyam dancers shows that when Bharatanatyam dancers incorporated stretching into their training routine, their range of motion improved and consequently, their hip mobility increased.[16] As mentioned earlier, this increase in hip mobility directly results in a decrease in ACL strain. Moreover, a study has found that female athletes, particularly in sports like soccer and basketball, are disproportionately affected by ACL injuries linked to poor hip mobility and lack of neuromuscular control.[41] Incorporating hip-focused mobility and control drills into training routines could offer critical protection, especially for dancers or athletes whose movement practices do not already include these components.

Given the distinct strengths and weaknesses of various dance disciplines (summarized in Table 1), we recommend that dancers incorporate techniques and conditioning strategies from multiple styles, along with supplemental physical training, to address biomechanical gaps that contribute to ACL injury risk.

Ultimately, the most effective approach to ACL injury prevention in dancers involves a multidisciplinary strategy that blends the strength and mobility benefits of Bharatanatyam, the alignment precision of ballet, and the expressive, adaptive movement patterns of modern dance. By addressing individual biomechanical vulnerabilities, such as muscle weakness, joint misalignment, or hip immobility, through targeted cross-training, dancers can better safeguard their bodies against the long-term risks of repetitive strain and acute ligament injuries. This integrative approach not only supports injury prevention

but also enhances overall performance and longevity in a physically demanding art form.

Table 1: Risk Factors, Protective Mechanisms, Recommended Additions, and Areas for Further Research of three styles of dance (ballet, Bharatanatyam, and modern)

Dance Style	Risk Factors	Protective Mechanisms	Recommended Additions	Areas Requiring Further Research	Sources
Ballet	Weak supporting muscles	Consistent knee alignment	Strength trainings, specifically targeting the hamstrings	Lower limb muscle strength of ballet dancers compared to dancers of other styles	19, 26, 27
Bhratanatyam	Lack of flexibility	Strong supporting muscles	Incorporate a variety of lower limb stretches into training	Knee alignment in aramandi and mandi positions	15, 16, 32
Modern	Inconsistent knee alignment	Reduced strain	Add consistent alignment training into routine	How modern training differs from classical training	8, 20, 27

Table 1 shows the strengths and weaknesses of each dance style, in addition to what we recommend could be added to their training. This table highlights areas for future research to be conducted.

Table 2: Population, Protective Method, Key Metrics, and Main Finding Relative to ACL of studies presented throughout the paper.

Study	Population	Method	Key Metrics	Main Finding Relevant to ACL	Source
Withrow et al.	Cadaver Knees	Applied load in flexion with valgus	ACL Strain	ACL strain increases when valgus is added vs flexion alone	26
Ericksen et al.	Female soccer players and dancers	Analyzing biomechanical data regarding knee and ankle flexion	knee and ankle flexion	Female soccer players have a higher incidence of ACL injuries because they have less flexion in their knees due to differences in training programs	28
Evans et al.	Female and male soccer players	Reviewed various studies	Knee valgus angle	Unlike dancers, female soccer players are at a higher risk for ACL injuries than their male counterparts	29
Orishimo et al.	20 professional male and 20 professional female dancers	group-by-sex multivariate analysis of variance	Knee Valgus Angle	No significant difference between male and female dancer's knee valgus angles when landing	10
Jyothi S. et al.	Bharatanatyam dancers from various dance schools and non dancers from the general population	Wall Sit and Single-legged Hop Tests	Lower Limb Strength	Bharatantyam dancers had a higher level of lower limb muscle activation when compared to the general population because of their training regimens.	32
Zazulak et al.	13 female and 9 male Division I collegiate athletes	Surface EMG	Lower Limb Strength	delayed gluteal activation is associated with higher ACL injuries	34
Russel	Professional dancers of various styles	Reviewed various studies	Lower Limb Strength	Additional strength training in ballet dancers is associated with a drop in the amount of ACL injuries dancers have.	5
Tainaka et al.	patients with non-contact ACL injuries	adjusted odds ratio of hip range of motion	Hip Mobility	poor hip mobility, especially in extension and external rotation, is linked to an increased risk of ACL injuries	35
Jones	16 female dance students enrolled in a university	Force plates and EMG	GRF and muscle activation	More advanced leaps in ballet that would be performed by dancers with more training show higher GRFs, leading to a higher risk of ACL injuries.	39

Table 2 displays studies conducted across various sports and dance styles that prove that each dance type has unique strengths and weaknesses.

Conclusion

In this study, we used both biomechanical research and anatomical understanding to explore how forces imposed during dance affect the knee joint of a dancer. We have analyzed data from three representative dance styles: ballet, Bharatanatyam, and modern dance. When there was a lack of biomechanical data in a particular dance, we analyzed data from other non-contact ACL injuries and connected them to the dance style in question. Our research shows that modern dancers can benefit from the structured positions of ballet and Bharatanatyam. Additionally, Bharatanatyam dancers can benefit from the flexibility that ballet dancers have, while ballet dancers should focus on lower limb strength, as Bharatanatyam dancers train during their rehearsals. Ensuring that all dancers implement strengthening, flexibility, and consistency regimens in their training will reduce the risk of ACL injury. Dance schools could add a stretching or yoga section to their class to improve dancers' flexibility. Additionally, repetition of steps could build a more consistent form in modern dancers if implemented. Finally, strength training should be prioritized through weightlifting or similar exercise methods to reduce the risk of muscles not being activated in dance. By creating a more well-rounded and balanced training program, dancers would ideally gain injury prevention mechanisms that were explored in this paper across the three styles of dance. We also present general training guidelines that dancers can implement to reduce the risk of ACL injury. While dance follows techniques that date back many years, biomechanical analysis is a relatively new field and has not been fully employed in the field of dance. We hope this review can be used to improve the training program of dancers and initiate further research into the biomechanics of dance to reduce injury risks.

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References

1. Baker, J.; Scott, D.; Watkins, K.; Keegan-Turcotte, S.; Wyon, M. Self-Reported and Reported injury patterns in contemporary dance students. *Medical Problems of Performing Artists* **2010**, *25* (1), 10–15. https://doi.org/10.21091/mppa.2010.1003.
2. Bronner, S.; Ojofeitimi, S.; Rose, D. Injuries in a modern dance company. *The American Journal of Sports Medicine* **2003**, *31* (3), 365–373. https://doi.org/10.1177/0363546503030310030701.
3. Ojofeitimi, S.; Bronner, S.; Woo, H. Injury incidence in hip hop dance. *Scandinavian Journal of Medicine and Science in Sports* **2010**, *22* (3), 347–355. https://doi.org/10.1111/j.1600-0838.2010.01173.x.
4. Byhring, S.; Bø, K. Musculoskeletal injuries in the Norwegian National Ballet: a prospective cohort study. *Scandinavian Journal of Medicine and Science in Sports* **2002**, *12* (6), 365–370. https://doi.org/10.1034/j.1600-0838.2002.01262.x.
5. Russell, J. Preventing dance injuries: current perspectives. *Open Access Journal of Sports Medicine* **2013**, *199*. https://doi.org/10.2147/oajsm.s36529.

DOI: 10.36838/IJHSR811.240

6. Washington, E. L. Musculoskeletal injuries in theatrical dancers: site, frequency, and severity. *The American Journal of Sports Medicine* **1978**, *6* (2), 75–98. https://doi.org/10.1177/036354657800600207.
7. Milan, K. R. Injury in Ballet: A review of relevant topics for the physical therapist. *Journal of Orthopaedic and Sports Physical Therapy* **1994**, *19* (2), 121–129. https://doi.org/10.2519/jospt.1994.19.2.121.
8. Meuffels, D. E.; Verhaar, J. a N. Anterior cruciate ligament injury in professional dancers. *Acta Orthopaedica* **2008**, *79* (4), 515–518. https://doi.org/10.1080/17453670710015517.
9. Gharpinde, M. R.; Pundkar, A.; Dhanwani, Y.; Chandanwale, R.; Jaiswal, A. M. Navigating post-operative challenges: A comprehensive review of complications following anterior cruciate ligament (ACL) tear surgery. *Cureus* **2024**. https://doi.org/10.7759/cureus.67768.
10. Orishimo, K. F.; Kremenic, I. J.; Pappas, E.; Hagins, M.; Liederbach, M. Comparison of landing biomechanics between male and female professional dancers. *The American Journal of Sports Medicine* **2009**, *37* (11), 2187–2193. https://doi.org/10.1177/0363546509339365.
11. Andersen, H. N.; Dyhre-Poulsen, P. The anterior cruciate ligament does play a role in controlling axial rotation in the knee. *Knee Surgery Sports Traumatology Arthroscopy* **1997**, *5* (3), 145–149. https://doi.org/10.1007/s001670050042.
12. Jenkins, S. M.; Guzman, A.; Gardner, B. B.; Bryant, S. A.; Del Sol, S. R.; McGahan, P.; Chen, J. Rehabilitation after anterior cruciate ligament Injury: Review of current literature and recommendations. *Current Reviews in Musculoskeletal Medicine* **2022**, *15* (3), 170–179. https://doi.org/10.1007/s12178-022-09752-9.
13. Chhabra, A.; Elliott, C. C.; Miller, M. D. Normal anatomy and biomechanics of the knee. *Sports Medicine and Arthroscopy Review* **2001**, *9* (3), 166–177. https://doi.org/10.1097/00132585-200107000-00002.
14. Gopalakrishnan, G. *Kinematics and Kinetics Assessment of lower limb movement in Bharatanatyam Dancers - ProQuest*. https://www.proquest.com/openview/e5642bf3919d086e18d69d9ee36afcd2/1?pq-origsite=gscholar&cbl=2026366&diss=y.
15. Chathurani, G.; Dassanayake, Y. B.; Fernando, S. N.; Gunarathna, L. S.; Gunarathne, L. K.; Chandrasekara, N. C.; Senarath, D.; Wadugodapitiya, S. I. Prevalence of musculoskeletal injuries among university undergraduates following Sri Lankan traditional dancing. *PLoS ONE* **2023**, *18* (8), e0288155. https://doi.org/10.1371/journal.pone.0288155.
16. Paul, J.; Kapoor, S. Dance-related Injuries among Bharatanatyam Dancers. *Indian Anthropological Association* **1998**, *28* (2), 21–33.
17. Li, G.; DeFrate, L. E.; Rubash, H. E.; Gill, T. J. In vivo kinematics of the ACL during weight-bearing knee flexion. *Journal of Orthopaedic Research®* **2004**, *23* (2), 340–344. https://doi.org/10.1016/j.orthres.2004.08.006.
18. Gorwa, J.; Kabaciński, J.; Murawa, M.; Fryzowicz, A. On the track of the ideal turnout: Electromyographic and kinematic analysis of the five classical ballet positions. *PLoS ONE* **2020**, *15* (3), e0230654. https://doi.org/10.1371/journal.pone.0230654.
19. Fotaki, A.; Triantafyllou, A.; Koulouvaris, P.; Skouras, A. Z.; Stasinopoulos, D.; Gkrilias, P.; Kyriakidou, M.; Stasi, S.; Antonakis-Karamintzas, D.; Tsolakis, C.; Savvidou, O.; Papagiannis, G. Excessive Knee Internal Rotation during Grand Plié in Classical Ballet Female Dancers. *Sports* **2024**, *12* (2), 54. https://doi.org/10.3390/sports12020054.
20. Portnova, T. Modern dance as an American alternative to classical ballet. *Rupkatha Journal on Interdisciplinary Studies in Humanities* **2021**, *13* (4). https://doi.org/10.21659/rupkatha.v13n4.71.
21. Krasnow, D.; Wilmerding, M. V.; Stecyk, S.; Wyon, M.; Koutedakis, Y. Biomechanical Research in Dance: A Literature Review. *Medical Problems of Performing Artists* **2011**, *26* (1), 3–23. https://doi.org/10.21091/mppa.2011.1002.
22. Mills, K. R. The basics of electromyography. *Journal of Neurology Neurosurgery & Psychiatry* **2005**, *76* (suppl_2), ii32–ii35. https://doi.org/10.1136/jnnp.2005.069211.
23. Xiao, Y.; Wang, M.; Li, Y.; Sun, Z.; Liu, Z.; He, L.; Liu, R. High-Adhesive Flexible Electrodes and their manufacture: A review. *Micromachines* **2021**, *12* (12), 1505. https://doi.org/10.3390/mi12121505.
24. Germer, C. M.; Farina, D.; Elias, L. A.; Nuccio, S.; Hug, F.; Del Vecchio, A. Surface EMG cross-talk quantified at the motor unit population level for muscles of the hand, thigh, and calf. *Journal of Applied Physiology* **2021**, *131* (2), 808–820. https://doi.org/10.1152/japplphysiol.01041.2020.
25. Yu, B.; Garrett, W. E. Mechanisms of non-contact ACL injuries. *British Journal of Sports Medicine* **2007**, *41* (suppl 1), i47–i51. https://doi.org/10.1136/bjsm.2007.037192.
26. Withrow, T. J.; Huston, L. J.; Wojtys, E. M.; Ashton-Miller, J. A. The effect of an impulsive knee valgus moment on *in vitro* relative ACL strain during a simulated jump landing. *Clinical Biomechanics* **2006**, *21* (9), 977–983. https://doi.org/10.1016/j.clinbiomech.2006.05.001.
27. Turner, C.; Crow, S.; Crowther, T.; Keating, B.; Saupan, T.; Pyfer, J.; Vialpando, K.; Lee, S.-P. Preventing non-contact ACL injuries in female athletes: What can we learn from dancers? *Physical Therapy in Sport* **2017**, *31*, 1–8. https://doi.org/10.1016/j.ptsp.2017.12.002.
28. Ericksen, H. M.; Vogelpohl, R. E. Lower extremity biomechanical differences between female dancers and soccer players. *International Journal of Athletic Therapy & Training* **2020**, *25* (5), 254–257. https://doi.org/10.1123/ijatt.2019-0087.
29. Evans, J.; Nielson, J. L. Anterior cruciate ligament knee injuries. *StatPearls* **2021**.
30. Collings, T. J.; Diamond, L. E.; Barrett, R. S.; Timmins, R. G.; Hickey, J. T.; Du Moulin, W. S.; Williams, M. D.; Beerworth, K. A.; Bourne, M. N. Strength and biomechanical risk factors for non-contact ACL injury in elite female footballers: a prospective study. *Medicine & Science in Sports & Exercise* **2022**, *54* (8), 1242–1251. https://doi.org/10.1249/mss.0000000000002908.
31. Devan, M. R.; Pescatello, L. S.; Faghri, P.; Anderson, J. A prospective study of overuse knee injuries among female athletes with muscle imbalances and structural abnormalities. *PubMed* **2004**, *39* (3), 263–267.
32. S, J.; B, S. Assessment of muscle strength in female Bharatanatyam dancers. *International Journal of Physical Education, Sports and Health* **2018**, *3* (2), 621–625.
33. Khou, S. B.; Saki, F.; Tahayori, B. Muscle activation in the lower limb muscles in individuals with dynamic knee valgus during single-leg and overhead squats: a meta-analysis study. *BMC Musculoskeletal Disorders* **2024**, *25* (1). https://doi.org/10.1186/s12891-024-07759-6.
34. Zazulak, B. T.; Ponce, P. L.; Straub, S. J.; Medvecky, M. J.; Avedisian, L.; Hewett, T. E. Gender comparison of hip muscle activity during Single-Leg landing. *Journal of Orthopaedic and Sports Physical Therapy* **2005**, *35* (5), 292–299. https://doi.org/10.2519/jospt.2005.35.5.292.
35. Tainaka, K.; Takizawa, T.; Kobayashi, H.; Umimura, M. Limited hip rotation and non-contact anterior cruciate ligament injury: A case–control study. *The Knee* **2013**, *21* (1), 86–90. https://doi.org/10.1016/j.knee.2013.07.006.
36. The female ACL: Why is it more prone to injury? *Journal of Orthopaedics* **2016**, *13* (2), A1–A4. https://doi.org/10.1016/s0972-978x(16)00023-4.

37. Leslie, E. R. Three-dimensional biomechanical analysis of landing from grand jeté : the effect of ballet footwear on selected kinetic and kinematic variables. *MSU Libraries Digital Collections* **2002**.
38. Harper, D. J.; McBurnie, A. J.; Santos, T. D.; Eriksrud, O.; Evans, M.; Cohen, D. D.; Rhodes, D.; Carling, C.; Kiely, J. Biomechanical and Neuromuscular Performance Requirements of Horizontal Deceleration: A Review with Implications for Random Intermittent Multi-Directional Sports. *Sports Medicine* **2022**, *52* (10), 2321–2354. https://doi.org/10.1007/s40279-022-01693-0.
39. Jones, Y. Comparison of Ballet and Modern Dance in terms of Kinetics, Kinematics, and Muscle Activation during Landing for College Dancers. *Scholar Works at UT Tyler* **2015**.
40. Ruan, M.; Zhang, Q.; Wu, X. Acute effects of static stretching of hamstring on performance and anterior cruciate ligament injury risk during Stop-Jump and cutting tasks in female athletes. *The Journal of Strength and Conditioning Research* **2017**, *31* (5), 1241–1250. https://doi.org/10.1519/jsc.0000000000001783.
41. The female ACL: Why is it more prone to injury? *Journal of Orthopaedics* **2016**, *13* (2), A1–A4. https://doi.org/10.1016/s0972-978x(16)00023-4.
42. Postural implications of foot stability in classical ballet. On Pointe. https://alysserina.wordpress.com/tag/biomechanics-2/ (accessed 2025-08-16).
43. Shannon, N. How Superior is Rehab for ACL Injuries? | Shannon Clinic. Shannon Clinic. https://shannonclinic.com.au/blog/are-the-media-reports-right-on-acl-management/.

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RESEARCH ARTICLE

Simulating Hatchet Oar Blade Motion Using SnappyHexMesh and Turbulence Modeling in OpenFOAM

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ABSTRACT: This work models the hydrodynamics of the blade of a rower by means of computational fluid dynamics in the open-source software OpenFOAM, wherein simulations were carried out on a convex hatchet oar geometry at various blade angles (-20˚ to +20˚) to study the pressure distribution, wake formation, and force coefficients, using a blockMesh generated computational domain, steady simulations with simpleFoam. The results show that a 0˚ blade angle results in the highest total force (Cd=1.7994) due to an optimum pressure differential-wake coherence balance, and so is the most efficient blade-angle for a rower to maintain throughout the middle of the stroke. An entrance angle of approximately -20˚ was found to minimize drag, which indicates an efficiency of a catch/Entry angle of -20˚ before inevitable rotation toward 0˚ during the drive. The results present a computational basis for blade shape and kinematics optimization in rowing propulsion.

KEYWORDS: Computational Fluid Dynamics, Rowing Blade, OpenFOAM, Rowing Propulsion, Turbulence Modeling.

Introduction

At the heart of rowing propulsion is a moving blade and a moving fluid, each pushing and yielding to the other. Describing that exchange: how force becomes motion, how motion disturbs the water, how the nature of the flow creates velocity and pressure, is the job of the Navier–Stokes equations.[1] It accounts for how velocity changes not just over time, but over space: how a fluid speeds up, how it shears, how it spreads or narrows or decelerates. In rowing, that happens along the blade surface, in the pressure gradients that it creates, and in the vortices that it creates behind it. The essence is this: fluid momentum is altered by forces within—viscosity, pressure, and inertia. Water near the blade sticks to it; it slows down, swirls around, and stratifies. Water farther away reacts to those changes. Near the surface, thin layers form where velocity gradients are greatest—boundary layers, sensitive to blade angle and motion.[2] Further away, the bulk flow curves and becomes vortices, especially at the edges.[3] All of it is regulated by the same principles, contained in the same equations.

Since water can't be compressed to any significant degree at these speeds, conservation of volume necessitates that fluid that enters some location must leave from somewhere else. That necessity—what mathematicians call "divergence-free"—along with the pressure and velocity fields, binds them together tightly.[1] You can't change one without affecting the other. What makes the system difficult to solve—and interesting to study—is its nonlinearity. Water doesn't simply respond to forces; it transmits them. A whirling blade doesn't simply disturb water at the moment it passes; it changes the way the next moment will be. That feedback is what makes rowing propulsion more than a simple cause-and-effect system. The same laws and equations of Fluid dynamics govern hurricanes, airplane wings, and ink spreading through water.[4] But in rowing, the environment is small, the conditions are more localized, and the results are more immediate. Each stroke is an in-the-moment experiment in unsteady flow.[5]

Turbulence occurs when the orderly patterns of flow break down into layers of uncertainty: when viscosity is overcome by inertia, and small perturbations are no longer damped, but amplified.[4] In rowing, this happens around and behind the blade, where flow is separated, sheared, and careened into vortices. These vortices, formed at the blade edges, possess momentum and energy, marking the edge between smooth pressure-driven motion and the complex, swirling aftermath. As they interact and stretch, some remain coherent, others break into smaller eddies, cascading energy downwards through scales.[3] This process is set by equations, but is also effectively impossible to do by hand, thus requiring computational modeling or experiment to mark the edge between the elegant and the chaotic in each stroke.

These vortices also influence the unsteady pressure field and create fluctuations in lift and drag. The stroke efficiency is not only a matter of blade speed and angle, but of whether or not these vortices are stable and attached, or detach randomly into the wake. This is where lift and drag coefficients, Cl and Cd, enter the picture. They describe how effectively the blade is converting motion into force, and they change with blade angle, flow separation, and formation of vortices.[4] A small change in angle or speed will make the flow go from smooth and efficient to turbulent and wasteful. Understanding how these coefficients respond to blade geometry and stroke kinematics is the key to developing an efficient propulsion system.[5] This paper aims to incorporate the described factors to simulate and determine the optimal blade angles in terms of pressure, force, and turbulence for different moments throughout the stroke.

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Methods

The simulations were carried out with OpenFOAM (version 11), an open-source CFD package. The computational domain was generated with blockMesh. A large rectangular domain was produced to minimize boundary effects. A simplified convex hatchet oar blade was inserted into this domain and turned to discrete angles between -20° and +20°.

The following boundary conditions were implemented in OpenFOAM to simulate realistic water flow around the blade.

The numerical domain used inlet velocity boundary conditions on the lower face (Z = -0.5) in modeling blade motion in water. Zero-gradient pressure boundary conditions on the upper outlet (Z = +0.5) modeled natural wake development. Symmetry boundary conditions on the side, front, and back faces minimized computational expense and removed edge effects in modeling the infinite span flow behavior of the blade.

The necessary Oar blade geometries were generated from a Python script that generates STL files by tilt angle, starting from a definition of a 2D oar shape with realistic cleaver-blade size (500 mm long, 250 mm wide). A cambered surface shape is defined by a parabolic thickness distribution with a 10mm maximum camber in a 2mm base thickness. The 2D shape was then triangulated by Delaunay triangulation, then extruded to form top and bottom surfaces connected by vertical side walls. The geometry was lastly rotated around the centre point to make the tilt angle (-20° to 20° at discrete steps), and the resulting triangular mesh was saved as a watertight STL file ready for CFD simulation.

The final computational mesh was created with the OpenFOAM snappyHexMesh utility, which refines arches and surfaces automatically. This utility works through three separate stages:

Stage 1: Castellated Mesh Creation

- Surface refinement levels were used to properly follow the blade's surface geometry
- Refinement boxes were created around the blade to guarantee proper resolution in the wake region
- Maximum refinement level: 4 (cell size = background_cell_size / 2^4)
- Minimum refinement level: 3 (for base resolution)

Stage 2: Surface Snapping

- Castellated mesh was snapped to match the STL surface geometry of the oar blade
- Feature edge refinement was used to capture sharp edges and corners
- Surface normal smoothing iterations: 3
- Tolerance settings optimized to preserve geometric quality

Stage 3: Boundary Layer Addition

- Prismatic boundary layer cells were added next to the blade surface
- First layer thickness: 0.3 (relative to local cell size)
- Number of boundary layers: 3
- Growth ratio: 1.2
- Total boundary layer thickness: ~0.93 (relative units)

The numerical model is based on the discretization of the Navier–Stokes equations in OpenFOAM using the finite volume method.[1] These equations are expressed in a conservative form for mass and momentum:

$$\nabla \cdot u = 0$$

$$\partial u/\partial t + (u \cdot \nabla)u = - (1/\rho) \nabla p + \nu \nabla^2 u$$

where u is velocity, p is pressure, ρ is fluid density, and ν is kinematic viscosity.

Steady-state simulations were performed initially with simpleFoam to validate mesh quality, numerical stability, and boundary conditions.[7] The turbulence model used was k–ω SST, known to model correctly flow separation and vortex transport phenomena, which are of importance for the rowing blade performance.[8]

Upon validation, the blade was rotated up to each specified angle in increments, and simulations were performed until the force coefficients obtained converged. The results of the simulations included the time average of the drag and lift coefficients (Cd and Cl) and of the moment coefficient (Cm). The coefficients were found by performing surface integrals of the pressure and viscous stresses on the blade using the solver.[4] The velocity and pressure fields were exported at each step and visualized using ParaView-5.13.3. Within ParaView, there could be detailed observation of wake structures, pressure gradients, and isolated flow separation zones for the various simulated blade angles. In the future, there are plans to incorporate unsteady simulations using the features pimpleFoam and dynamicsMesh into the simulation in order to emulate real rowing more closely.

Results and Discussion

To assess the hydrodynamic performances of a rowing blade at different pitch angles, several steady state simulations have been carried out by simpleFoam in OpenFOAM. The blade shape was a basic convex hatchet profile within a large computational space to reduce edge effects. Simulations were performed for blade angles of –20° up to +20° in 5° steps. For each case, pressure and velocity field monitoring, aerodynamic coefficients extraction, and flow structure visualization in ParaView were performed.

The main quantities to be studied were the drag coefficient (Cd), the lift coefficient (Cl), the moment coefficient (Cm), and the magnitude of resulting forces. These were derived at each angle and processed to find the best arrangements for mounting propulsion and for stability and entry. Some important highlights:

$$F = (1/2)\, \rho\, C_A\, A\, v^2$$

where:

- $p = 1000\ kg/m^3$ (density of water)
- C_A = coefficient of lift (Cl) or drag (Cd)
- $A = 0.125\ m^2$ (cross-sectional area of the blade: 0.5m × 0.25m)
- $v^2 = 2\ m/s$ (velocity of the blade through water)

From that equation, the drag and lift forces were extracted via OpenFOAM from the surface pressure. Then the forces

were normalized by the dynamic pressure (1/2pv^2) and reference area.

$C_d = F_d / ((1/2)\rho v^2 A)$

$C_l = F_l / ((1/2)\rho v^2 A)$

Maximum Drag Configuration (Best for Power Transfer):
- Blade Angle: 0°
- Drag Coefficient (Cd): 1.7994
- Lift Coefficient (Cl): -0.0005
- Total Force Magnitude: 1.7994

Maximum Lift Configuration (Lateral Stability):
- Blade Angle: 15°
- Drag Coefficient (Cd): 1.6922
- Lift Coefficient (Cl): -0.0020
- Total Force Magnitude: 1.6922

Minimum Drag Configuration (Blade Entry/Catch Phase):
- Blade Angle: -20°
- Drag Coefficient (Cd): 1.5563

Maximum Total Force Configuration (Overall Propulsion):
- Blade Angle: 0°
- Same as Max Drag Configuration

Table 1: Force Coefficient Results.

Angle (°)	Cd	Cl	Cm
-20	1.5563	-0.0012	-0.0209
-15	1.6442	-0.0018	-0.0204
-10	1.7225	-0.0016	-0.0219
-5	1.7757	-0.0013	-0.0225
0	1.7994	-0.0005	-0.0229
5	1.7797	-0.0014	-0.0211
10	1.7582	-0.0016	-0.0206
15	1.6922	-0.0020	-0.0186
20	1.5939	-0.0014	-0.0182

Table 1 shows a complete distribution of how such coefficients change with blade angle. Both net force and drag coefficient can be modeled with a negative parabola with a vertex peak at 0° and equal negative rate of change in either direction to the ends of 20° or -20°. This parabolic result trend with a peak at 0° proves that the mid-stroke blade position plays a large role in thrust generation. These results align with the pressure field indicated in Figure 2: the 0° blade angle displays a high-pressure front and has a consistent low-pressure wake.

As expected, the lift coefficient was negative for all tested angles (from -20° to 20°), given that the blades face downwards relative to the flow. Another indication of the relative believability of these results is the incredibly small ratio between lift forces and drag forces for all angles. However, the relatively small amount of lift coefficient does not invalidate its role within the stroke, as it is an important contributor to stroke stability through lateral corrections. Figure 4 most directly illustrates how the lift force is always smaller than the drag force by an order of magnitude, supporting the conclusion that drag plays the largest role in rowing propulsion.

Similar to the lift coefficient, the moment coefficient is negative for all angles. As the angle increases from -20 to 20, so does the moment coefficient. These results are similar to those of steady torque, which is generated by asymmetrical pressure distribution, therefore indicating the influence of the moment coefficient on handle control and force.

Velocity and pressure field visualizations (Figures 2 and 3) show strong wake formation and pressure gradients around the blade surfaces. At 0°, the blade created a clean downstream wake with mirrored high-pressure buildup on the leading surface and low-pressure trailing wake. In positive angles larger than 0°, stronger wake regions and further downstream flow separation on the blade were observed with increased inefficiency. Such flow characteristics are in direct relation to the decrease of the total force with angle, as seen in Figure 1.

Such regimes of wake turbulence and flow separation, as existing, could be related to the calculation of the Reynolds number. The Reynolds number for this case analysis has been computed by the application of the relative water velocity (U = 2m/s) together with the chord length of the blade (c = 0.5m):

$Re = \rho Uc/\mu = (1000 \times 2 \times 0.5) / (1\times10^{-3}) = 1\times10^{6}$

This supercritical Reynolds number possesses fully turbulent flows with the current boundary layer transition and the strong wake. The positive blade angles (> 0°) for the turbulent wake indicate the separation of the flows within the adverse pressure gradients, sufficient to overcome the boundary layer momentum, as clearly visible from the velocity field visualisations for +15° and +20°.

For $Re = 1\times10^{6}$, the boundary layer switches automatically to turbulent flow near the leading edge, producing the high wake formation and pressure gradients observed in Figures 2 and 3. The 0° wake characteristic showed attached turbulent flow with late separation, but the presence of turbulence with increasing positive angle shows boundary layer separation early along the suction side of the blade due to the adverse pressure gradient. In the RANS simulation, there was no wake turbulence present at the angle of simulation, perhaps an indication of the favorable pressure gradients. Wake turbulence was not observed for the -20° angle of attack in the present steady RANS simulation, suggesting favorable pressure gradients that may delay boundary layer separation. The absence of turbulence at -20 degrees could also have been influenced by the boundary conditions encoded in the implementation of the steady RANS simulation.

At –20°, where the drag force is minimized in the Drag Coefficient vs Blade Angle graph (Figure 1), would be the op-

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timal position for blade entry to maintain a smooth entrance. In a simulation that aims to maximize net turbulence of the stroke, a minimized entry turbulence may seem unintuitive. However, the compromise is optimized to allow angle entry with a smaller resistive load without overtly compromising the boat's acceleration downstream.

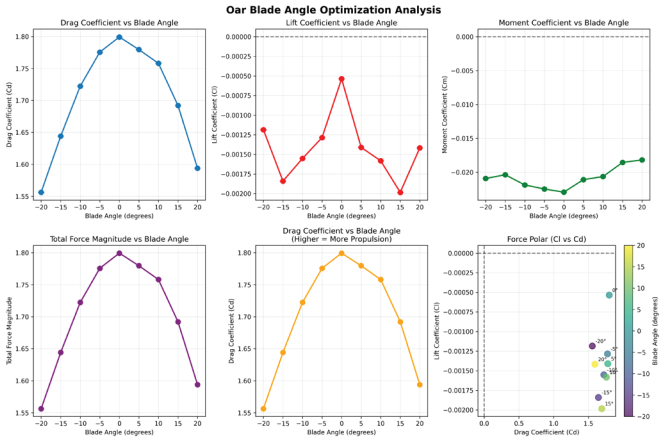

Figure 1: Oar Blade Angle Optimization Analysis Graphs. Simulation post-analysis graphs of Cd, Cl, Cm, and total force magnitude with blade angle from −20° to +20°: displaying a parabolic dependence, resulting in maximum drag and total force at 0°, and minimized drag at −20°.

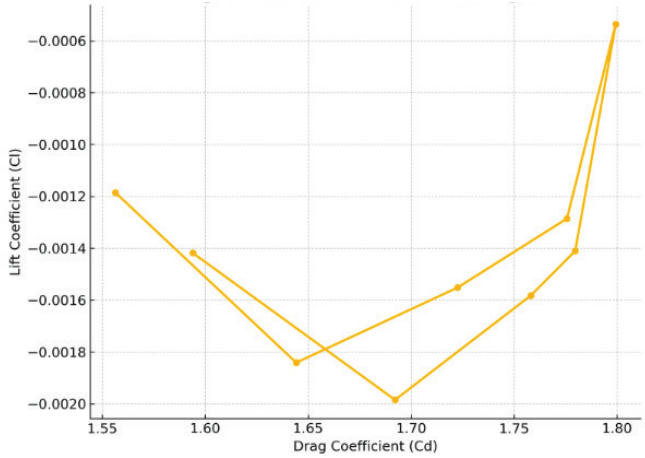

Figure 2: Cd vs Cl for Different Blade Angels.

Within shows two lines; each point represents the increase in blade angle from -20° to 0° and the decrease from 20° to 0°. Given how similar these lines are, it confirms the parabolic relationship between Cd/Cl and the blade angles.

Conclusion

This study determined that, given a steady-state water condition, the blade angle that will generate the maximum net force is 0°. The steady-state condition describes the rower in the middle of the stroke post-entry, where he seeks to simply maximize propulsion. However, for other periods of the stroke, the rower is inclined to compromise. When the rower places their blade into the water, doing so with the maximum drag would disrupt the velocity and smooth glide of the boat. The simulated angle of 20° had the minimized drag force, allowing for a less disruptive and resistive blade entry. Therefore, the entry angle of 20° followed by an instant rotation into 0° would maintain the boat's smooth glide and allow for an undisruptive acceleration as the blade engages with maximum drag throughout the rest of the stroke.

The OpenFOAM code used to produce the hydrodynamic blade simulations can be found along with a CSV dataset of force and moment coefficients.

(https://github.com/NecritsSoup/OpenFOAM-simulation)

Further research is considered, as these files provide a framework for more unsteady simulations as well as implications for rowing analysis and equipment development.

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I attest that the ideas, graphics, and writing in this paper are entirely my own.

References

1. Batchelor GK. *An Introduction to Fluid Dynamics*. Cambridge: Cambridge University Press; 2000. Eldredge JD, Jones AR. Leading-edge vortices: mechanics and modeling. *Annu Rev Fluid Mech* 2019;51:75–104.
2. Sujono S, Saputra E, Ismail R. Analysis of oar blade hydrodynamics for rowing propulsive mechanism: experiment and computational fluid dynamics simulation. *CFD Lett* 2019;11(3):112–123.
3. Bardina JE, Huang PG, Coakley TJ. *Turbulence Modeling Validation, Testing, and Development*. NASA Technical Memorandum 110446. Moffett Field, CA: NASA Ames Research Center; 1997.
4. Schlichting H, Gersten H. *Boundary-Layer Theory*. 9th ed. Berlin: Springer; 2017.
5. Weller HG, Tabor G, Jasak H, Fureby C. A tensorial approach to computational continuum mechanics using object-oriented techniques. *Comput Phys* 1998;12(6):620–631.
6. Menter FR. Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA J* 1994;32(8):1598–1605.
7. Grift EJ, Tummers MJ, Westerweel J. Hydrodynamics of rowing propulsion. *J Fluid Mech* 2021;918:A29.
8. White FM. *Fluid Mechanics*. 8th ed. New York: McGraw-Hill Education; 2016.

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Sean Schwartz is a senior at Episcopal High School. He spends a great deal of time rowing, playing the piano, and playing cello in his school orchestra. Drawing on his experience as a varsity rower and his interest in computational modeling, Sean has undertaken several research projects related to fluid dynamics and oar blade propulsion.

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REVIEW ARTICLE

Leveraging Transformer Architecture and Deep Learning Models for Plagiarism Prevention in Music Composition

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ABSTRACT: Advancements in Artificial Intelligence have brought many new changes in numerous fields, including digital media, content creation, visual arts, and music, by empowering translation, composition, and originality evaluation. However, with the rise of AI generating creative content, such as musical compositions, it has demonstrated the ability to imitate human works. This capability is causing concern for almost inadvertent plagiarism, highlighting a need for building strategies and support that can guarantee the creativity of AI-driven compositions. This paper explores the application of deep learning models and, by extension, transformer architectures to avoid literary theft in music composition and generation. This paper also evaluates strategies for music transcription, originality assessment, and multimodal music modeling, leading to an analysis of existing approaches to propose a comprehensive framework for plagiarism detection and prevention. This paper leverages transformer-based architecture and other various techniques, including sequence-to-sequence, data augmentation, and self-supervised learning, to ensure creativity and ethical compliance in AI-generated content. By analyzing and comparing findings from multiple studies and integrating advanced AI methodologies, this work expects to highlight the potential for multi-disciplinary applications of these models. Furthermore, this study underscores the importance of originality assessment tools in safeguarding intellectual property rights while fostering innovation in the music industry.

KEYWORDS: Robotics And Intelligent Machines, Machine Learning, Transformer Technology, Deep Learning, Plagiarism Detection.

Introduction

As AI is rapidly growing and expanding in all fields, artificial intelligence-generated content (AIGC) is found everywhere. With the application of AI in fields such as music, many concerns have been raised about the content and legalities it produces, leading to plagiarism of younger or newer artists' work as a byproduct of AIGC.[1] Recent research highlights the role of transformer technology in generating new music using AI, while still safeguarding the intellectual property of the original composition. Studies in this field have explored methodologies such as multimodal music representation modeling, sequence-to-sequence architectures, and data augmentation to protect the original composition.[2]

Numerous models are built and enhanced to create new and innovative solutions in the field of AI and Machine Learning. Transformer models and deep learning technologies have revolutionized how data is processed and generated, particularly in the field of music. Transformers, such as Google's Music Transformer and OpenAI's MuseNet, utilize multi-layered neural networks to analyze patterns and relationships in data to compose new music.[3] The deep learning networks and transformer models are able to learn complex structures from large datasets, gaining the ability to generate highly original outputs, though their reliance on existing works also raises concerns about unintentional plagiarism.[4]

This paper explores how transformer-based models and deep learning technologies can be enhanced and utilized to avoid copyright infringement in music generation. By analyzing recent studies and leveraging on the modern methodologies, this article aims to propose a framework that balances innovation and ethical compliance, ensuring that AI-generated music contributes to the evolving creative landscape while protecting the original content.

Discussion

1. Overview of Transformer Technology and Deep Learning in Music Composition:

1.1 Deep Learning Models:

Deep Learning, at its core, is a multi-layered neural network that learns directly from data without any manual feature extraction to find patterns and make predictions (Figure 1). Various deep learning architectures exist, such as Convolutional Neural Networks (CNNs), which are effective at analyzing spatial data like images, and Recurrent Neural Networks (RNNs), which are designed for sequential data like music or text. A transformer is another multi-layered neural network architecture that can learn complex patterns and hierarchical features from data. Applications like OpenAI's MuseNet and Google's Music Transformer have used some proprietary transformer-based mechanisms to analyze and compose new music on request, often proving their capability of mimicking specific styles or genres.[5] However, this capability also introduces significant challenges like plagiarism.

In the context of music composition, the model must read vast amounts of publicly available datasets for musical notes and audio & video files and go through multiple layers to identify underlying patterns such as melody, rhythm, and harmonic

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structure.[6] Each layer performs a specific function and feeds the output to the next connected layer. While the model and tools are built to expand possibilities, concerns have arisen about the ethical and legal implications of the outcome. Models are being trained on existing and original musical works, so any output is some form of reproduction of original work's patterns and melody fragments that might closely resemble copyrighted compositions and unintentional plagiarism. In the creative industries, particularly music generation, deep learning has been used to create original compositions, generate harmonies, and even mimic the styles of specific artists.[7]

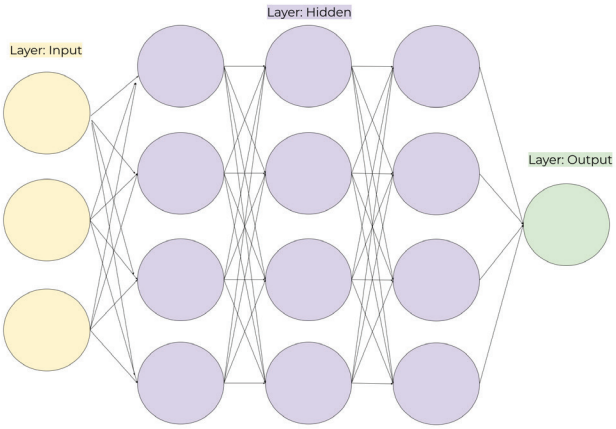

Figure 1: A graphical image of a deep learning model shown as layers of connected nodes. The model shown has an input layer that takes in the data, then processes the data through the interconnected series of hidden layers, and sends a result at the output layer.

1.2. Transformer Models:

The transformer model is an enhanced machine learning neural network model that uses a self-attention mechanism to efficiently process entire sentences in parallel and understand the context of the sentence. This mechanism understands and preserves the meaning of each element in the sequence, unlike recurrent neural networks (RNNs) and long short-term memory networks (LSTMs),[8] which process one word at a time (Figure 2). The model is built from two key components, the encoder and decoder. An encoder reads input sequences and is able to create contextual representations of the sequences. A decoder uses the representations to generate the output sequence. This architecture allows for the transformer to preserve the meaning of each element and model short-term and long-term dependencies with high accuracy. This model has been effectively used in the field of music composition to capture the intricate structure and flow of music notes & text and identify more patterns and significantly improve the quality of output. We could efficiently use this model for composing new music without copyright infringement or for checking if the composition is plagiarized. OpenAI's MuseNet and Google's Music Transformer use this model and capture both short-term and long-term dependencies to generate music.

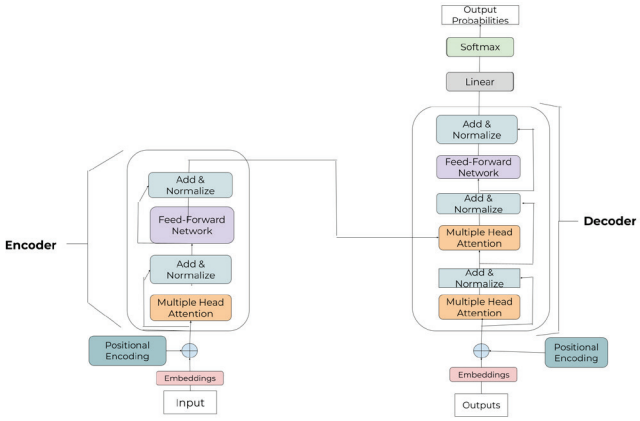

Figure 2: Transformer architecture showing information flow. The beginning input sequence goes through an encoder, which extracts the context of each element. The encoder then sends the information to the decoders, which use the information to create an output probability. This lets the Transformer keep relationships across entire sequences efficiently and preserve meaning from input to output.

1.3. Summary of Models and Impact:

While AI applications in the field of music expand the possibilities of music composition, it intricately brings issues regarding the ethical and legal implications of the compositions it generates. Learning from existing datasets of music and related files, these models can generate highly convincing compositions. However, the output may often overlap with the original works they were trained on. It could be a complete overlap or slight modifications in melody and chord progressions, and could bring considerable intellectual property violations. Deep learning models are often described as "black boxes" due to the difficulty in assessing their decisions.[9] This creates a bigger issue as it becomes harder to determine whether the generated piece is indeed original or subtly plagiarized. While AI has revolutionized music composition and helped in curating more musicians, specifically newcomers, it is vital to have a progressive development in complementary technologies like plagiarism detection for ensuring that AI-driven creativity remains both ethical and legally compliant.

2. Current Applications in Music Generation and Originality Assessment:

2.1. Originality Assessment Tools in AI Music Generation:

Originality Assessment Tools are critically important to prevent unintended plagiarism.[10] They use implementations of similarity scoring techniques, like cosine similarity or dynamic time warping, to compare generated output against available datasets. These tools often rely on symbolic representations of music such as MIDI data (Musical Instrument Digital Interface), a digital standard that stores musical information not as sound, but as instructions, such as which notes are played, how long they last, and how hard they are pressed on a keyboard. Because MIDI files capture the structure of music rather than including recordings of instruments, they are useful for training machine learning models and comparing sequences for melodic similarity, harmonic overlap, and rhythmic patterns.[11] The goal of these tools is to measure and ensure the generated music diverges sufficiently from the model data. MuseNet,

an originality assessment tool, typically uses similarity scoring techniques to compare the works.

2.2. Integration of Originality Scoring with Generation:

Modern transformer models are sophisticated and have originality scoring integrated in the process. Due to its multi-layered neural network, adding the scoring as one of the layers is not a surprise feature. For example, we could have a model that can be trained with constraints and penalize the generation of highly similar melodic fragments during output synthesis (Figure 3).[12] Some post-generation tools evaluate for the uniqueness score after its creation, flagging sections that may require revision to avoid potential infringement. This dual-layered approach ensures a balance between creative flexibility and the protection of intellectual property.

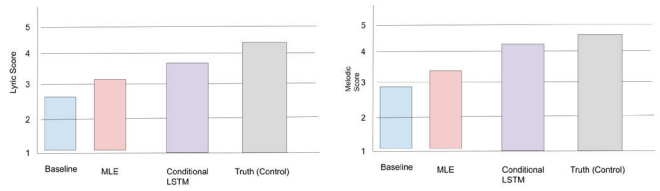

Figure 3: Tables of lyrical and melodic scoring between different model generations and analysis on a scoring of 1-5. The table consists of four bars: Baseline, MLE (Maximum Likelihood Estimation), Conditional LSTM, and Truth (control). Each bar represents the lyric or melodic score, depending on the graph, of the model generations, with higher values indicating more corresponding accuracy between generated melodies and lyrical input. The Baseline and MLE models show lower scores due to more generic melodic outputs. However, the Conditional LSTM shows improved coherence between the generated melody and lyrical text when compared to the Truth control bar. These graphs show researchers a visualized effectiveness between human creativity and originality in melody generation.

3. Challenges in Music Plagiarism Detection:

3.1. What is Plagiarism in Music?:

The topic of defining plagiarism in music becomes complex when considering topics like multi-dimensionality and substantial similarity. Some topics needed to be analyzed more than the multi-dimensionality of the music and its plagiarism: melodic similarity, note-for-note copying, checking for repeating specific note sequences and chord progressions, resemblance to other harmonies, structural overlap, and even checking for broader patterns in music, such as phrasing, tempo, and song structure.[13] The complexity and multidimensionality of the topic make defining and identifying plagiarism in music fundamentally challenging. Music often could rely on shared harmonics, cultural motifs, themes, and classical rhythms. Some may often credit the original composer for using their rhythms, while some may inadvertently include them in their compositions. So, plagiarism in music is as important as protecting any intellectual property. It helps in the longevity of the original composers and the entire musical industry. We may notice some of our favorite tunes sound very similar to other hit songs. It is challenging to identify plagiarism in music, especially with a limited set of defined chords and progression sequences. An example of this may be the well-known song "Flowers" by Miley Cyrus, allegedly plagiarizing Bruno Mars's "When I Was Your Man" in terms of lyrics and melodies.[14] While they may both sound the same in terms of lyrics, message, and melody, these are both still enjoyable songs that happen to share defined chords and progression, leading to prime research issues regarding how machines should analyze and detect plagiarism in pieces. For the focus of the article, plagiarism is simplified into the fact of analyzing melodic, harmonic, and the structural integrity of AI-driven compositions and focusing on if the models can pick up on existing motifs that may be prominent in other pieces, thus being plagiarized, or if the themes are too broad to be relatively close to any existing pieces, thus being somewhat original.

3.2. Limitations of Existing Detection Tools:

Traditionally, plagiarism detection has been based on certain rules. While these rules have led to innovations that could catch and flag some works, they struggle to handle the nuances of creativity. Historically, rule-based checks were built to check exact note sequences or chord patterns, leading towards potential failure to capture certain methods of variations like a model using live transpositions or rhythmic modifications that alter surface details yet maintain the musical essence of a piece to avoid plagiarism detection.[15] For example, tools like Melisma Music Analyzer rely on symbolic pattern matching, which has the limitations of overlooking abstract similarities between pieces. Other AI-driven models, on the other hand, offer more enhanced pattern recognition for users but can ultimately overflag legitimate creative overlaps due to the models' extreme sensitivity towards data similarities. Ultimately, plagiarism detection reaches a standstill. Too many flags can make a piece uninteresting and spread heightened fear across the music industry. However, multiple false positives may result in low trust in the checking process of plagiarism detection and may cause inconvenience to both parties.

3.3. Balancing Originality Enforcement and Creative Freedom:

As discussed, there are multiple challenges with the pressing issue of creative freedom with the application of machine learning models. The issue essentially is with using models ethically, especially in plagiarism detection. The models need to be within a state to balance creative freedom with the power to enforce originality. Music, by nature, involves innovative and continuous repetition of harmonic and melodic patterns to create a work of art adorned by all. An example of the continuous repetition in patterns is seen in common chord progressions like the I-V-vi-IV progression sequence, being extremely versatile and used across multiple genres of music throughout time.[16] The example shows that imposing rigid detection standards, such as strict rules on how plagiarism should be detected, could lead to a reduction in creativity because artists are discouraged from using shared musical language, such as chord progressions. However, models that use a more moderate approach towards detection risks would also not be very beneficial, as it allows for subtle bits of plagiarism to go undetected. Therefore, there is an urgent need to develop an effective detection system that must account for both musical innovation and traditionally accepted pattern repetition, distinguishing between influence and infringement.

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4. Methods for Plagiarism Prevention Using Transformer Models:

4.1. Sequence Comparison, Feature Extraction, and Self-Supervised Learning:

Multiple studies have proven that transformer models utilize techniques such as feature extractions and sequence to show promising results in the fields of plagiarism detection and even prevention. For example, the use of feature extractions in systems such as the chroma vectors and Mel-Frequency Cepstral Coefficients (MFCCs) has allowed for a deeper and more accurate analysis within patterns beyond the basic note-for-note comparisons.[17] The technique of sequence comparisons means using functions that involve breaking down information into usable data for models, or in this case, breaking down parts of musical pieces, such as rhythm, pitch, and intervals, into usable data for symbolism and detection models. This data is then sent into the model to be analyzed with pre-made similarity metrics to analyze plagiarism.[18] Both the techniques of sequence comparison and feature extraction can be used to allow transformer models to identify structural similarities within certain musical elements, such as key or tempo differences, helping models study and accurately describe plagiarism better.

Other transformer models, such as self-supervised learning (SSL), have been proven to be a strong and accurate plagiarism detection tool. SSL has shown potential in plagiarism detection, especially in musical generation, as seen in many studies.[19] SSL has taken the approach of training a model on large datasets without many labels, allowing for the development of identifying patterns and relationships in data more efficiently than other models. Contrastive learning and other learning patterns have proven to be distinguished techniques to allow the model to differentiate the original and plagiarized compositions by generating negative samples during training. Other forms of learning, such as data augmentation, can improve a model's ability to detect similarities across datasets, utilizing tempo and transposition alterations to reduce bias in originality assessment.[20]

4.2. Hybrid Approaches: Similarity Detection and Creative Constraints:

Checking and preventing plagiarism involving hybrid approaches that would combine similarity detection with creative constraint mechanisms has shown promising results. A multi-layer transformer model could generate music while continuously evaluating the similarity of each segment against a reference dataset and generating similarity scores. If the generated similarity score exceeded a predefined threshold, the multi-layer transformer model could alter its generation process in real time through certain methods, such as adjusting melodic intervals or rhythmic patterns to create and protect the original composition.[21] Moreover, certain creative constraint mechanisms, like forcing the generation of non-repetitive motifs and limiting the reuse of particular harmonic patterns, can be integrated during music generation. This hybrid of using mechanisms and models ensures that the generated compositions remain both innovative and compliant with intellectual property standards.

5. Case Studies and Results:

5.1. Deep Learning in Music Similarity Detection:

Several studies have applied various deep learning models to detect similarities, with notable success in advancing plagiarism detection in music. For instance, a study employing convolutional neural networks (CNNs) trained on spectrograms demonstrated how visual representations of audio can effectively capture melodic and harmonic features (Figure 4).[22] CNNs were chosen because they are especially good at recognizing patterns within images, and they can use spectrograms to turn sounds into a form of visual output to show how frequencies change over time. This, overall, makes the CNNs more practical than models like transformers, as models like transformers require larger datasets and more computational power. The study tested with CNNs on a variety of music genres found high accuracy in distinguishing musical styles and detecting similarities, showing that using spectrograms can reliably capture the "fingerprint" of a music piece. Another successful example is the use of Siamese networks, which compare pairs of musical inputs and measure their similarity scores is another successful example.[23] These approaches enable us to go beyond simple symbolic representations in identifying similarities in the music.

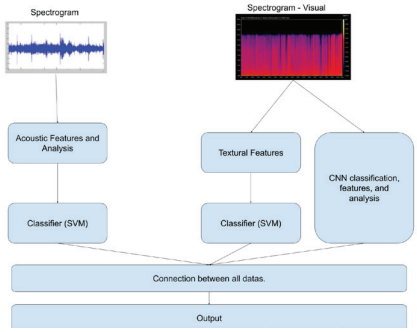

Figure 4: Diagram of CNN trained on spectrograms and how it can capture and evaluate melodic and harmonic features.[22] This diagram shows the pipeline of audio processing by converting audio signals to spectrograms. The spectrograms are then used within CNNs to identify recurring spectral patterns relating to melodic and harmonic structures. The CNN then pools the layers to compress the data while maintaining key features of the frequency. It then connects all the data from classifiers to evaluate whether the two inputs share overlap in melodic and harmonic content.

5.2. Metrics for Plagiarism Prevention:

If detecting plagiarism in music is a daunting task by itself, the performance of achieving such a feat with the best score is yet another. Performance in plagiarism is often evaluated using: precision, which measures how accurately the system identifies plagiarism cases without over-flagging original work; recall, which assesses its ability to detect all instances of plagiarism in a dataset; and F1 score, which provides a single performance indicator while balancing the metrics.[24] In one of the benchmark studies, models like Music Transformer achieved precision rates exceeding 85% for melodic similarity detection, underscoring their effectiveness.[25] However, achieving high re-

call remains a challenge due to the subtlety of variations in musical compositions.

5.3. Impact of Case Studies on Practical Application:

Our case studies demonstrate the potential of deep learning based applications for music originality assessments. Integrating metrics with qualitative analysis, like human evaluations of flagged outputs, researchers can refine models to better align with creative and cultural contexts. This balance of human interpretability and technical accuracy is vital for the advocacy of AI tool usage and legitimacy in creative industries and continues to support creativity.

6. Ethical and Legal Implications:

6.1. Intellectual Property in AI-Generated Music and Transparency:

Protecting intellectual property rights from AI-generated music is an important task and comes with a lot of intricate questions. Determining liability is equally challenging from AI-generated tunes. Does the responsibility fall on the developer, the user, or the AI system itself? Current copyright laws, often designed for human creators, struggle to address these ambiguities.[26] As with time and technology, the binding legal frameworks need some updates to consider the unique nature of AI creativity. Transparency in how AI systems that generate and evaluate music is crucial for their ethical use. Explainable AI, or XAI, shows insights into the decision-making processes of models, enhancing trust and accountability.[27] For example, an AI tool that flags potential plagiarism should clearly state which elements of a composition, melody, harmony, or rhythm triggered the flag. Providing this level of detail can help creators address issues proactively and avoid unnecessary legal disputes.

6.2. Balancing Innovation and Ethics:

People must create a balance between ethical standards and innovation to grow and change AI technology. AI tools have unlocked unparalleled levels of creativity for audiences, but have also brought about the risks of intellectual property theft, raising alarm for concerned people. Fixing this issue would require policymakers, researchers, and legalists to collaborate and establish new guidelines that could promote responsibility in AI development with the mindset of protecting intellectual rights.

7. Future Directions and Innovations:

7.1. Advances in Model Architecture:

Future advancements in transformer models could focus on enhancing their ability to multi dimensional analysis and provide more insights into explainability. Techniques that could combine audio, text, and symbolic data could improve the precision of similarity detection.[28] Additionally, advancements in sparse and adaptive-based attention mechanisms may allow models to process longer compositions without compromising computational efficiency, enabling more detailed analysis. Collaboration between technologists and musicians will play a pivotal role in shaping the future of plagiarism prevention.[29] Exchanging valuable insights into the nuances of creativity and originality would help technologists design better mechanisms to validate the composition. Hackathons and joint research projects are some of the initiatives that can accelerate innovation in the field.

7.2. Expanding Ethical and Cultural Contexts:

Cultural and historical knowledge has become so advanced and critical that integrating it with AI systems may allow for better originality and credibility of AI-generated music. As an example, a model study trained on a diverse knowledge set of global musical traditions could analyze and understand that certain cultural overlaps and shared motifs can be avoided as plagiarism.[30] For instance, recognizing that melodies like national anthems or folk songs carrying deep cultural meaning in the world would help an AI avoid misclassifying them as plagiarized content, which would also ensure that generated music shows accuracy and cultural respect for world traditions.

■ Conclusion

With the trending and growing innovations in transformer and deep learning models, artificial intelligence has expanded and evolved in creating music and other artistic expressions that seem almost life-like and man-made, shifting attention towards the overall originality, ethical, and legal debates of AI. Transformer and deep learning models have expanded the field of creativity towards a wider span of artists and can even play a critical role in helping copyright protection and originality enforcement. This article leverages multi-layer neural networks and their functionality to bring about examples of transformer models improving and safeguarding intellectual property rights. This article raises awareness towards originality assessments in order to further protect and preserve the ethics of AI-generated music. There are many tools available to the general public, which are all capable of generating compositions, and many techniques, such as self-supervised learning, which have shown effectiveness in evaluating plagiarism. The challenges of defining plagiarism boundaries by balancing between creativity and originality highlight the inherent complexity and limitations of the systems. With the expansion of AI, ethics and legalities must stand as a top priority, along with accountability and transparency being within the purview of artists, technologists, and legal experts to address these concerns. Research must also focus on refining models and architectures to improve plagiarism detection accuracy, fostering an innovative future for AI-driven music composition.

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References

1. Li, Y., Milling, M., Specia, L., & Schuller, B. W., "From audio deepfake detection to AI-generated music detection -- a pathway and Overview." 2024-12-10. [Online]. Available: https://arxiv.org/abs/2412.00571
2. WATANABE, K., & GOTO, M., "A text-to-lyrics generation method leveraging image-based semantics and reducing plagiarism risk. IEICE Transactions on Information and Systems.", 2024-11-13. [Online]. Available: https://www.jstage.jst.go.jp/article/transinf/advpub/0/advpub_2024EDP7104/_article
3. Lupker, Jeffrey A. T., "Music for Self-Attention", ProQuest, 2021. [Online]. Available: https://www.proquest.com/openview/1c3a99464fb55bd7fe8aa6bbc8d81325/1?pq-origsite=gscholar&cbl=18750&diss=y
4. 서울대학교 대학원, "Automatic music lead sheet transcription and melody similarity assessment using Deep Neural Networks. SNU Open Repository and Archive: Automatic Music Lead Sheet Transcription and Melody Similarity Assessment Using Deep Neural Networks", 2023-1-1. [Online]. Available: https://s-space.snu.ac.kr/handle/10371/193130
5. Ferreira, P., Limongi, R., & Luiz, "Generating Music with Data: Application of Deep Learning Models for Symbolic Music Composition." 2023. [Online]. Available: https://doi.org/10.3390/app13074543
6. Hernandez-Olivan, C., & Beltrán, J. R., "Music composition with Deep Learning: A Review.", 2022. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-031-18444-4_2
7. Deltorn, J.-M., "Deep Creations: Intellectual Property and the Automata. Frontiers in Digital Humanities", 2017. [Online]. Available: https://doi.org/10.3389/fdigh.2017.00003
8. Sherstinsky, A., "Fundamentals of Recurrent Neural Network (RNN) and Long Short-Term Memory (LSTM) network." Physica D: Nonlinear Phenomena, 2020. [Online]. Available: https://doi.org/10.1016/j.physd.2019.132306
9. Hassija, V., Chamola, V., Mahapatra, A., Singal, A., Goel, D., Huang, K., Scardapane, S., Spinelli, I., Mahmud, M., & Hussain, A., "Interpreting Black-Box Models: A Review on Explainable Artificial Intelligence. Cognitive Computation, 16(1)", 2023. [Online]. Available: https://doi.org/10.1007/s12559-023-10179-8
10. Dai, S., Donahue, C., Zhu, J., & Xia, G., "Thesis Proposal Towards Artificial Musicians: Modeling Style for Music Composition, Performance, and Synthesis via Machine Learning." 2024. [Online]. Available: https://www.cs.cmu.edu/afs/cs.cmu.edu/Web/Posters/Shuqi_PhD_Thesis_Proposal.pdf
11. Yin, Z., Reuben, F., Stepney, S., & Collins, T., "A good algorithm does not steal – it imitates": The originality report as a means of measuring when a music generation algorithm copies too much.", 2021-1-1. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-030-72914-1_24
12. Yu, Y., Srivastava, A., & Canales, S., "Conditional LSTM-GAN for Melody Generation from Lyrics. ACM Transactions on Multimedia Computing, Communications, and Applications, 17(1), 1–20", 2021. [Online]. Available: https://doi.org/10.1145/3424116
13. Alzahrani, S., Salim, N., Abraham, A., "Understanding Plagiarism Linguistic Patterns, Textual Features, and Detection Methods", Ieeexplore.ieee.org, 2024. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/5766764
14. Siemons, J., "Miley Cyrus, Bruno Mars Songs' parallels sit at heart of IP case.", Bloomberg Law, 2024-9-24. [Online]. Available: https://news.bloomberglaw.com/ip-law/miley-cyrus-bruno-mars-songs-parallels-sit-at-heart-of-ip-c ase
15. Mitseas, P., "Deep learning methods for cover song identification. Αρχική Σελίδα", 2023-4-13. [Online]. Available: https://dione.lib.unipi.gr/xmlui/handle/unipi/15492
16. Bergstrom, T., Karahalios, K., & Hart, J. C., "Isochords. Proceedings of Graphics Interface 2007 on - GI '07", 2007. [Online]. Available: https://doi.org/10.1145/1268517.1268565
17. Abdul, Z. Kh., & Al-Talabani, A. K., "Mel Frequency Cepstral Coefficient and its Applications: A Review.", IEEE, 2022. [Online]. Available: https://doi.org/10.1109/ACCESS.2022.3223444
18. Pon Abisheka, C. Deisy, & P. Sharmil. "T-SRE: Transformer-based semantic Relation extraction for contextual paraphrased plagiarism detection. Journal of King Saud University - Computer and Information Sciences, 102257–102257.", 2024. [Online]. Available: https://doi.org/10.1016/j.jksuci.2024.102257
19. Liu, X., Zhang, F., Hou, Z., Mian, L., Wang, Z., Zhang, J., & Tang, J., "Self-supervised Learning: Generative or Contrastive", IEEE Transactions on Knowledge and Data Engineering, 1–1, 2021. [Online]. Available: https://doi.org/10.1109/TKDE.2021.3090866
20. Gonçalves, G., "A Comparative Study of Data Augmentation Techniques for Image Classification: Generative Models Vs. Classical Transformations", ProQuest, 2020. [Online]. Available: https://www.proquest.com/openview/7221c51b7be5f9d8fdf73e-88375a76e0/1?pq-origsite=gschol ar&cbl=2026366&diss=y
21. Zhang, N., Yan, J., & Briot, J.-P., "Artificial intelligence techniques for pop music creation: A real music production perspective. Accueil - Archive ouverte HAL.", 2023-12-24. [Online]. Available: https://hal.science/hal-04363458/
22. Costa, Y. M. G., Oliveira, L. S., & Silla, C. N., "An evaluation of Convolutional Neural Networks for music classification using spectrograms. Applied Soft Computing, 52, 28–38", 2017. [Online]. Available: https://doi.org/10.1016/j.asoc.2016.12.024
23. Guo, R., "AI Pop Music Composition With Different Levels of Control: Theory and Application." 2023. [Online]. Available: https://www.researchgate.net/profile/Rui-Guo-60/publication/379513028_AI_Pop_Music_Composition_with_Different_Levels_of_Control_Theory_and_Application/links/660d20f2390c214cfd31134
0/AI-Pop-Music-Composition-with-Different-Levels-of-Control-Theory-and-Application.pdf
24. Gupta, D., "IDENTIFYING DOCUMENT-LEVEL TEXT PLAGIARISM: A TWO-PHASE APPROACH", Journal of Engineering Science and Technology. 2017. [Online]. Available: https://jestec.taylors.edu.my/Vol%2012%20issue%2012%20December%202017/12_12_9.pdf
25. Garg, M., Gajjar, P., Shah, P., Shukla, M., Acharya, B., Gerogiannis, V. C., & Kanavos, A., "Comparative Analysis of Deep Learning Architectures and Vision Transformers for Musical Key Estimation", 2023. [Online]. Available: https://doi.org/10.3390/info14100527
26. Watiktinnakorn, C., Seesai, J., & Kerdvibulvech, C., "Blurring the lines: how AI is redefining artistic ownership and copyright", Discover Artificial Intelligence, 2023. [Online]. Available: https://doi.org/10.1007/s44163-023-00088-y
27. Sankalpa Thalpage, N., "Unlocking the Black Box: Explainable Artificial Intelligence (XAI) for Trust and Transparency in AI Systems", Institute of Cited Scientists, 2023-6-26. [Online]. Available: https://ics.events/journal-of-digital-art-humanities/unlocking-the-black-box-explainable-artificial-int elligence-xai-for-trust-and-transparency-in-ai-systems/
28. Baltrusaitis, T., Ahuja, C., & Morency, L.-P., "Multimodal Machine Learning: A Survey and Taxonomy", IEEE Transactions on

Pattern Analysis and Machine Intelligence, 2019. [Online]. Available: https://doi.org/10.1109/tpami.2018.2798607
29. Micunovic, M., & Balković, L., "Author's rights in the digital age: how Internet and peer-to-peer file sharing technology shape the perception of copyrights and copywrongs", Libellarium: Journal for the Research of Writing, Books, and Cultural Heritage Institutions, 2016. [Online]. Available: https://doi.org/10.15291/libellarium.v0i0.232
30. Eilifsen, T. N., " Mimicking the Student: A Feature-Based Approach for Detecting AI-Generated Texts and Verifying Authorship in Educational Settings", Ntnu.no, 2024.

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REVIEW ARTICLE

Beyond The Music: Understanding K-pop As a Global Business Model

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ABSTRACT: K-pop has grown from a Korean music style into a global industry, reshaping the way people think about pop culture. Its rise is not only about catchy music but also the result of strong business models, government support, digital platforms, and the active role of fans. This paper brings these perspectives together to show how K-pop's success is built on the mix of culture, strategy, and innovation. The study uses a review of existing research and case examples to connect insights from politics, economics, and cultural studies. The main finding is that K-pop's success cannot be explained by looking at any single factor in isolation. Instead, its global impact comes from how culture, business strategies, and fan practices all reinforce one another inside a connected system. Still, issues like artist well-being, profit distribution, and long-term sustainability remain. Future research should focus on smaller agencies, fan communities, and new technologies.

KEYWORDS: Economics, Cultural Economics, Globalization, Business Models, K-pop Industry.

Introduction

Over the past two decades, K-pop has expanded from a local Korean music industry into a worldwide cultural force. Its influence is seen not just in music but also in tourism, fashion, and digital media. Scholars have studied K-pop through multiple lenses—politics, economics, cultural studies, and innovation[1]—but many of these studies focus on just one angle at a time. This review aims to build a more holistic understanding of K-pop's success by connecting insights across disciplines. It looks at how government policy, copyright law, industry innovation, fandom, and global marketing all interact to make K-pop a sustainable business model.

Discussion

An introduction to the K-pop industry and its success - From politics and culture to innovation:

In order to understand the particulars of the K-Pop industry, a thorough review of the relevant literature is required. Messerlin and Shin analyzed the main economic forces behind the remarkable evolution of K-pop in terms of how it spread from South Korea to the rest of Asia, the US, Latin America, and the Middle East.[1] They analyzed industry data like sales, exports, and online visibility (such as YouTube views) to measure K-pop's impact. They used comparative analysis to compare South Korea's music industry with other countries like France, Japan, and the US. They also applied market concentration tools like the Herfindahl index to see how competitive the Korean music market is. Their study looked at pricing models, especially how low online music prices in Korea created pressure to produce more music and go global. K-pop grew fast because of Korea's strong internet, low online prices, and lots of competition between music companies. This pushed K-pop companies to go global and create many different types of songs and groups. Even though the Korean government built the internet infrastructure, it was small private companies that used it the most to grow K-pop. K-pop also became very visible around the world through free platforms like YouTube. The success of K-pop did not come from governmental support, but from smart business choices. Small companies made the right kind of music and used the internet well. Their focus on visuals and global appeal helped K-pop grow outside of Korea. Messerlin and Shin's study shows that through creative business strategies and the utilization of technology, a big cultural impact can emerge.[1] Despite the important aspects raised by Messerlin and Shin, their paper lacks full data on production internalization and the challenge of measuring visibility as it digitalizes, as they did not discuss this in depth. In addition, their study lacks direct data from K-pop companies. The paper relied heavily on public statistics and secondary sources. Also, most data is from 2006 to 2013, while there is a potential imbalance between the two main aspects discussed in their study (i.e., the economic and emotional factors). The authors challenge other popular explanations on the rise of K-Pop, like public subsidies and cultural proximity, and they highlight the contribution of private sector innovations and the competitive market.[1]

In a later study, Parc, Messerlin, and Moon analyzed the relationship between copyright regulations and the rise of K-pop, focusing on how a well-balanced copyright system and piracy influenced the global success of Korean pop music.[2] Their study uses an economic and business-based approach that includes real-world data, historical analysis, and international comparisons. It applies Porter's Diamond Model to study the competitiveness of the K-pop industry and explore how piracy and copyright laws affected its growth. This framework helps them understand the impact of market conditions, technology, and government policy on K-pop's global rise. The authors find that K-pop's success is linked to weak copyright laws and the spread of pirated music in Korea, especially from the 1960s

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to the 2000s. Piracy made global music more accessible to young Koreans, which encouraged creativity and helped develop a unique Korean style. The internet and social media helped K-pop spread globally without relying on strong copyright protection. Instead of depending on album sales, K-pop companies earned money through concerts, merchandise, and fan engagement. The authors argue that strict copyright laws are not always needed for cultural growth. They argue that a well-balanced copyright system that avoids monopolies and allows free access to content can support creativity and innovation. The K-pop case shows that openness to global influences, smart use of digital tools, and flexible copyright policies can help cultural industries grow in a competitive world. Some are implied, such as generalizing Korea's case to other cultural markets, and the lack of deep empirical datasets. The paper mainly focuses on the Korean context and does not offer much comparison with other countries. It lacks quantitative data to support some of its conclusions and does not explore the long-term risks of weak copyright systems in depth. The paper pushes back against the common belief that strict copyright laws always lead to more creativity. Instead, it shows that having more relaxed copyright rules can actually help culture grow and spark innovation in unexpected ways.[2]

Most recently, Saeji explored how K-pop fans have moved from being just consumers to becoming active producers in what the author calls the "K-pop adjacent industries."[3] These include fan-run businesses, content creators, educators, and community builders who operate outside of official entertainment companies. The goal is to understand how these participants influence, support, and benefit from the K-pop ecosystem. The study uses a qualitative approach based on long-term ethnographic research. Saeji conducted both in-person and online interviews with 17 individuals involved in the K-pop adjacent industries, including fans, artists, journalists, YouTubers, dancers, and group order managers. The study also incorporates personal observations, case studies, and analysis of media and fan practices. It was found that K-pop's rise has also given birth to an entire shadow economy made up of passionate fans who turn their enthusiasm into entrepreneurial ventures. The key participants in this context create everything from merchandise and YouTube content to tours and fan events. While they do not produce music directly, their work helps build the image and global reach of K-pop idols. These adjacent industries also act as bridges between idols and international fans. Despite often operating informally or without licenses, their impact on fan culture and the K-pop economy is significant. The paper argues that K-pop adjacent industries play a major role in shaping K-pop's global success. They blend passion with entrepreneurship and fill gaps left by official companies, offering customized, fan-centered experiences. While they exist in a legal grey area, their presence adds richness and interactivity to K-pop culture. These industries highlight how fans can shift from passive consumers to powerful contributors in global pop culture. While the paper offers an important insight into the industry, it does not discuss some challenges, like the long-term sustainability of fan businesses or the legal grey areas they operate in. It also lacks quantitative analysis and mostly reflects individual experiences, which may not represent the broader industry. The paper builds on central theories like "participatory culture" and "shadow economies," and it adds new insights by focusing on how fan entrepreneurship blurs the line between fandom and the actual industry.[3]

In 2020, Jin explored how J-pop and K-pop differ in their approaches to hybridity, particularly in relation to globalization and cultural production, while it identified how the mutual influence and divergence between the two industries shaped the identity and global positioning of K-pop.[4] The author used a comparative discourse analysis, combining textual analysis and political economy. The qualitative approach used in Jin's paper traces the historical transformation of K-pop in relation to J-pop, analyzing content, production systems, idol culture, social media, and copyright practices. K-pop was initially influenced by J-pop, especially in idol training systems and music production, but evolved differently due to its strong digital strategy, social media usage, and more politicized hybrid identity. While J-pop remained domestically focused and restricted by copyright control, K-pop adapted to global markets by embracing English mixing, fan engagement, and visual production. The study also highlights the structural and textual hybridization of both industries, and it concludes that K-pop has moved beyond its J-pop roots by developing its own hybrid cultural space—a "third space"—that blends local and global influences. This hybridization, especially through digital platforms and sociocultural messaging, helped K-pop gain worldwide popularity. In contrast, J-pop's "odorless" and depoliticized approach limited its international reach. The study focuses on discourse analysis and cultural theory without including industry data or fan perspectives. This narrows the analysis to a theoretical level and limits its practical applicability. Jin's study engages with key debates on hybridity, cultural identity, and transnational media, and it contributes to the literature by framing K-pop's rise as part of a larger shift toward hybridized cultural forms in the digital age, which distinguishes it from J-pop's more localized approach.[4]

Business Model and System of the K-pop Industry:

In a recent study, Liu examines how Korea's collectivist culture has shaped the structure and business model of its music industry, and how this has helped K-pop succeed globally.[5] The paper also considers how the industry may evolve in the face of future challenges and technologies like Web 3.0 and virtual idols. The author uses a literature-based analytical approach, reviewing previous academic sources and industry trends to explain the evolution of Korea's music business models. The paper divides the industry's development into three stages—Music Industry 1.0, 2.0, and 3.0—based on historical shifts in production, digitalization, and fan engagement, and it finds that Korea's idol trainee system, assembly-line production structure, and collectivist mindset created a high-efficiency industry model. This model emphasizes group success over individual creativity. The paper also identifies key strategic phases, including the Global-Local-Global (G-L-G) strategy and its evolution into G-L-G+V (virtual), reflecting the integration of advanced technologies like AI and online

fan platforms. Korea's collectivist and systematic approach has helped the K-pop industry become globally competitive, but it may also limit individuality and creativity. As the industry enters a new digital era, it must balance standardized systems with innovation and authenticity. The author argues that adaptation to virtual platforms and maintaining artist distinctiveness are essential for future sustainability. The paper is largely theoretical and lacks empirical data to support its claims, and it also generalizes the impact of collectivist culture without presenting counterexamples or variability across different K-pop companies. The paper supports the view that K-pop's structure is shaped by Korea's societal values while also offering a framework to assess how those values influence long-term sustainability in a digital era.[5]

Lee compared the competitiveness of entertainment management companies in Korea and Japan, in an attempt to explain why Korean firms, especially those in K-pop, have been more successful in the global market.[6] Lee's study examines firm strategies, innovation, and market responses and applies a qualitative comparative analysis of entertainment firms in both countries. It uses Porter's Diamond Model to evaluate factors like demand conditions, related industries, and firm strategy. The author also reviews historical development, industry structure, and case studies of companies such as SM Entertainment (Korea) and Johnny & Associates (Japan). The study finds that Korean entertainment companies have been more competitive globally due to greater innovation, openness to foreign markets, and faster adaptation to digitization. In contrast, Japanese firms were slower to digitize, relied heavily on domestic markets, and lacked transparency in management. Korean companies also benefit from training systems, in-house production, and strong global branding. The study concludes that flexible, innovation-driven strategies give Korean firms an edge in the entertainment industry. Korea's ability to embrace globalization and technology helped K-pop grow rapidly, while Japan's traditional models limited international reach. It is recommended that entertainment companies adopt more open, strategic, and consumer-oriented approaches to stay competitive. Despite the important elements considered in the study, the research relies mainly on secondary sources and case comparisons without primary data. It also focuses on only two countries, which limits the global scope of competitiveness analysis. The conclusion connects to broader discussions on globalization, cultural industry strategies, and innovation, and it emphasizes how the open and innovation-driven business models help Korean firms outpace their Japanese counterparts.[6]

Kim and Doo look at how web dramas featuring K-pop idols can make money on Korean portal websites like Naver and Daum.[17] They wanted to figure out if using K-pop idols as lead actors in web dramas helps make those dramas more profitable and what kind of viewer behavior leads to revenue. The authors used big data analysis and focused on actual viewing and engagement data from the two specific web dramas starring K-pop idols: *EXO Next Door and I Order You*. They examined data from online platforms like Naver TV Cast and applied statistical modeling to understand the connection between clicks, views, ad revenues, and idol involvement. They found that having K-pop idols in lead roles significantly boosts viewership and ad revenue. The paper also showed that fan engagement, especially through repeat views and sharing, plays a huge role in making these dramas profitable. Ad placements and tie-in product promotions are also more effective when idols are featured. This study suggests that web dramas can be a solid business model, especially when they feature K-pop idols. This approach benefits both the entertainment companies and the portals by tapping into loyal fanbases and driving monetizable traffic. However, there are a few limitations: the data collection was confined to Mainland China; the star power was measured by the static variable; static data was still used for prediction in each stage, and the time weight of input variables was ignored. The paper contributes to ongoing discussions about how idol marketing, digital media, and fan behavior work together to create new revenue streams in the K-pop industry. It supports the idea that platform-based content strategies and multi-channel branding are central to K-pop's success in the digital age. It also adds to the literature on cultural convergence, which shows how drama and music can merge into a single monetization ecosystem.[7]

Further, Kim studies the internal flaws in K-pop's revenue model, especially how profits are unevenly distributed between music creators and distributors. The author argues that without reform, this imbalance could slow K-pop's creative growth and long-term sustainability. The study uses a policy review and data analysis approach. It compares domestic and overseas music revenue structures and analyzes market patterns using data from Google Trends, government white papers, and inter-industry production tables. In Korea, music creators receive far less of the profit than in Western markets (e.g., 36% in Korea vs. 70% on iTunes). Flat-rate subscription models used in Korea favor distributors and reduce creator earnings. K-pop plays a major role in boosting other industries like fashion, cosmetics, food, and tourism. This means that its sustainability affects the broader economy. Also, the system is overly complex and lacks transparency, discouraging creators and putting long-term quality at risk. For K-pop to remain globally competitive, structural reform is needed to ensure fairer profit distribution. Encouraging collaboration across industries and developing win-win models (like KT Music × Nexon partnership) could help strengthen the industry's sustainability. However, no direct interviews or insider testimonies were used—only data from public and government sources. The research focuses on the system as of 2012, which may not reflect newer platform changes (e.g., global streaming platforms like Spotify or YouTube monetization in the 2020s). This paper adds to discussions about creative labor rights, platform fairness, and digital content economies. It echoes concerns raised in cultural policy literature about exploitation in music industries and supports broader ideas around the economic sustainability of creative industries.[8]

Recently, Cho, Bian, and Lee explored how SM Entertainment, one of Korea's biggest entertainment companies, used digital transformation to change its business model.[15] The authors wanted to show how technology, platforms, and new

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revenue strategies helped the company grow and stay competitive in the K-pop industry. The study uses a case study approach. It focuses only on SM Entertainment, collecting data from company reports, industry statistics, and past research. It examines SM's digital strategies in areas like content production, distribution, and fan engagement. The authors found that SM moved away from relying mainly on music sales and concerts to a platform-based model. This included using fan community apps, live-streaming concerts, and selling virtual goods. By expanding into new digital areas, SM was able to connect directly with fans around the world and open more revenue streams. The paper also shows how SM created an ecosystem where music, merchandise, and digital content all work together. SM's case shows that in today's music industry, success isn't just about producing songs—it's about building a digital ecosystem. The authors argue that other companies can learn from SM's focus on platforms, global reach, and innovation to stay sustainable in the fast-changing entertainment market. However, the paper only focuses on one company, SM Entertainment, so the findings might not apply to other K-pop agencies with different strategies or resources. It also relies mostly on secondary sources like company reports and industry data, which can be biased or leave out behind-the-scenes challenges. There's no direct input from artists, fans, or smaller labels, which means some perspectives on the impact of digital transformation are missing. This study adds to the bigger conversation about how digital technology is changing the global music industry. It supports the idea that cultural industries now compete more as platform-based businesses than just content producers. It also connects to discussions on sustainability in K-pop by showing how digital ecosystems can keep revenue flowing even when physical sales drop. This makes it relevant to debates on innovation, globalization, and cultural economics.[9]

And lastly, in 2022, Kim and Kwon explained how K-pop has managed to grow into a global cultural force, focusing on its distinctive production system.[16] The authors aim to show how the way K-pop is made, marketed, and consumed is different from other music industries, and why these differences matter for its worldwide success. The study uses a historical case study method, reviewing past research, industry reports, and company examples to analyze the K-pop production system. It looks at different parts of the K-pop system, including the trainee program, song production, choreography, international promotion, and fan involvement, to show how they all connect into one efficient system. The authors find that K-pop's production system is built on long-term artist training, tight management of group concepts, and strong global marketing strategies. Fandom culture plays a huge role—fans actively promote K-pop companies and adapt content for different countries while keeping a consistent "Korean" identity. The paper also shows how K-pop companies adapt content for different countries by adjusting languages, collaborating with local artists, adding region-specific cultural elements, and tailoring promotions for local media, while still keeping the same "Korean" identity through language influence, performance style, and high production quality. The paper relies only on secondary sources. It focuses mostly on big, well-known companies like SM, JYP, and YG. This means the results may not reflect the whole industry, especially smaller labels. This research fits into bigger conversations about cultural globalization and the role of industrial systems in creative success. It supports the idea that global cultural influence comes from both the content itself and the way it is produced and marketed. It also adds to debates on how local culture can be adapted for global audiences without losing its identity.[10]

Theoretical and strategic developments in the rise of the K-pop Industry:

In a recent study, it was analyzed whether the K-pop industry is truly innovative, and explained how innovation has shaped its development.[7] The authors apply a new model called the M-ies model. This model looks at how innovators (I) respond to changing environments (E) by using strategies (S) that create innovation over time. Examples from real K-pop companies like SM Entertainment and comparisons to industries like semiconductors are used. The authors use a mix of theory, business history, and real-world case studies to support their ideas. The authors find that K-pop grew through constant innovation, especially during times when the Korean music industry faced challenges. Companies like SM Entertainment used new ideas to create idols, change the business model, and reach global fans through digital platforms. Innovation was not just in the music but also in training systems, marketing, and creating global fanbases. The study shows that innovation gave K-pop the power to compete worldwide and turn threats into new opportunities. Innovation is the main factor of K-pop's success. K-pop companies stayed competitive by creating new products, using smart strategies, and adapting to changes like digitalization. The paper says that for K-pop to stay successful in the future, it must continue to innovate and respond to global trends with creative ideas and technologies. There is a solid theoretical argument provided, but the study does not include detailed data like interviews or industry stats, which does not allow for a wider application of the findings. The study focuses heavily on SM Entertainment and does not fully analyze other companies or recent changes in the K-pop landscape. Also, since the model developed is theoretical, it lacks broad data or global comparisons. The paper positions itself against static economic models like Porter's Diamond and emphasizes the need for dynamic models in analyzing cultural industries, adding a fresh perspective to innovation literature.[11]

Kim and Kang, in the same year, explored how K-pop became globally successful by looking at two main business strategies: product adaptation and the internationalization of its music supply chain.[8] Their study focuses on how K-pop adjusted its products for different markets and collaborated with producers and choreographers from other countries to increase its global appeal. The paper is qualitative and draws from historical case studies of K-pop companies (especially SM Entertainment), industry data, and examples from Japan, China, and Western markets. International business and innovation theories are utilized to explain how K-pop adapted to foreign markets and managed upstream partnerships. K-pop succeeded in-

ternationally by adapting its products for local tastes—using foreign producers, creating multilingual idols, and including non-Korean members in idol groups. The authors also highlight the importance of key managers who bridge cultural gaps and guide idols' localization. Through examples like BoA and EXO in Japan and China, the paper shows that K-pop's success is not just about the music—it is about how it is made, promoted, and customized. The authors propose two key ideas: (1) K-pop's global success is linked to its international collaboration in the production stage (like songwriting, choreography, and idol training), and (2) product adaptation—changing the language, image, and style of K-pop for different countries—plays a big role in winning over international audiences. These strategies, combined with effective managers who understand the local culture, have helped K-pop become a major cultural export. The paper admits that it is qualitative and focused only on K-pop, which limits generalization. It also calls for quantitative research and comparative studies with J-pop to further validate the findings. Interestingly, the paper engages with business theories like product adaptation and upstream supply chain management and contributes by applying them to the cultural sector—a novel perspective in K-pop literature.[12]

Earlier in 2021, Lee looked at how K-pop companies have changed their structure and leadership style over time, focusing on the role of "artist-leaders"—founders who were also performers.[21] The author wanted to understand how these leaders guided their companies from being small, founder-led businesses to large global entertainment corporations. The study uses a narrative analysis approach within a multiple case study design. It examines interviews, public speeches, and historical accounts from the three biggest K-pop companies (SM, YG, and JYP) to see how leaders told stories and created narratives during different stages of organizational change. Lee identifies three main stages of strategic organizational change: the entrepreneurial phase (focused on charisma and personal leadership), the transformational change phase (where leadership narratives shift to handle growth and challenges), and the established phase (focused on a company-wide vision rather than one individual). The research shows that storytelling and branding by artist-leaders were essential in building trust, motivating staff, and maintaining the company's identity as it expanded. The study concludes that while personal charisma and artistic skill were crucial in the early stages, long-term success depended on changing leadership styles and shifting the narrative toward organizational sustainability and shared vision. The research looks only at three major K-pop companies, so it may not reflect the experiences of smaller agencies. It relies on public materials and narrative interpretation, which can be subjective and shaped by what sources are available. It's also focused on the Korean industry, so the findings may not directly apply to other countries' creative sectors. This work adds to conversations about leadership and organizational change in the creative industries. It challenges the idea that charisma alone can sustain a company and shows the importance of evolving leadership strategies as a business grows. It also links to global discussions on how cultural industries adapt when moving from start-ups to major corporations while keeping their original identity.[13]

Interestingly, Lopes, Oh, and Pyun identified that K-pop's rise can be understood through globalization and postcolonial cultural industries. The authors wanted to explain how Korea, a country that was colonized less than a century ago, could become one of the music markets in the world and compete directly with industries from places like the US and Japan. The paper is a conceptual and theoretical overview. It reviews existing studies and introduces eight articles in a special issue, each examining K-pop from different angles such as music style, fandom diversity, and business strategies. Together, they are used to show how K-pop fits into larger theories of globalization, symbolic capital, and innovation. The authors show that K-pop's success is not just about catchy songs—it is built on a combination of innovative production strategies, diverse and active fandoms, and symbolic value. They highlight how K-pop firms use concrete storytelling, gender diversity, and global collaboration to expand worldwide. The paper also shows that K-pop's achievements challenge old assumptions that cultural dominance only comes from Western countries. K-pop's case suggests that postcolonial nations can build globally competitive cultural industries by combining creativity, strong business strategies, and inclusive fandom cultures. The authors argue that this example broadens how we think about innovation and globalization in music. The article serves mainly as an introduction to a special issue, so it summarizes other research rather than presenting new data itself. Because of this, it doesn't go into deep details about specific case studies. Also, it focuses mainly on Korea, so comparisons with other postcolonial music industries are not fully developed. This paper adds to bigger conversations about cultural globalization, postcolonial studies, and innovation in creative industries. It challenges the idea that cultural exports must come from historically dominant Western powers, which shows how K-pop is reshaping global music markets. It also links to debates on fandom, gender, and symbolic capital by highlighting how non-Western pop can succeed internationally with its own distinct strategies.[14]

While Smarnmit explored how K-pop companies use foreign idols, especially Thai idols, to expand into the global market. The goal was to understand the strategies behind including non-Korean members and how that influences fan satisfaction and market growth. The research used a qualitative approach. Data came from in-depth interviews with three groups (Thai fans, non-Thai fans, and people who dislike Thai idols), combined with sentiment analysis of YouTube comments and review of related documents. The generalized double diamond model was used as a framework to explain competitiveness. The study found four main strategies: (1) K-pop's idol production system and emphasis on appearance, (2) using Thai idols plus social media promotion, (3) adapting content to local markets and considering market size, and (4) support from industries like TV and video streaming. Interviews showed that Thai idols such as Lisa, Bambam, and Nichkhun were well accepted because of their looks, talents, and multilingual skills. Having Thai members also helped groups gain recognition in Southeast Asia, China, and beyond. Using foreign idols

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is an effective strategy for K-pop companies to strengthen their global reach and create more diverse group images. The paper concludes that while ability and appearance are important, strong company support and effective marketing are equally necessary for foreign idols' success. The study only focused on Thai idols and fans in a few countries, so it may not fully reflect global perspectives. It also relied on online comments and interviews with a relatively small sample size, which cannot capture the whole diversity of fan options. It connects to the globalization of pop culture and how non-Western industries expand abroad. It adds to discussions on cultural hybridity and inclusivity, which shows that foreign members help K-pop stay competitive internationally. It also raises questions about representation, fan perception, and whether this strategy can be sustained long-term.[15]

The role of digitalization and globalization in the development and evolution of the K-pop Industry:

In an earlier study, Parc & Kawashima explored how the Korean and Japanese music industries responded differently to digitization, and how those strategies impacted their international competitiveness—especially explaining K-pop's global success and J-pop's relative decline.[9] The authors applied Porter's Diamond Model to analyze national competitiveness across four areas: factor conditions, demand conditions, related industries, and firm strategy. They break digitization into two phases—Digitization 1.0 (Internet emergence) and 2.0 (smart devices and streaming)—and assess how both industries responded during each. They use a mix of qualitative historical analysis, industry data, and real-world business responses from companies in Korea and Japan. K-pop embraced digitization early by shifting toward digital distribution, streaming, and visual-centered music. Companies restructured internally, adopted global strategies, and lowered costs through integration. In contrast, J-pop clung to physical sales, complex copyright systems, and avoided platforms like YouTube—limiting international access. Korean companies used digital tools to globalize, while Japanese firms focused on their domestic market. They concluded that business strategy—more than market size or cultural quality—determined international success. The Korean industry gained a global edge by embracing digitization and adapting its business models. The paper concludes that timely, business-driven responses to technology are key to cultural competitiveness, offering lessons for other countries navigating the digital shift in creative industries. The study didn't use primary data such as interviews with company executives, and it doesn't reflect post-2018 trends in global music streaming. It also could have benefited from including fan or consumer perspectives. The paper challenged culture-centric explanations and shifted the debate toward economic strategy and industry structure in cultural globalization.[16]

Later, Parc & Kim analyzed how the Korean music industry embraced digitization and used it to drive the global success of K-pop.[10] The authors aimed to identify the structural and strategic changes that allowed Korea's music sector to thrive despite piracy and market challenges. The paper applied a revised version of Porter's Diamond Model to explore the K-pop industry's transformation across four areas: production, distribution, consumption, and performance. The analysis is qualitative and combines historical data, industry observations, and cultural insight to explain how digitization reshaped business, consumer behavior, and industry structure. Korea's music industry transitioned from analog to digital, offline to online, and from album-focused to song- and video-driven consumption. Entertainment companies integrated vertically(distribution training) and embraced platforms like YouTube and streaming services early on. Digitization helped producers target both local and global audiences through collaborations, high-quality visuals, and storytelling. K-pop became not just music but a multi-platform cultural product. The authors argued that embracing digitization rather than resisting it gave Korea a competitive edge. K-pop's rise was not just cultural but also business-driven, fueled by integration, innovation, and adaptability. The study suggests that countries seeking to grow their cultural industries should focus on systematic innovation, not just cultural preservation or subsidies. The paper noted the lack of earlier literature and explained that its findings are based on qualitative insights. Also, the paper focuses mainly on industry and company strategies, but less on fan behavior or a consumer-side perspective. It also doesn't include direct data from stakeholders like artists or producers. The paper connects its findings to broader conversations on cultural exports, digitization, and innovation, contributing a business-focused angle to K-pop research.[17]

Most recently, Wirawan & Wibawarta explored how J-pop and K-pop have influenced each other throughout their development and how globalization has shaped their rivalry, collaboration, and adaptation.[11] The paper focused on how K-pop surpassed J-pop internationally and how J-pop has responded strategically. This study used a qualitative comparative research method with data collected from books, journals, and online sources. It applied Giddens' theory of globalization and reflexive modernity to examine cultural shifts and industry adaptations between Japan and South Korea. The paper found that while J-pop laid the groundwork for idol culture, K-pop adapted and expanded globally through better use of digital platforms and international marketing. J-pop responded by forming overseas sister groups, integrating traditional elements, and collaborating with K-pop agencies. The analysis also showed how K-pop's proactive digital strategy helped it dominate Japanese charts and influence the local market. The authors concluded that both J-pop and K-pop are products of reflexive modernity, constantly evolving under global influence. While K-pop has taken the lead in global influence, J-pop maintains its cultural identity and adapts through innovation and collaboration. The mutual influence between the two forms of pop culture reflects the dynamic exchange facilitated by globalization. The authors didn't explicitly mention limitations. The analysis relied on secondary sources and general cultural observations without empirical data. It also lacked perspectives from industry insiders or fans, which could have added depth to the comparison. The paper contributed to broader discussions on cultural globalization and reflexive modernity. It aligns with existing scholarship that views K-pop's

rise and J-pop's adaptation as outcomes of evolving global and regional influences.[18]

Earlier, Kong provided a comprehensive and structured analysis of K-pop's international success by exploring how external environmental factors and internal business strategies interact to support the global expansion of K-pop. The author used a mixed-methods approach. Quantitative tools like Google Trends and YouTube Music Insights were used to measure global visibility, while qualitative insights are drawn from industry interviews and content analysis. Frameworks like PEST analysis, Porter's Five Forces, and Value Chain Analysis are applied to structure the macro, industry, and internal environment. The author found that K-pop's global rise is due to a combination of strategic industry planning, favorable government policies, and the rise of digital platforms. Korean entertainment firms benefit from centralized systems for talent training, branding, and global promotion. Simultaneously, macro factors like social media, cultural hybridization, and regional partnerships (e.g., in Japan) help K-pop penetrate foreign markets. The thesis concluded that K-pop's globalization is not just cultural but highly business-driven. The industry's ability to align internal structures with changing external opportunities (like YouTube's global reach or government support) creates a model of sustainable cultural export. The paper argued that success comes from the synergy between internal capabilities and external conditions, making K-pop a strong case study in creative industry globalization. The author acknowledged that the research relied mostly on secondary sources, such as company reports, public data, and literature, rather than primary interviews or fieldwork. Also, while tools like Google Trends and YouTube Insights were used, the analysis lacks in-depth qualitative data from insiders (e.g., artists, producers), which would strengthen the claims about internal strategies. The conclusions align with broader discussions on cultural exports, creative industries, and the role of strategic business models in globalization. The author emphasizes the synergy between internal capabilities and external opportunities, reinforcing existing knowledge and ideas about innovation and adaptation in cultural industries.[19]

Success factors and the sustainability of the K-pop Industry:

In a study conducted a few years ago, Kim, Jung, Roh & Choi identified the key factors that drive the success and long-term sustainability of the K-pop industry, using both statistical modeling and qualitative insights.[13] The study focuses on how different internal and external variables influence fan satisfaction and business outcomes. The authors applied a mixed-methods approach. They used a Structural Equation Model (SEM) to measure relationships between variables (e.g., idol image, fandom satisfaction, content quality), and a Fuzzy Set Qualitative Comparative Analysis (fsQCA) to explore different configurations that can lead to success. The data was collected from online surveys of K-pop fans. The SEM results show that content quality and idol characteristics are major drivers of fan satisfaction. Meanwhile, fandom marketing and social media use significantly impact brand trust and loyalty. The fsQCA results suggest that different combinations of factors can still lead to success, showing that there is no single path to sustainability. These findings highlight the multidimensional nature of the K-pop industry's success. The study concluded that K-pop's sustainability relies on maintaining strong fan engagement, producing high-quality content, and adapting marketing strategies to digital platforms. It also argues that flexible business models are needed, since multiple factor combinations—not just one—can lead to continued success. This suggests that innovation, diversity, and adaptability are key to the industry's future. In the study, the sample is limited to online K-pop fan respondents, which may not represent all fandoms equally. The structural equation model (SEM) is based on self-reported perception, which can introduce bias or subjectivity. The fuzzy set analysis (fsQCA) provides limited generalizability due to the specific conditions tested. The conclusion supports existing research on cultural industry sustainability and fan engagement. It emphasizes that K-pop's success stems from both strategic planning and digital fan interaction. The study also contributes by showing that multiple factor combinations, not just one model, can lead to success.[20]

On the same matter, Kim, Hwang, and Kim examined which factors in the K-pop production and promotion process contribute most to its sustainability—measured through fan engagement on social media and interest in visiting Korea.[19] The authors used a mixed-methods approach, combining a Structural Equation Model (SEM) and Fuzzy Set Qualitative Comparative Analysis (fsQCA). The SEM identifies statistically significant relationships between six proposed "success factors" and outcomes like SNS citizenship behavior and tourism intention. The fsQCA tests combinations of these factors for more complex causal patterns. The survey data were collected from global K-pop fans across eight countries. The SEM analysis found that casting, producing/promotion, and content quality had the greatest influence on fan engagement (SNS citizenship behavior), which in turn positively affected fans' intention to travel to Korea. Interestingly, social media, training, and producer reputation were not statistically significant in SEM but emerged as influential in the fsQCA. This suggests that different combinations of factors can lead to sustainability outcomes, depending on context. K-pop's sustainability is driven by more than just one dominant factor. Instead, multiple success factor combinations can achieve the same outcomes. This points to the importance of strategic diversity in content creation and fan engagement. The study recommends industry players adopt flexible, context-sensitive strategies to support global growth and cultural tourism. The authors note that their sample was limited to eight countries and that the success factors explored were restricted to six specific dimensions. The study only considers two outcome variables (SNS behavior and tourism), leaving out other markers of sustainability like labor conditions or agency governance. Also, there is no qualitative data from fans or insiders to add depth to the interpretation. However, the paper contributes to broader discussions on fan engagement, cultural tourism, and creative industry sustainability. It supports ideas from prior studies on production strategy and Hallyu branding, but challenges the assumption that social media is always the most influential factor. It also

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strengthens the academic link between K-pop and the United Nations' Sustainable Development Goals (SDGs).[21]

Further, Kim *et al.* examined how South Korea's cultural policy has supported the growth of the K-pop industry and what changes are needed to ensure its sustainability.[20] The authors argue that Korea must go beyond cultural policy and shift toward policies that consider artist rights, mental health, and ethical management practices. The paper uses a policy analysis approach, reviewing historical government strategies and the evolution of state-supported cultural industries. It draws on secondary sources such as government white papers, industry data, and prior academic literature to evaluate the relationship between state intervention, industry expansion, and ethical gaps in K-pop's system. It was found that the Korean government's early support of K-pop was crucial for its global growth, but current policies lack provisions for labor protection, well-being, and corporate governance. The study highlights structural issues such as contractual exploitation, overwork, and mental health crises, calling for new regulatory frameworks to protect artists while maintaining creative competitiveness. K-pop's sustainability will depend not only on market strategies or technological innovation but also on a policy shift toward ethical, inclusive governance. The authors argue for integrating labor rights, transparency, and participatory governance into the cultural industry model to ensure its long-term viability. However, the study mainly focuses on Korean domestic policy and does not assess how international governance models or global collaborations could influence sustainability efforts. All in all, Kim *et al.* study adds to the literature on cultural policy and sustainability by emphasizing the need for ethical frameworks in global entertainment. It builds on prior debates about the limits of soft power and expands the discussion to include artists' well-being and social responsibility as core pillars of sustainable cultural industries.[22]

In a recent study, Min evaluated the factors driving the competitiveness of the K-pop industry and proposed strategies to ensure its long-term sustainability, using the Diamond Model as a framework for industry analysis.[18] The study employs a qualitative, industry-level analysis grounded in Porter's Diamond Model, focusing on firm strategy, demand conditions, supporting industries, and factor conditions. It draws from corporate case studies (especially the "Big 4": HYBE, SM, JYP, and YG), government reports, and secondary data to map the competitive landscape and sustainability concerns in the K-pop industry. The paper identifies multiple drivers of competitiveness: global idol recruitment and training, group branding strategies, artist-fan platform engagement (e.g., Weverse, Bubble), and synergy across K-Wave industries. However, it also highlights governance issues, overreliance on founder-led production systems, and the need to modernize business structures. The study emphasizes the shift toward IP-centered business models and strategic alliances with IT platforms like Kakao and Naver to sustain growth. The study concludes that K-pop's strength lies in platform-based fan engagement, multi-label expansion, and cross-industry collaboration. To maintain global influence, the industry must address internal governance, support artists' well-being, and adopt new metrics beyond physical album sales. Strategic partnerships and transparent corporate structures are essential for resilience in a fast-evolving digital and cultural market. The paper briefly acknowledges limitations in terms of relying heavily on secondary data and industry reports rather than primary fieldwork or interviews. The analysis centers primarily on the major agencies (HYBE, SM, JYP, YG), which may overlook dynamics in mid-size indie labels. Additionally, there is limited attention to consumer or artist perspectives on sustainability. The conclusions contribute to ongoing discussions around sustainability, governance, and innovation in cultural industries. By integrating both cultural and economic factors, the paper aligns with literature on platformization and global creative competitiveness, offering a practical lens on K-pop's long-term viability.[23]

Synthesis:

Considering the aforementioned area investigated in the literature, a synthesized approach to understand the evolution of the K-pop industry is presented here. From the literature, it is evident that K-pop's success is not just cultural—it is business-driven. Studies like Messerlin & Shin show how competition, low music prices, and internet use pushed companies to go global and innovate.[24] Copyright and piracy shaped the industry. In particular, Parc, Messerlin & Moon argue that relaxed copyright laws and even piracy gave young Koreans access to global music.[25] It boosted creativity and made K-pop more competitive. Certain analytical themes were identified:

1. Innovation is a constant theme: Lee & Pyun explain that K-pop companies survived challenges by innovating in everything—idol training, marketing, and fan platforms—turning threats into new opportunities.[7]

2. Hybridity matters: Jin shows how K-pop borrowed from J-pop but went further by mixing languages, styles, and politics. They created a hybrid cultural identity that appeals globally.[26]

3. Fans are more than consumers: Saeji highlights how fans started creating businesses, content, and events that support idols—what she calls "K-pop adjacent industries." This shows K-pop's ecosystem is bigger than just companies.[27]

4. Global adaptation is key: Kim & Kang found that K-pop agencies adjusted music, idols, and even group members to fit different markets, while still keeping a strong "Korean" core.[8]

5. Digitalization gave K-pop the edge: Parc & Kawashima and Parc & Kim show how Korea embraced streaming, YouTube, and digital platforms early, while Japan stuck to CDs. That decision helped K-pop spread all around the globe.[9,10]

6. Sustainability is essential: Kim, Jung, Roh & Choi found that sustainability depends on many factors, including high-quality content, strong idol images, and engaged fandoms. Different combinations of these factors can still work—there's no single formula.[13]

7. Challenges remain: Researchers like Min and Kim *et al.* point out that governance issues, artist well-being, and fairer revenue distribution need attention if K-pop is going to stay sustainable in the long run.[18,20]

Conclusion

The study brings together different perspectives on K-pop to show how K-pop's rise shows that its success is built on more than just catchy songs or flashy performances. It comes from a mix of smart business strategies, innovations, fan involvement, and Korea's unique cultural background. Companies have a strong training system, global marketing, and digital platforms, while fans help expand the industry worldwide. Still, challenges like artist well-being, fair profit distribution, and sustainability remain. As the industry grows bigger, it cannot rely only on founder charisma or fast innovation. It also has to think about governance, ethics, and how to stay creative without overworking idols. For future research, it can be suggested that more empirical data collection is needed, such as surveys and interviews with idols, fans, and company data, since the most current work relies heavily on secondary sources. Using mixed-method approaches that combine statistical models(like SEM or social network analysis) with qualitative case studies could provide a fuller picture. Theories of cultural hybridity, platform capitalism, and organizational change could also be applied more systematically to explain K-pop's global strategies. Finally, researchers could build new conceptual frameworks that compare large agencies with smaller or independent labels, and explore how new technology like AI, virtual idols, and metaverse platforms will reshape K-pop's sustainability and identity.

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References

1. Messerlin, A.; Shin, W. The Success of K-pop: How Big and Why so Fast? *Asian Journal of Social Science* 2016, *45* (4). https://doi.org/10.1163/15685314-04504003
2. Parc, J.; Messerlin, P.; Moon, H. The Secret to the Success of K-pop: The Benefits of Well-Balanced Copyrights in Corporate Espionage, Geopolitics, and Diplomacy. In *Issues in International Business*, IGI Global: Hershey, PA, 2017. https://doi.org/10.4018/978-1-5225-1031-4.ch008
3. Saeji, C. T. Making Icons: The Rise of the K-pop Adjacent Industries. *Inter-Asia Cultural Studies* 2024. https://doi.org/10.1080/14649373.2024.2365594
4. Jin, D. Y. Comparative Discourse on J-pop and K-pop: Hybridity in Contemporary Local Music. *Korea Journal* 2020, *60*(1), 40–70. https://doi.org/10.25024/kj.2020.60.1.40
5. Liu, R. The Business Model and System of the Korean Music Industry within a Collectivist Society. *SHS Web of Conferences, APMM 2024* 2024. https://doi.org/10.1051/shsconf/202419301017
6. Lee, J. Analyzing the Competitiveness of Entertainment Management Companies of Korea and Japan. Master's Thesis, Seoul National University, 2017.
7. Oh, S. J.; Kim, Y. J.; Doo, I. C. Study of Profit Model of Web-Dramas on Portal Sites Using Big Data; Focused on the Web-Dramas with the K-pop Singers as Lead Casts: "EXO Next Door" and "I Order You." *Multimedia Tools and Applications* 2017, *76*, 6097–6110. https://doi.org/10.1007/s11042-016-3556-2
8. Kim, S. Y. Investigation on the Management Status of K-Pop Revenue Model and Finding Ways for Improvement. *International Journal of Trade, Economics and Finance* 2012, *3* (5), 343. https://www.ijtef.com/papers/224-CF305.pdf
9. Cho, J.; Bian, Y.; Lee, J. Leading Digital Business Model Transformation in the K-pop Industry: The Case of SM Entertainment. *Asia Pacific Business Review* 2023, *29* (5), 1394–1424. https://doi.org/10.1080/13602381.2023.2229761
10. Kim, J.; Kwon, S.-H. K-Pop's Global Success and Its Innovative Production System. *Sustainability* 2022, *14* (17), 11101. https://doi.org/10.3390/su141711101
11. Lee, J.; Pyun, L. Is There Innovation in the K-pop Industry? A Theoretical Perspective. *Asia Pacific Business Review 2023*. https://doi.org/10.1080/13602381.2023.2264042
12. Kim, B.; Kang, B. K-pop's Internationalization in the Product Adaptation and the Upstream Music Supply Chain in Korea, China, Japan, and the West. *Asia Pacific Business Review* 2023. https://doi.org/10.1080/13602381.2023.2230156
13. Lee, D. Strategic Organizational Change and Artist-Leadership in the K-pop Industry: A Narrative Analysis Approach. Doctoral Dissertation, University of Warwick, 2021.
14. Lopes, P.; Oh, I.; Pyun, L. The Globalization of Postcolonial Pop Music: Putting the Success of the K-pop Industries into Theoretical Perspectives. *Asia Pacific Business Review* 2023, *29* (5), 1243–1250. https://doi.org/10.1080/13602381.2023.2229761
15. Smarnmit, S. The Strategy of Using Foreign Idols to Make K-POP Entertainment Companies Success in the Global Market: The Case Study of Thai K-POP Idols. *Journal of Business Administration* 2020.
16. Parc, J.; Kawashima, N. Wrestling with or Embracing Digitization in the Music Industry: The Contrasting Business Strategies of J-pop and K-pop. *Keio Communication Review* 2018. https://archium.ateneo.edu/cgi/viewcontent.cgi?article=1215&context=kk
17. Parc, J.; Kim, S. D. The Digital Transformation of the Korean Music Industry and the Global Emergence of K-Pop. *Sustainability* 2020, *12* (18), 7790. https://doi.org/10.3390/su12187790
18. Wirawan, C. H.; Wibawarta, B. The Development Dynamics of J-Pop and K-Pop in Japan and South Korea in the Globalization Era. *International Journal of Research in Education, Humanities and Commerce* 2024, *5* (3), 40–59. https://doi.org/10.37602/IJREHC.2024.5303
19. Kong, H. Y. The Globalization of K-pop: The Interplay of External and Internal Forces. Master's Thesis, Furtwangen University, MBA WS14/16, 2016.
20. Kim, J.-h.; Jung, S.-h.; Roh, J.-s.; Choi, H.-j. Success Factors and Sustainability of the K-Pop Industry: A Structural Equation Model and Fuzzy Set Analysis. *Sustainability* 2021, *13* (11), 5927. https://doi.org/10.3390/su13115927
21. Kim, S.; Hwang, S.; Kim, J. Factors Influencing K-pop Artists' Success on V Live Online Video Platform. *Telecommunications Policy* 2021, *45* (3), 102090.
22. Kim, J. H.; Kim, K. J.; Park, B. T.; Choi, H. J. The Phenomenon and Development of K-Pop: The Relationship Between Success Factors of K-pop and the National Image, Social Network Service Citizenship Behavior, and Tourist Behavioral Intention. *Sustainability* 2022, *14* (6), 3200.
23. Min, B.-S. The K-pop Industry: Competitiveness and Sustainability. *International Journal of Cultural Policy* 2024. https://doi.org/10.1080/10286632.2024.2366979

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RESEARCH ARTICLE

Using Real-Time Crowd Data to Reduce Overstimulation and Anxiety in Adolescents and Young Adults

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ABSTRACT: Crowded public spaces often cause intense anxiety and sensory overload for neurodivergent youth, limiting their independence and daily functioning. Through this project, results showed that the group of surveyed neurodivergent individuals (13-24) in Massachusetts would most likely experience reduced anxiety when given access to real-time crowd data before visiting public spaces. Interviews resulted in qualitative data and were based on a small sample size. The interviews revealed that the majority of participants who experienced increased anxiety in crowds valued simple features like notifications of peak times, which will help them plan daily activities more comfortably. Additionally, customizable features to work with their preferences, such as environment, noise levels, and more. The secondary research confirmed that the majority of neurodivergent youth avoid grocery stores, gyms, and community centers due to sensory issues, and the app could directly address this barrier by giving them tools for a less overwhelming experience. Analysis of both primary and secondary data confirmed the proposition that providing reliable real-time crowd tracking increases independence, reduces social isolation, and helps close mental health disparities for neurodivergent youth. This research highlights the potential for expanding real-time data about different environments beyond Massachusetts.

KEYWORDS: Entrepreneurship, Social and Behavioral Science, Neurodivergent, Independence, Anxiety.

Introduction

Neurodivergent teens and young adults with anxiety or sensory sensitivities frequently encounter challenges in navigating crowded public spaces. They are unable to predict the noise, lighting, or density of crowds, often leading to the avoidance of essential activities.

The affected population primarily includes individuals aged 13-24, specifically neurodivergent youth with conditions such as autism, ADHD, or social anxiety, as well as those with milder sensory sensitivities. In Massachusetts, nearly 18.2-18.4% of young adults experience anxiety disorders, and urban and suburban environments with frequent crowds heighten the challenge.[1] Additionally, about 20% of Massachusetts teens are experiencing a mental health disorder, and 31.9% are facing anxiety disorders.[2]

The state largely contains middle-class families, with most owning smartphones but lacking access to specialized mental health support or alternatives. Current trends indicate that affected individuals prefer digital tools that increase predictability, reduce anxiety, and allow participation in public spaces.

The study of over 10,500 Spanish adults with high sensory processing sensitivity found that individuals with high overstimulation experienced significant anxiety in everyday social interactions and crowded environments.[1] For example, participants reported feeling mentally exhausted and overwhelmed when exposed to crowded areas or overstimulating environments, leading them to withdraw from social situations or avoid public places. High overstimulation was also linked to lower vitality, increased body pain, and a greater tendency to use unhealthy coping strategies such as self-criticism and social withdrawal. These findings illustrate how sensory overload can directly affect mental and physical well-being, especially in situations where social demands are high. These results connect to research on supporting neurodivergent adolescents and young adults in crowded or socially intense settings.[3]

Overstimulation can trigger anxiety, prompting avoidance behaviors that limit participation in daily activities and reduce quality of life.[4] By understanding how overstimulation causes stress in public spaces and social interactions, tools such as real-time crowd tracking apps can help highly sensitive individuals prepare and manage anxiety, making social environments more accessible and reducing sensory overload-related stress.

Existing tools provide vague crowd information but fail to offer detailed sensory data or real-time updates, leaving a clear gap in user needs. There is an increased demand for a mobile application that provides accurate, customizable updates on both crowd density and environmental sensory factors, enabling individuals to plan outings and maintain autonomy.

The absence of suitable tools limits independence, reduces participation in essential activities, and contributes to mental health challenges. neurodivergent youth are nearly twice as likely to experience anxiety or depression compared with neurotypical peers, highlighting the severity of the problem. This is evident in Figure 1 because, as the rate of autism in adolescents and individuals is growing, so is their level of anxiety. This clearly emphasizes the issue of the absence of tools that will promote independence, because with anxiety, individuals are more likely to face overstimulation and have a shutdown.[5]

The proposed solution is a mobile application that tracks real-time crowd density and environmental sensory factors such as noise and lighting. Its primary features include a live map of locations such as stores, gyms, and coffee shops. The app

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will also include a forecast of busy periods, personalized alerts to prevent overstimulation, and user-generated reporting to improve accuracy. Development will rely on smartphone location data, user feedback, and potential partnerships with public venues to access more detailed information.

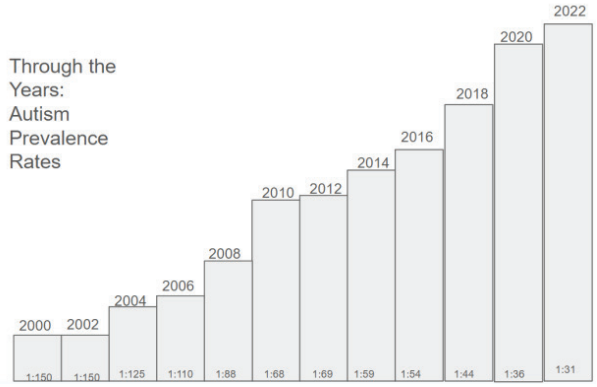

Figure 1: Data on the increase in Autism in the last 2 decades. Based on CDC surveillance data, it is shown that annually, the rate of young adults facing autism is growing, which emphasizes the need for a tool that could prevent spikes of anxiety in these individuals.
Bohnsack, Chris. "CDC Releases New Autism Prevalence: 1 in 31 Children in the U.S. Identified With Autism." Southwest Autism Research & Resource Center (SARRC), April 16, 2025. Accessed August 24, 2025. https://autismcenter.org/autismprevalence/.

As of right now, the demand for real-time crowd and sensory data is partially addressed by general navigation apps and social media, which provide basic crowd estimates for stores, gyms, and public venues. Some venues display projected peak hours online. However, these tools focus primarily on crowd size and do not account for noise, lighting, or other sensory triggers. The market reports that existing solutions lack personalization, accuracy, and real-time updates, which limits their effectiveness in reducing anxiety or sensory overload.

Currently, few producers are providing real-time crowd information, and very few address sensory sensitivities or anxiety-specific needs. The market is concentrated around crowd estimation apps, which offer basic data but lack customizable alerts or live sensory information. Most times, those statistics are inaccurate and don't update frequently. Most products are widely available online, though smaller developers may face challenges acquiring sensors to track crowds or tools to predict the environment, limiting their ability to compete.

The current research aims to explore the extent to which neurodivergent individuals face excess anxiety and overstimulation in a public outing, causing them to leave or have an unpleasant experience.[6] The implementation of a mobile application that provides real-time crowd density and sensory information will reduce anxiety and sensory overload for neurodivergent teens and young adults, enabling them to plan outings more confidently and participate in public spaces with greater independence and comfort.

Methods

Procedure:

10 neurodivergent individuals aged 13 to 24 were interviewed to collect primary data on experiences with crowded public spaces and sensory overload. 5 interviews were conducted online, and 5 were conducted in person. All participants provided consent to share their responses, participation was voluntary, and they were able to skip any questions they did not feel comfortable answering. The interviews began with simple, open-ended questions to allow participants to share general experiences, which then led to more in-depth questions to explore how crowding and sensory overload affected their daily routines.

Questions included:

- Are you currently diagnosed with Anxiety, Autism, or any behavioral challenge?

- How does overstimulation affect you in a public place? If it does, how do you try to overcome the challenge?

- How many times in the past few weeks have you faced overstimulation?

Each interview lasted approximately 15 to 30 minutes, depending on the degree to which the topic impacted the participant's daily life. Responses were kept anonymous and used solely to understand the development of a mobile application designed to help neurodivergent adolescents and young adults navigate public spaces more comfortably.

Table 1: Description of the diagnoses and behavioral challenges faced by the interviewees. This data table, based on the interviews, shows the diagnoses of individuals interviewed. Most of the interviewees had been diagnosed with autism.

Of the 10 surveyed neurodivergent young adults (13-24)	
Diagnosed Autism and face overstimulation	7
Undiagnosed Autism and face overstimulation	3

The secondary research conducted for this study focused on understanding the prevalence of crowd-related anxiety in neurodivergent adolescents and young adults, exploring strategies for grounding, avoidance, and sensory regulation, and identifying market trends and data relevant to potential app users. The research questions helped determine how common crowd-induced anxiety is among neurodivergent young adults, what coping mechanisms are currently used, and how existing tools and services fail to address these needs.

Results

Data Collected:

The data collected from both primary and secondary sources provides insight into the proposition that a mobile app offering real-time crowd and sensory information would meet a significant unmet need for neurodivergent individuals.

Primary Data Analysis: Qualitative Interviews:

The qualitative interviews revealed that crowded public spaces such as grocery stores, gyms, and malls frequently trigger anxiety and sensory overload for neurodivergent individuals aged 13 to 24 in Massachusetts. There were 3 main themes that emerged: avoidance behaviors, coping strategies, and trust

in technology. Participants reported avoidance behaviors and reliance on the Google Maps data, which was usually inaccurate. One stated, "I went on Google Maps before going to Market Basket once, and it was inaccurate. Google Maps stated that around 8 a.m., it is the least busy on the weekends, but it was packed, and I was so overstimulated that I left." Many expressed a strong desire for accurate, real-time updates that included sensory-specific details such as noise levels, lighting, and overall environment intensity. Customizable notifications and updated quiet hours were frequently mentioned as features that would improve daily experiences and increase confidence in public settings. Customization promotes accessibility for all different users regardless of disabilities or any type of barriers. The interviews consistently highlighted a gap in current tools, emphasizing the importance of specificity and personalization in crowd-sensing technology. Additionally, many expressed coping strategies such as mindbreaks, breathing methods, but in the end, they said it would be a more efficient process if there was an app that they could trust to keep track of environments and crowd levels.

Interviewees also suggested making a feature to select stores to their liking, such as places like Target, Walmart, Costco, and big chains. Additionally, participants stated that the app should have a feature to set preferred times to go out. With that, the app can then send a notification with how busy the place is, and users can use that to decide what to do. Ultimately, the interviewees stated that they would prefer a customizable approach.

Furthermore, as seen in Figure 3, many of the individuals decided to leave the public space due to overstimulation. It is evident that overstimulation is currently difficult to manage, and access to real-time data is essential for effectively reducing it. This is because overstimulation overwhelms the brain's ability to process information, and this triggers the body's stress response, making it harder to adapt to the environment. Although some do try to stay and overcome the challenge, most individuals cannot.[7]

Additionally, as seen in Table 1, all individuals faced overstimulation at least once in a public environment. Some of the individuals were not diagnosed with anxiety or autism, and also did not have any behavioral challenges, but still faced overstimulation. That emphasizes the need for real-time data because overstimulation in public places impacts more than just individuals with autism.

Table 2: How overstimulation affected the interviewees and how they decided to handle the situation. This data table, derived from the interviews, highlights the comparison of individuals who had to leave a public space due to overstimulation.

	Experienced overstimulation or sensory overload at a public space but stayed and tried to overcome the challenge.	Experienced overstimulation or sensory overload at a public space and left the place due to the impact.
Male (3)	2	1
Female (7)	5	2

Within the interviews, several divergences appeared in how neurodivergent individuals experienced and managed overstimulation. Some participants reported grocery stores and gyms as their most overwhelming environments, while others emphasized social events, concerts, or even public transit as the hardest to navigate. A few interviewees described leaving spaces immediately when overstimulated, but others preferred strategies such as finding quieter corners, using headphones, or waiting out the crowd. There were also differences in perceptions of technology. While many saw potential in real-time crowd updates, others doubted whether any app could truly capture the unpredictability of public spaces. These divergences highlight that although there is a need for better support, the specific triggers and coping mechanisms varied widely across individuals.

Secondary Data Qualitative and Quantitative Market Research:

The research revealed that individuals with other health conditions, such as high blood pressure, diabetes, or chronic stress, often experience heightened anxiety in crowded environments.[5] Many of these individuals rely on online ordering, pickup, or home delivery to avoid the stress of crowded places, indicating a clear behavioral trend that supports the need for tools providing real-time crowd data.[6] In Massachusetts, there are approximately 900,000 individuals aged 13 to 24, and studies indicate that roughly 18.2-18.4 percent of this population experiences anxiety disorders or sensory sensitivities triggered by the environment.[7] The most frequently avoided locations include grocery stores, gyms, and malls, particularly during afternoons and weekends.

This data complements the primary interviews by providing a broader understanding of the potential market size and showing the limitations of existing tools. While interviews offered detailed personal experiences, the secondary research gave quantitative context and background information on neurodivergent youth and the disorders. Additionally, through primary interviews, it was evident that many of the neurodivergent individuals faced excess overstimulation in public spaces. They also expressed the usage of coping strategies, such as apps that can help their brain calm back down.

Evidence showed that using breathing strategies is useful and effective for neurodivergent individuals because it allows their brains to reset.[8]

■ Discussion

The qualitative data gathered in the interviews showed initial support for the proposition that neurodivergent individuals face excess anxiety and overstimulation in a public outing, causing them to leave. The primary interviews and secondary research suggested that crowded public environments such as grocery stores, gyms, and malls frequently trigger anxiety and sensory overload for this population. Convergences across the data revealed consistent avoidance behaviors and reliance on inaccurate third-party information, confirming that there is a real and unmet need for accurate crowd data. These convergences supported the proposition by showing that users want

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accurate tools to make informed decisions about when and where to go. Additionally, both primary and secondary data emphasized the importance of customizable notifications, preferred locations, and quiet hour alerts, highlighting that personalization is essential for use.

Divergences highlighted considerations for the app design. While secondary data indicated widespread interest in crowd tracking apps, some interviewees expressed hesitation about trusting new technology unless reliability could be verified. This revealed that simply providing real-time data is insufficient. Trust, accuracy, and transparency are the main concerns of the app and should be clearly addressed.

Several challenges were encountered during the study, primarily related to participant recruitment and data accuracy. Finding neurodivergent individuals aged 13 to 24 who experienced anxiety or sensory overload in public spaces proved more difficult than anticipated, which limited the sample size and diversity. The biggest limitation is the fact that there are only 10 interviewees, which limits the generalizability of the data.

All participants were recruited through the interviewer, which may have resulted in a sample more aware of or concerned about anxiety and sensory challenges than the broader population. Additionally, the study focused exclusively on one age group and geographic area, limiting generalizability. The sample size for interviews was small, and participants' concerns about data accuracy were not fully explored through secondary sources.

Implications for future implementation:

Based on participant interviews and their real-life experiences, an app made as a promising solution could help manage anxiety and overstimulation. It could provide real-time crowd density, noise, and lighting levels, customizable notifications, and an accessible, low-stress interface for neurodivergent individuals aged 13 to 24. The system could focus on smartphone location inputs, public sensors, and user feedback to deliver timely updates and personalized alerts.

Participants also raised concerns about the reliability of real-time sensory data, revealing a gap between user expectations and current technological limits. While the interviews offered rich qualitative insights, they could not capture long-term usage patterns or determine which features most effectively reduce anxiety across different subgroups. Some users also feared becoming too reliant on the app, worrying that consistently overwhelming readings might discourage them from going out altogether. These concerns helped clarify that the concept has value, but its success depends on dependable data, personalization, and attention to behavioral support.

Crowd-related anxiety remains a major barrier for neurodivergent young adults, and public health and market reports show rising demand for digital tools that offer tailored sensory information. The findings indicate that a well-designed app with customizable alerts and real-time data could help users navigate public spaces more comfortably. Future work could explore long-term behavioral impacts, usage patterns, and which sensory metrics are most helpful, as well as expand research to additional age groups and geographic or demographic contexts.

This gap highlights a clear opportunity for a new product that prioritizes accuracy, real-time updates, and customization, offering features such as personalization of preferred locations, alert notifications for low crowd periods, preferred timings, and adjustable filters for specific environmental triggers. By addressing both crowd density and sensory-specific needs, the app can differentiate itself from existing navigation and wellness tools while providing accurate and efficient data.

The data should be collected ethically by making sure all users consent to how their data will be used. However, if they don't want their data used, they can use a version that shows an estimated number of people and environment checks. The app could help people, but also respect how their data is shared. We must gather data from a vulnerable population and make sure all the data that is estimated is from past, accurate, and real-time data.

■ Conclusion

This study highlights the potential of a mobile app providing real-time crowd density and sensory environment information to support neurodivergent teens and young adults in Massachusetts. Currently, many neurodivergent individuals experience anxiety when overstimulated, and that leads to lower independence and avoidance of certain public places. The research demonstrates that anxiety and sensory overload in public spaces remain significant barriers to participation and that accurate, customizable, and reliable crowd data could improve confidence and decision-making. The app could be highly customizable so that all different users can use it with ease. Additionally, the app should have features where users can consent to their data being used. This will ensure that the app is ethical and transparent to all users. The findings suggest that a digital tool prioritizing personalization and user-friendly design can meet an unmet need. As well as help limit excess anxiety in neurodivergent individuals.

Additionally, public institutions and universities can integrate this tool to improve accessibility for students with behavioral challenges or disabilities. There can be a feature to show the environment of a certain class, and students can use the app to filter classes by their specific needs. This will be highly beneficial for students who are neurodivergent and struggle in noisy or crowded areas.

Furthermore, partnerships with public transit could be beneficial because many neurodivergent individuals avoid public transport because it is hard to predict how many people will be there. With an app that shows the current crowd size and predicts how many people will be there later, individuals can plan their trip more easily.

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I attest that the ideas, graphics, and writing in this paper are entirely my own.

References

1. Pérez-Chacón, M.; Borda-Mas, M.; Rivera, F.; Chacón, A.; María Luisa Avargues-Navarro. *Analysis of the Moderator Effect of Overstimulation on the Relationships between Indicators of Health-Related Quality of Life, Extraversion, and Maladaptive Coping Strategies in People with Sensory Processing Sensitivity*. Current Psychology 2024. https://doi.org/10.1007/s12144-024-06507-2.
2. Teen/Adolescent Mental Health Treatment | Newton, MA | Crown. Crown Adolescent Health | Teen Mental Health Treatment. https://crownadolescenthealth.com/teen-treatment-newton/ (accessed 2025-11-07).
3. (ADDA Editorial Team. A*DHD & sensory overload: Managing overstimulation. ADDA - Attention Deficit Disorder Association*. https://add.org/sensory-overload-adhd/.
4. Team, N. editorial. Overstimulation Explained: Understanding Sensory Overload in Everyday Life and Asperger's. NeuroLaunch.com. https://neurolaunch.com/how-to-explain-overstimulation/ (accessed 2025-08-02).
5. Study links high levels of stress hormones to increased blood pressure, cardiovascular events | NHLBI, NIH. www.nhlbi.nih.gov. https://www.nhlbi.nih.gov/news/2021/study-links-high-levels-stress-hormones-increased-blood-pressure-cardiovascular-events.
6. Wirtz, J.; Mattila, A. S.; Tan, R. L. P. *The Role of Arousal Congruency in Influencing Consumers' Satisfaction Evaluations and In-Store Behaviors*. International Journal of Service Industry Management 2007, 18 (1), 6–24. https://doi.org/10.1108/09564230710732876.
7. How To Identify And Manage Overstimulation. www.henryford.com. https://www.henryford.com/blog/2023/12/how-to-identify-and-manage-overstimulation.
8. Ng, H.-Y. H.; Wu, C. W.; Hsu, H.-C.; Huang, C.-M.; Hsu, A.-L.; Chao, Y.-P.; Jung, T.-P.; Chuang, C.-H. Neurological Evidence of Diverse Self-Help Breathing Training with Virtual Reality and Biofeedback Assistance: Extensive Exploration Study of Electroencephalography Markers. JMIR Formative Research 2024, 8, e55478–e55478. https://doi.org/10.2196/55478.

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Vanshika Seku is a senior in high school. Hers ultimate goal is to start a business where people who are underprivileged can learn how to manage their own finances at a low cost. She believes that everyone, no matter their background, should be able to be financially stable. The proposed in my research is to make an impact on individuals through hers work and have a role in my own community to serve as a leader and look out for members in my community. Thank you so much for taking the time to read and support my research.

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REVIEW ARTICLE

Combatting The Inequities of Modern Urban Infrastructure in American Cities

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ABSTRACT: Urban infrastructure has long served as a tool of exclusion by reinforcing segregation through hostile design and disproportionate resource allocation. These patterns have contributed to persistent social and economic disparities across American cities. This paper analyzes these patterns and poses corresponding solutions ranging from zoning reforms to modular housing to complete streets. These comprehensive reforms in transportation, housing, and public space planning can address structural inequities, dismantle long-standing barriers, and support the creation of more inclusive and equitable urban communities.
KEYWORDS: Urban Planning, Public Policy, Transportation, Housing, Public Spaces.

Introduction

Social inequities in the past decades have become increasingly embedded into modern urban architecture: whether that be strategically uncomfortable park benches, uneven distribution of public amenities, public spaces inaccessible by public transportation, or scarcity of safe and well-lit gathering spaces in lower-income neighborhoods. While this infrastructure is common and appears to serve purely technical purposes, it has long acted as a tool of social organization by quietly reinforcing racial, economic, and spatial exclusion.

In cities around the world, the Great Depression had severe implications financially, culturally, and politically. As a direct result, unemployment, mass evictions, and homelessness in the 1900s skyrocketed. Millions of people were forced to resort to slum-living on the streets, sleeping in subways, or waiting all day in queues, hoping to get accepted to a public shelter.[1] Simultaneously, government funding dedicated to creating safe and upkept public spaces had plummeted. Entire neighborhoods were neglected and stripped of essential resources, and by the end of the Great Depression, living conditions were entirely inhumane: unsanitary, dangerous, and devoid of basic rights and dignity. Even so, as cities began to get back on their feet, funding was still incredibly sparse. In response to this shortcoming, government officials working to decrease home foreclosures, known as the Home Owners' Loan Corporation (HOLC), classified neighborhoods into one of four colors:[2]

- GREEN was the highest classification. GREEN neighborhoods housed the white affluent population; were viewed as "safe" investments due to their racial homogeneity, higher property values, and established wealth; and were HOLC's priority in receiving loans, public investment, and infrastructural development.

- BLUE was the second-highest classification. BLUE neighborhoods were "still desirable," but they perhaps bordered "hazardous" neighborhoods or consisted of older buildings, putting them at a lower property value and thus were a lower priority.

- YELLOW was the third highest classification. YELLOW neighborhoods were labeled as "definitely declining" and were often home to working-class white families or racially mixed populations. While not yet considered "hazardous," they were seen as highly risky locations for investment due to heterogeneous demographics and proximity to "hazardous" neighborhoods.

- RED was the lowest classification. RED neighborhoods were the most aid-deprived classification. Primarily inhabited by Black, immigrant, and working-class families, RED neighborhoods were subject to immense racial discrimination and were labeled as "hazardous." They also saw a constant flux of people that HOLC believed was creating unstable communities prone to crime and social disorder. With no expectations of sustaining property values, RED neighborhoods were considered unworthy of any long-term investments.

With these color classifications, HOLC created and published Residential Security Maps for cities worldwide. Known as "redlining," each city map outlined its neighborhoods in either green, blue, yellow, or red, indicating whether or not it was deserving of public investment, protection, and resources. Redlining not only reflected existing prejudices but also, as an official government policy, laid the foundation for deeper social divides by institutionalizing exclusion and embedding inequality into urban development. Systemically approved exclusion stemming from policies such as redlining is still manifested in public transportation, housing, and public spaces today.

There is an urgent need for just urban development in rapidly growing cities, where infrastructure increasingly perpetuates societal inequality. This paper examines the social disparities manifested through public infrastructure in rapidly developing, urban American cities and how civil engineering can be used to promote higher equity. Section 1 will discuss transportation: its affordability, accessibility, safety, disproportionate funding allocation, and proposed solutions. Section 2 will discuss housing: the history of gentrification and zoning laws, affordability and housing cost inflation, slum-living, and proposed solutions.

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Section 3 will discuss public spaces: disproportionate distribution between neighborhoods, defensive architecture, neglect of environmental threats, and proposed solutions. By analyzing historical policy documents, various maps, and comparative case studies of urban neighborhoods outside of America, this paper will reveal how urban planning and civil engineering can be used as instruments to promote social equity in urban American cities, rather than as weapons against it.

Transportation

Urban cities employ public transit, highways, and street design to favor the wealthier neighborhoods while marginalizing the lower-income communities. Through examining the public spaces only accessible via highway, lack of sufficiently shaded sidewalks for pedestrians, disproportionate allocation of transit allocation, and qualifications of a "complete street," this body section identifies the flaws in urban American cities' transit systems and proposes solutions.

Before the invention of the automobile, transportation in cities primarily meant traveling on foot. Proximity was crucial, so schools, markets, workplaces, and homes were often all clustered together within neighborhoods. When horse-drawn streetcars, trolleys, and early rail systems began to emerge, communities first experienced racial disparities through vehicles: segregation in waiting areas for buses and trolleys became common, and faster transportation enabled wealthier populations to live further away from the lower-income families who could not afford to do the same. With increasingly more effective solutions to forced geographic intimacy, the advancement of transportation in cities quickly proved its capability to exacerbate social divisions.

The invention and mass production of cars in the 20th century, in fact, amplified this effect to an unprecedented degree. As personal car ownership skyrocketed, America's priorities shifted to accommodate this new surge of needs, evident through the 1956 Federal-Aid Highway Act, which re-apportioned billions of dollars from public transportation funds to support the construction of highways. Not only did this mean that widely accessible transportation was receiving less funding from the government, but that money was now for highways: only a usable form of transportation for the small percentage of Americans who were wealthy enough to afford their own car. In fact, approximately 20% of funding for surface public transportation is allocated towards public transit, while the remaining 80% is earmarked for highways.[3]

Although they were marketed as symbols of modernity and economic progress, highways directly reinforced racial segregation and economic stratification. City planners deliberately routed major expressways through Black, immigrant, working-class, and redlined neighborhoods, displacing thousands of residents who were already politically disadvantaged. These highways, additionally, were used as tools of division and physically divided cities into fragments. Highways ensured that cities were entirely un-navigable by those without cars, by excluding them from supposedly public spaces. Robert Moses, an urban planner in New York City, for example, designed many parks and highways with intentionally limited access. His highways leading to his parks included many low bridges that could not accommodate public buses, suggesting that he did not want those without their own car to access his parks.

HOLC's redlined maps further enabled the exclusive nature of highways. Green and yellow outlined neighborhoods reaped the benefits of the increased transportation opportunities and large investments. Meanwhile, red and yellow neighborhoods were severely underfunded and often forced to remove public transportation altogether. This ultimately left them with inadequate transit options, cutting them off from parts of the city with abundant job opportunities, schools, and healthcare services. This lack of connectivity further entrenched socioeconomic inequalities, as residents in redlined areas were unable to take advantage of the growing economic opportunities that highways and better transportation options provided to wealthier, predominantly white communities.

Beyond highways, the design of streets in urban cities has historically been centered around accommodating automobiles, often at the expense of pedestrians and cyclists. Roads were widened, streets were straightened, and public spaces were redesigned to prioritize the movement of vehicles. These decisions were made with little regard for pedestrians or cyclists, creating urban spaces that are often inhospitable to those who don't own or drive a car. Sidewalks became narrower, bike lanes virtually nonexistent, and pedestrian crossings were rarely prioritized. This car-centric focus in city planning created environments that were often uncomfortable and unsafe for those without cars, particularly in lower-income neighborhoods. As highways and major roads frequently divided communities, it became increasingly difficult to navigate the city without a car, perpetuating the cycle of inequality. Yet in redlined and underfunded areas, this unsafe street design, coupled with a lack of accessible, well-funded public transportation, further isolates residents, deepening existing socioeconomic disparities.

To address these issues, urban planners and civil engineers should advocate for the concept of "complete streets": a framework that seeks to design streets that are safe, accessible, and inclusive for all users, regardless of their mode of transport. Complete streets incorporate features like wider sidewalks, dedicated bike lanes, safer pedestrian crossings, and better access to public transportation. By reimagining street design to serve not just cars, but also pedestrians, cyclists, and transit riders, cities can reduce the physical and social barriers that segregate communities and promote more equitable urban development.[4] Complete streets can ensure that redlined neighborhoods receive the same level of infrastructure upgrades and resources as wealthier green and yellowlined communities. Features such as wide, well-lit sidewalks, safe pedestrian crossings, dedicated bike lanes, and traffic-calming measures (e.g., speed bumps, raised intersections) not only will enhance mobility and safety but also foster greater inclusion. Complete streets will cater to all individuals, including children, the elderly, people with disabilities, and those without access to cars, thus reducing the marginalization of lower-income or historically underserved populations. Additionally, complete streets address these issues by shrinking the car-centric ideal. Designing streets that are not only safe

for pedestrians and cyclists but also have easy access to public transit will help cities provide more equitable mobility options for all residents. Features like bus lanes, transit stations, and bike-sharing programs integrated into street design make it easier and more affordable for people to travel without relying on their car. Complete streets will work to break the social cycle of car dependence by enhancing the pedestrian and bicyclist experience through higher safety and comfort.

From highways that cut through and displaced lower-income neighborhoods to the lack of investment in public transit for those who need it most, the way America has organized its transportation systems has severely exacerbated existing social inequities. Redlining, coupled with car-centric street designs, makes it nearly impossible for many people without cars to access the workplaces, schools, and public spaces. Implementing more complete streets can help reconnect neighborhoods and give all residents equal access to the city.

Housing

Housing should provide the foundation for stability, social and economic opportunity, and help foster community. Yet in many American cities, housing policies and market forces have perpetuated inequality through exclusionary zoning, gentrification, and the neglect of affordable housing needs. In fact, the American housing crisis is rooted in decades of biased policies that have systematically restricted access to affordable, adequate, and secure housing for marginalized communities. These dynamics have created a system where the ability to live in a safe, stable, and well-connected neighborhood is increasingly reserved for the wealthy. This body section examines the roots of inequitable housing policy, the modern consequences of rising costs and displacement, and potential solutions that reframe housing as a human right rather than a market commodity.

Exclusionary zoning laws are local regulations dictating what forms of housing can be built in specific neighborhoods. Practiced in almost every American community, these laws have played a central role in shaping the economic and racial geography of American cities. Its discriminatory regulations create invisible entry barriers for certain demographics; limit housing diversity and affordability; ban multifamily dwellings; and impose large minimum lot sizes. Exclusionary zoning, similar to many aspects of public transit systems, legally reinforces racist ideologies and limits lower-income families' access to high-opportunity districts with more places of work, higher education, safer streets, and greater public investment.

Alongside zoning restrictions, gentrification has emerged as one of the most prevalent forms of displacement in American cities. As a "profit-driven race and class reconfiguration of urban, working-class communities of color that have suffered from disinvestment," gentrification transforms neighborhoods by forcefully removing the low-income community residing in the area due to the influx of wealthier and higher-prioritized populations.[5] Gentrification often begins when older buildings are refurbished into modern apartments, upscale cafes, or boutiques, and neighborhoods begin catering to the tastes of their new audiences. Newcomers are attracted to this culturally-rich yet refurbished and modern space, and increasingly drive up demand for housing, art, and other goods. Accordingly, property values and rents increase significantly. Then suddenly, residents can no longer afford to live in their own neighborhoods. Gentrification reveals how housing systems in American cities prioritize economic gain over residential stability in lower-income communities– how they can harm without even a second thought.

Historically, through exclusionary zoning, gentrification, and redlining, low-income Americans in quickly developing cities have been forced to resort to living in slums: overcrowded, dilapidated, unsanitary, and crime-infested residential areas used by those experiencing extreme poverty.[6] Even where housing exists in sufficient numbers, it often remains financially out of reach for the majority of residents. So ultimately, the government fails to support citizens' housing needs. Yet, instead of working to lessen the urban American housing crisis, city planners have continued to primarily develop higher-income segments, exponentially expanding the void of equity in the housing options. As a result, slums have grown increasingly common. After all, they provide solutions: slums satisfy bare-minimum living conditions, are affordable for low-income families, and, above all, can be conveniently proximate to work and social infrastructure.[6]

The history of gentrification, exclusionary zoning, and the growth of slums in American cities reveals the deeply-rooted neglect and discrimination against marginalized communities. Exclusionary zoning laws have restricted access to opportunity, while gentrification forces low-income residents out of once-affordable neighborhoods. Leaving unsanitary, dangerous, and substandard slums as the last refuge for many. Together, these forces illustrate how housing in American cities echoes the prioritization of wealthy populations and the neglected needs of marginalized communities.

To address these issues, zoning reform is critical. Zoning reform is one of the most powerful ways cities can dismantle the legal barriers perpetuating housing inequality. Traditional exclusive zoning dictates the number and types of houses that can be built in certain neighborhoods. It is rooted in exclusionary practices designed to keep out renters, immigrants, and people of color. This type of zoning significantly limits housing supply, drives up prices, and concentrates wealth and opportunity in already advantaged areas. Reforming these regulations is essential for creating more inclusive and just communities. The Minneapolis 2040 Plan is an example of a zoning reform working to close housing disparities. One of its primary goals is to eliminate single-family zoning citywide to allow for duplexes and triplexes in all residential neighborhoods. This will increase housing supply and also diversify the types of housing available, thus enabling more people to live in high-opportunity areas, which were once reserved solely for wealthy and predominantly white communities.[7] While Minneapolis 2040 was implemented in 2020, it is not too late for other states to support their cities. Mainstreaming similar reforms across more American cities would help begin reversing centuries of exclusionary practices and foster more racially and economically integrated communities. Reforming zoning, which can

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look like reducing minimum lot sizes, removing parking minimums, and permitting mixed-use developments, has the power to and should be utilized as a tool for inclusion.

In addition to Project Minneapolis 2040, American cities can look to Vienna, Austria, for housing inspiration. These large-scale social housing programs have successfully implemented municipally owned and subsidized housing options for residents of all incomes. They are also located in desirable areas, often within walking distance from cinemas to bars; highly affordable, "a fraction of typical rents for similarly sized and similarly located apartments in other major European cities," and offer very enjoyable living conditions. This is all attributable to the fact that the majority of apartments and homes in Vienna are owned by the city.[8] This ensures long-term affordability and dependability. By adopting a similar approach, American cities too could create stable, high-quality housing for all residents while combatting pressures of rapid development and gentrification.

Lastly, another promising solution to the American housing crisis could be the implementation of modified modular housing. Modular homes are prefabricated units that are constructed in factories, transported to their final destination, and then become liveable spaces upon a few minor assemblies. By being constructed in factories rather than on-site, modular homes eliminate construction delays caused by weather and benefit from precision machinery, making them some of the most efficient, cost-effective, and high-quality housing options available. Additionally, the production of modular homes is flexible and can be designed to accommodate different family sizes, income levels, and more personal needs.

Because these homes can be personalized, mass-produced, and delivered quickly, they offer a viable solution to the American housing crisis. Modular housing can ameliorate zoning bottlenecks, support mixed-income neighborhoods, and make high-quality housing more accessible and affordable for all communities.

Exclusionary zoning laws, the gentrification of low-income neighborhoods, and the normalization of slum-living have all perpetuated the American housing crisis of largely unaffordable, segregated, or unsafe living options. However, reformed zoning policies, social housing, and increased use of modular housing have the power to create cities that offer inclusive, high-quality, and accessible housing.

Public Spaces

Public spaces, in their name, are supposedly meant for the entire public population to enjoy. However, in reality, they consist of hostile defensive designs, uneven distribution of amenities, and varying levels of upkeep across different neighborhoods. Thus, public spaces, much like urban American transportation and housing systems, exclude lower-income areas and contradicts its alleged purpose. This body section examines how public spaces have historically catered to or excluded certain demographics and suggests ways these spaces can be reimagined through inclusive design.

Figure 1:

Figure 2:

Defensive architecture can look like benches segmented by armrests to prevent lying down, metal spikes embedded into flat surfaces, or sloped window sills that make it impossible to comfortably sit there. (Figure 1) is pictured to the left. I captured this image. (Figure 1) depicts a common bench in New York City, an American city ranked among the greatest homeless populations. This bench offers comfortable temporary seating, but, obstructed by armrests, is intentionally not long enough to allow someone to lie down. The photo of this bench was taken in the Upper West Side in Manhattan, a particularly wealthy neighborhood within New York. Its placement and design are very intentionally exclusive. (Figure 2) is pictured to the right.[10] This image is from The Neighborhood Design Center. (Figure 2) depicts a series of large boulders in the shoulder of grass next to a larger road.[10] At first glance, these boulders may simply appear as a strange stylistic decision. In reality, they serve as another form of hostile architecture meant to deter homeless individuals from camping out on these grassy patches.

While it is often justified as improving public safety and reducing maintenance, defensive architecture very directly targets the homeless populations by making public spaces uninhabitable for them.[11] The intent is not to create supportive environments for entire neighborhoods to share, but rather to discourage certain individuals from resting in and finding refuge in these shared areas. Defensive architecture treats the homeless population as a nuisance that should be removed rather than recognizing that they are people who need extra supportive infrastructure, social services, and a more inclusive housing system. Defensive architecture criminalizes the homeless population seeking rest and shelter in public spaces and implements "solutions" that ultimately reinforce the invisibility of marginalized groups and push them further out of spaces that should belong to everyone.

Exclusion can also occur through the uneven distribution of public amenities. Often, wealthier neighborhoods enjoy well-maintained parks, beautiful libraries, elaborate sports facilities, many public restrooms, and shaded sidewalks, while lower-income areas often lack these amenities completely. Having public access to restrooms, safe and well-lit streets, and clean drinking fountains are basic human right. City planners' decisions to limit lower-income communities' access to these rights indicate that they don't have a standing regarding public spaces.[12] Even when public amenities do exist in low-income neighborhoods, they are often subject to neglect and don't receive proper upkeep. These conditions are another indication that public spaces in low-income neighborhoods are not a pri-

ority for investment or care, reinforcing the message that those neighborhoods are less deserving of safe and well-maintained environments.

To address these issues, equal distribution of public amenities must become a mandate rather than an afterthought. Stricter guidelines should be present when civil engineers and urban planners design cities to ensure that every neighborhood, regardless of its income level, racial composition, or historical redlining status, has equal access to high-quality public spaces and amenities. Official access standards should be implemented and passed before construction can begin. Some of their requirements could include that all residents live within a certain distance (perhaps half a mile or less) from public parks, libraries, drinking fountains, and restrooms. These stricter guidelines should also ban the use of defensive architecture. Especially in rapidly developing urban cities, the number of Americans experiencing homelessness is skyrocketing– increasing as much as a 12% increase every year.[13] As devastating and shocking as this statistic may be, it is the harsh reality of our world. Homeless response systems are doing their best to accommodate as many people as possible, but time and time again fall short. Simultaneously, defensive architecture eliminates the remaining public spaces that offer comfort, safety, and refuge for these populations. Public spaces should support all members of a community: privileged and vulnerable. By redesigning urban infrastructure with inclusivity and empathy at its core, cities can begin to restore dignity and security to those experiencing homelessness. Rather than pushing vulnerable populations further into the margins, we must create environments that offer access to basic needs, such as shelter, hygiene facilities, and rest areas, in public spaces. A truly equitable city uplifts every individual through compassionate policies, thoughtful design, and community-driven solutions.

Much like the social housing solutions inspired by Vienna, Austria, public spaces can promote higher inclusivity by observing other countries. Superkilen park in Copenhagen is a large public park spanning 750 meters throughout the city. Adorned with neon signs representing every nationality of its residents, Superkilen was constructed with the hope that it would foster social integration and celebrate cultural diversity within the community.[14] The Superkilen park demonstrates how public spaces can celebrate diversity and encourage interaction among all members of a community. By taking inspiration from Superkilen, urban American cities can reimagine their public spaces to prioritize inclusivity, cultural representation, and community engagement.

Public spaces in many American cities have historically excluded marginalized communities through defensive architecture and unequal access to amenities. Instead of defensive architecture and uneven distribution of amenities, parks and plazas could feature flexible seating, accessible facilities, public art, and athletic facilities. Additionally, by taking inspiration from Superkilen, American cities can reimagine public spaces as inclusive, welcoming environments rather than sites of exclusion. Designing with empathy transforms public spaces into platforms of equity, dignity, and shared enjoyment, ensuring that all residents can feel a sense of belonging in and respect from their environment.

Conclusion

The history of American urban infrastructure reveals how transportation, housing policies, and public spaces are wielded as tools that deliberately exclude vulnerable populations. These inequities are not remnants of the past, but active realities that continue to shape cities today. However, these systems can be reimagined as tools for equity. Complete streets can combat car-centric and divided neighborhoods; zoning reform can prioritize residents' stability over profit; and inclusive public spaces can serve and celebrate all members of communities. With a framework built on empathy and equity, urban planning and civil engineering can be reoriented to prioritize accessibility, equity, and inclusive communities.

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References

1. The Power Broker by Robert A. Caro. Page 323.
2. New York City Department of Health and Mental Hygiene, The Lingering Imprint of Redlining on Health, https://a816-dohbesp.nyc.gov/IndicatorPublic/data-stories/redlining/.
3. Bullard, Robert D. "All Transit Is Not Created Equal." Race, Poverty & the Environment 12, no. 1 (2005): 9–12. http://www.jstor.org/stable/41555221.
4. Smart Growth America, Complete Streets, https://www.smartgrowthamerica.org/program-of-work/complete-streets/.
5. Phillips, Dawn. "Planning for People, Not Profit." Race, Poverty & the Environment 20, no. 2 (2015): 78–83. http://www.jstor.org/stable/43873236.
6. HARISH, SWASTIK. "URBAN DEVELOPMENT, HOUSING AND 'SLUMS.'" India International Center Quarterly 43, no. 3/4 (2016): 184–98. http://www.jstor.org/stable/26317324.
7. City of Minneapolis, Minneapolis 2040: Land Use Regulations, https://minneapolis2040.com/implementation/land-use-regulations/#:~:text=Minneapolis%202040%20went%20into%20effect,access%20to%20jobs%20and%20housing.
8. Philip Oltermann, "The Social Housing Secret: How Vienna Became the World's Most Livable City," The Guardian, January 10, 2024, https://www.theguardian.com/lifeandstyle/2024/jan/10/the-social-housing-secret-how-vienna-became-the-worlds-most-livable-city.
9. "From Sears & Roebuck to Skyscrapers: A History of Prefabricated and Modular Housing" by Amanda Marquit
10. Neighborhood Design Center, "Understanding Hostile Architecture: The Cause and Effect of Restricting," Neighborhood Design Center, https://ndc-md.org/news-and-stories/understanding-hostile-architecture-the-cause-and-effect-of-restricting.
11. Neighborhood Design Center, "Understanding Hostile Architecture: The Cause and Effect of Restricting," Neighborhood Design Center, https://ndc-md.org/news-and-stories/understanding-hostile-architecture-the-cause-and-effect-of-restricting.

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12. LEGACY, CRYSTAL, and REBECCA LESHINSKY. "Tools for Equitable Urban Intensification." Built Environment (1978-) 39, no. 4 (2013): 408–21. http://www.jstor.org/stable/43296857.
13. National Alliance to End Homelessness, State of Homelessness, National Alliance to End Homelessness, https://endhomelessness.org/state-of-homelessness/.
14. Dezeen, "Superkilen Park by BIG, Topotek1 and Superflex," Dezeen, October 24, 2012, https://www.dezeen.com/2012/10/24/superkilen-park-by-big-topotek1-and-superflex/.

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Vivian Yim was born and raised in Manhattan, New York City. She is a senior at The Nightingale-Bamford School and will attend Cornell University College of Architecture, Art, and Planning to major in Urban and Regional Studies. Vivian is a creative leader with a strong passion for urban planning and its potential to mitigate the inequities caused by present-day infrastructure and policies. She is eager to study urban planning and public policy to learn how to effectively reimagine cities and one day bring them to life.

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RESEARCH ARTICLE

Akiya Mondai (Vacant Home Crisis)

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ABSTRACT: The akiya (vacant home) crisis in Japan endangers urban and rural economic vitality, with over 9 million abandoned properties forecast to grow to 21.67 million by 2033, due to depopulation compounded by related aspects of inheritance laws and cultural practices that are driving up fire risks or impairing local economies. However, Akiya Banks aside, the lack of institutional support and social mechanisms is inhibiting property demand matching. This study provides insight into the social and economic costs of the akiya mondai and an analysis of whether digitization can play a part in creating new uses for these properties. Based on six qualitative interviews conducted with residents, an entrepreneur, and municipal officials, as well as literature from academic articles and quantitative data on akiya rates and economic trends, the study highlights legal, financial, and cultural impediments. Research results support an argument for the application of a convenient remodeling assistance tool along with laws to develop cheap forms of community revitalization and financial growth.

KEYWORDS: Economics and Finance, Urban Economics, Vacant Home Crisis (Akiya mondai), Digital Platforms for Real Estate, Community Revitalization.

Introduction

The specific problem that our research focuses on is a phenomenon called "akiya mondai," which literally means hollow houses, whereby it indicates homes in Japan that have been left to deteriorate, with an estimated 9 million by 2023, with projections suggesting they are poised to balloon to as many as 21.67 million by 2033, given the declining population and aging demographics.[1] These abandoned properties, due to unresolved inheritance, high restoration cost, and cultural reticence against changing the use of legacy homes, sit on valuable land (10–15% market value depreciation in impacted areas), drive risks for safety and diminishment of community fabric, while there remains an unaddressed opportunity to transition them for residential or commercial functions as well as public asset use.[3] Our thesis is that municipal akiya banks underperform due to three distinct issues: low registration rates (3–5 %), poor user interfaces (outdated design that is hard to navigate), and insufficient legal or renovation support.[1] These issues are separate: low registration limits the number of properties available, poor interfaces reduce usability, and the absence of legal and renovation assistance creates practical barriers to action.

Consumer groups that suffer are young adults (20–40) looking for inexpensive places to live in urban areas, who often struggle to find affordable homes, spending a large part of their income on rent,[2] entrepreneurs needing cheap commercial spaces, who face high startup costs that delay their business growth,[2] and cities with decreasing tax revenues, which lose money from empty homes, potentially affecting local budgets.[5] But the problem is acute in urban centers like Tokyo, where land prices are high and inheritance disputes over homes are common, as well as in rural areas such as Koriyama City in Fukushima Prefecture, where young people are leaving, and homes sit empty. Middle-income young professionals and small business owners are hampered by financial barriers, while rural residents will have accessibility issues. High housing costs are economically devastating to urban residents, renovation expenses are a drain on entrepreneurs, and revenue loss is materially constraining municipal fiscal capacity.[4] Policies can drive demand, or they can fail to overcome cultural barriers. Entrepreneur 1 is based in Tokyo, and he wanted a property that was easy for renters to access, whereas young households wanted affordable, quality housing stock to raise their social value. Sustainable living trends are also promising.

Municipal akiya banks, online databases, and private platforms like SUUMO all offer the current supply to address the akiya mondai, but they have clearly fallen short of meeting consumer needs. Akiya banks have low registration rates or are seen as a place where old interfaces remain and higher-priced assets in private platforms, where, being private businesses, the focus is on reusing only properties that promise high profits, leaving less lucrative rural or dilapidated homes neglected. Its effectiveness suffers from the lack of legal process support and house renovation funding, along with inheritance issues.[5] The insufficient infiltration of the akiya sprawl is further hampered by a lack of legal partnerships to navigate complex regulations and the prevalence of properties with unclear ownership, making it difficult to identify and engage rightful owners.

Production availability is cramped with Akiya banks only available in some prefectures, and private services are patchy—fairer in cities but weaker in rural areas due to low registration.[6] Competitor offerings provide basic listings but lack renovation or municipal integration. Branding has been passive, with municipal websites as a means of targeting residents and no apparent plans for expansion.[9] Inputs include municipal staff and databases constrained by budget limits, etc. Moreover, government funding is often directed toward compensating those who demolish houses rather than addressing the root issue of revitalizing or reusing them.[5] Inheritance laws, governmental

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constraints on life insurance markets, and the like limit competition by increasing costs to supply these services with little if any added benefit.

The analysis, therefore, reveals a major market gap whereby existing supply is unable to satisfy an expanding demand for affordable, accessible, and well-supported reuse opportunities due in part to poor registration and interface provision.[7] This can lead to young residents, entrepreneurs, and municipalities falling through the cracks, given that publicly initiated solutions like municipal akiya banks or private platforms typically fail short of addressing legal or financial barriers effectively.

The stakes in this issue are truly immense and cross-functional, social, and political. It exists in the form of unaffordable housing and commercial spaces for individuals, resulting in economic hardship, not to mention the safety risks associated with vacant homes.[7] Even if the number of abandoned homes were to reach 21.67 million by 2033, as it will in the next few years, loneliness and isolation at the community level will only deepen and further decline over the long term, which is a possibility. On a social level, it affects communities, leading to an exodus in depopulated rural areas and growing marginalization of urban centers. As a political matter, the crisis is squeezing tax bases and making it harder for state officials to plan. Regulatory costs, such as inheritance laws, prevent producers from satisfying demand. The stakes show why this is a matter that must be addressed.[8] This research asks whether a digitally integrated platform that combines property matching, legal assistance, and renovation support can measurably increase akiya reuse.

To assess potential interventions, we conceptualize a digital platform that would connect property owners, aspiring entrepreneurs, and city administrations with vacant homes across Japan. The proposed system integrates property matching, renovation guidance, and legal counsel through an online interface accessible in both urban and rural areas. This study evaluates feasibility by analyzing required partnerships with municipalities and sector specialists, estimating development and operating costs, and considering how integrated services might address unmet housing needs. Implications for young residents, entrepreneurs, and local governments are treated as hypotheses for future pilot testing.

Methods

The examination employed a selective sampling method targeting likely prospects who might necessitate inexpensive real estate or be concerned about vacant homes in their neighborhood, chosen since it proved simpler to locate individuals with related viewpoints. Participants were selected based on standards like potential requirement for affordable housing or aversion to vacant properties, and were uncovered via contacts in specific districts or local governing functionaries. The diverse views were selected to reflect the key stakeholders of the initial business plan. Municipal representatives to address policy needs, an entrepreneur to capture commercial potential, and residents to understand community concerns, ensuring the platform could serve urban and rural markets effectively. Six people were interviewed: two municipal representatives (one from Setagaya Ward, Tokyo, and another from Koriyama City, equally in urban preparation roles, between 35–55 years of age), an entrepreneur (around 40–50 years old, tiny business owner from Setagaya Ward), and three occupants from Koriyama City (between 55–65 years old, careers unspecified). Discussions lasted approximately 30 minutes, were conducted face-to-face, and participants were informed regarding the study and provided approval through verbal consent. Challenges included scheduling difficulties with municipal representatives, overcome through persistent follow-up. A standardized interview guide was used for each stakeholder group, and responses were coded thematically to identify patterns.

Participant demographics are summarized in Table 1.

Table 1: Interview participant demographics.

Participant	Age Range	Profession	General Place of Residence
Municipal 1	35-45	Urban planning official	Setagaya Ward, Tokyo
Municipal 2	40-50	Urban planning official	Koriyama City, Fukushima
Entrepreneur 1	40-50	Small business owner	Setagaya Ward, Tokyo
Resident 1	55-65	Unspecified	Koriyama City, Fukushima
Resident 2	55-65	Unspecified	Koriyama City, Fukushima
Resident 3	55-65	Unspecified	Koriyama City, Fukushima

This sample includes both supply side voices, municipal officials and an entrepreneur, and community voices, residents, allowing the analysis to compare policy constraints with lived impacts. Participants also span an urban area, Setagaya Ward, and a rural city, Koriyama, capturing differences in market conditions and awareness.

The interviews were conducted using a customized set of structured questions for each group (residents, entrepreneurs, and government officials), and follow-up questions were modified based on the responses. Questions for government officials were adjusted to focus on policy issues, while questions for residents focused on the impact on the community. The following is a list of questions prepared for the interviews, with variations.

1. How do vacant homes affect your community/business/administration? Can you share specific examples?
2. Have you considered using a vacant home for housing/business/community, or policy purposes? Why or why not?
3. What support would make you more likely to use a vacant home?
4. What challenges make reusing or buying a vacant home difficult?
5. Have you heard of or used an Akiya Bank? What were your impressions, or what information would make it useful?
6. Would a digital platform that simplifies finding vacant homes and offers renovation support interest you? What features would be valuable?
7. Who would benefit most from vacant home reuse, and how might it impact the neighborhood/economy?

The secondary data was collected to answer: What are the social and economic impacts of vacant homes in Japan? What barriers prevent Akiya from reusing? What opportunities exist for a digital platform? Quantitative data sought included national akiya statistics and property value trends.2 Qualitative data focused on cultural barriers and policy constraints.[11] Sources included academic journals, government reports, and market analyses, with government reports being used most due

to their authoritative data. Challenges included English-language data, requiring translation tools.

Results and Discussion

The scale ranges from 1 (most negative sentiment) to 10 (most positive sentiment), used to gauge participants' attitudes toward vacant home reuse and a digital platform (Figure 1).

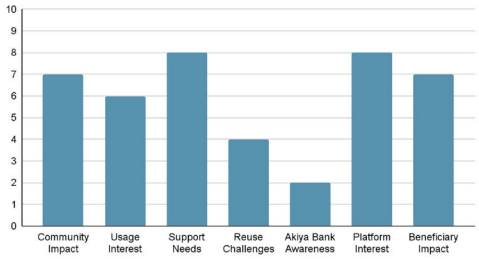

Figure 1: Sentiment analysis of interview responses.

Overall, respondents showed strong demand for support and high interest in a platform, while awareness of existing Akiya Banks was very low. The gap between high support needs and low familiarity suggests that better outreach, plus practical legal and renovation help, could unlock more reuse.

- Awareness and Attitudes:
  - ○ Community Impact (Concern): Satisfaction with addressing vacant homes' impact.
  Score: 7 – Moderate concern from residents and officials.
  - ○ Usage Interest (Interest): Interest in using vacant homes.
  Score: 6 – Mixed, with entrepreneurs keen but residents hesitant.
- Support and Barriers:
  - ○ Support Needs (Desirability): Desirability of support mechanisms.
  Score: 8 – Strong desire for financial and legal aid.
  - ○ Reuse Challenges (Difficulty): Perceived difficulties in reuse.
  Score: 4 – Significant challenges cited.
  - ○ Akiya Bank Awareness (Familiarity): Familiarity with akiya banks.
  Score: 2 – Very low awareness, with most participants unfamiliar.
- Solution Appeal:
  - ○ Platform Interest (Appeal): Appeal of a digital platform.
  Score: 8 – High interest in support features.
  - ○ Beneficiary Impact (Optimism): Optimism about benefits.
  Score: 7 – Moderate optimism from entrepreneurs and officials.

Illustrative quotes: A resident remarked, "We cannot sell the family home because it holds our ancestors' butsudan," illustrating cultural reluctance to repurpose family property. A municipal official noted, "Property titles are unclear; without clean ownership records, we can't proceed," underscoring legal barriers to reuse.

While many interviews uncovered shared concerns regarding vacant homes' detrimental effects, diverging viewpoints also emerged amongst stakeholders. Safety and security concerns were paramount, with residents noting crime and fire risks posed by derelict houses.[9] Affordability and opportunity captured both the desire for lower-cost housing and the economic potential of revitalizing vacant stock for small businesses. Regulatory barriers encompassed unclear property titles, inheritance issues, and zoning rules that hinder reuse, as outlined by officials. Yet across differences, a common demand was voiced, that is an access to reasonably priced dwellings. Moreover, compared to initial forecasts, strikingly low societal awareness of vacant properties presented an unforeseen barrier. With cultural hurdles and scant familiarity with available programs, educational outreach seems paramount to facilitate constructive dialogue.[2]

Trends in total housing stock, vacant homes, and vacancy rates are visualized in Figure 2, which illustrates both historical data and projections to 2033.

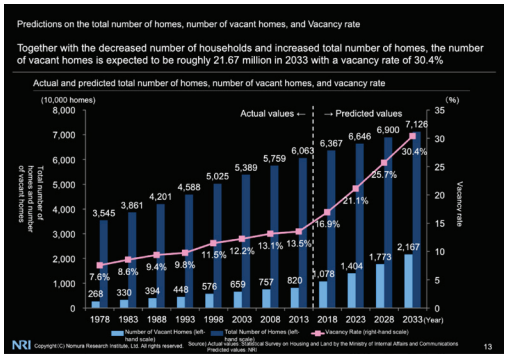

Figure 2: Actual and predicted total homes, number of vacant homes, and vacancy rate in Japan (1978–2033); projections imply ~21.67 million vacant homes and a 30.4% vacancy rate by 2033. Source: Nomura Research Institute (NRI) using MIC Housing and Land Survey data.

The projection indicates that vacancy growth accelerates over time, with vacant homes rising faster than the overall housing stock. This implies that without intervention, empty properties will become a structural issue rather than a short-term fluctuation.

A comparative summary of the proposed platform and Akiya Japan is presented in Table 2.

Table 2: Comparative analysis of the proposed digital platform and Akiya Japan across product, people, place, and promotion.

Aspect	Proposed Digital Platform	Akiya Japan (Competitor)
Product	Platform with matching, renovation, and legal support	Basic listing platform
Product Advantages	Comprehensive features; user-friendly design	Established listings; simple interface
Product Disadvantages	Unproven; high development costs	Limited features; no renovation support
People	Partnerships with governments, experts	Real estate agents, foreign investors
People Advantages	Diverse expertise; local engagement	Strong agent network
People Disadvantages	Building partnerships challenging	Less diverse; investor-focused
Place	E-commerce for urban/rural Japan	E-commerce, urban-focused
Place Advantages	Broad coverage	Strong urban presence
Place Disadvantages	Rural scaling issues	Limited rural reach
Promotion	Digital marketing, municipal PR	SEO, social media
Promotion Advantages	Credibility from municipalities	High visibility
Promotion Disadvantages	Initial low recognition	Less local engagement

Note: The proposed platform uniquely integrates legal and renovation support absent in existing akiya banks and competitors.

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The main advantage of the proposed platform is the integrated legal and renovation support that removes key barriers identified in interviews, whereas the competitor largely stops at listings. The table also shows a clear trade-off: broader public credibility and service depth versus higher cost and the need to prove performance.

Limitations and Future Directions:

The research could benefit from gathering a more nuanced range of perspectives to strengthen the understanding of the target audience's diversity. At present, insight is limited by the small sample of six participants, drawn primarily from specific districts within urban areas and omitting groups such as rural business owners or migrants. Younger city dwellers aged 20 to 30 were underrepresented, restricting generalizability.

Municipal officials posed scheduling challenges due to packed agendas, yet their viewpoints skewed results slightly toward policy matters rather than consumer needs. A variety of innovative reuse ideas likely went undiscovered through networks confined to select localities. While the qualitative depth from interviews proved valuable, statistical robustness suffered from scant data points.

Rural inhabitants alone faced queries, skewing conclusions toward cultural tradition and potentially underestimating demand emerging in cities. This focus on rural perspectives highlighted cultural barriers, particularly the role of butsudan, Buddhist altars in homes, which many residents view as sacred, making them reluctant to sell or repurpose ancestral properties due to spiritual and familial attachments, a tradition more prevalent in rural areas.[11] Broader outreach from the project's start may have prevented barriers like engaging pressured public servants. With more time and resources, the findings could be quantitatively validated through surveying 50 to 100 area inhabitants across demographics.

Gaps in awareness of digital literacy among older residents also went unaddressed, losing potential to enhance platform usability for all. Expanding participation to incorporate underserved populations such as migrants would deliver a richer, more nuanced sense of evolving preferences. Lessons show that comprehensive market exploration requires diligent planning to mitigate biases and encompass a full spectrum of perspectives.

The hypothesis that leveraging digital platforms could help address the growing demands for affordable housing was partially on the mark. However, further refinements are merited to maximize impact. In terms of business model, maintaining direct B2C and B2B avenues for engaging consumers and municipalities directly remains pivotal, while cultivating public-private partnerships through a B2G approach can help foster supportive policy integration. Regarding product design, accurately identifying affordable housing as an unmet need was an important starting point, but a more nuanced understanding of safety improvements and home renovation assistance as closely intertwined hidden priorities would better serve the target clientele, such as young professionals and municipalities. Additionally, compliance with Japan's zoning laws, such as the City Planning Act and Building Standards Act, poses a challenge, as converting residential vacant homes into commercial spaces requires rezoning approval, which can be slow and restrictive, especially in urban areas where land use is tightly controlled. Meanwhile, rural communities facing their own unique affordability challenges warrant dedicated focus. In rural areas where zoning laws are more flexible but ownership disputes are common, the platform must integrate legal support to navigate these regulations effectively. Expert municipal collaborations underscore necessary expertise, yet specialized legal counsel can prove equally integral to navigate inheritance complications. While optimizing online operations for Japan's major population centers made practical sense, an inclusive approach embracing both urban and rural locales throughout the country holds promise. Partnering with local governments for promotional efforts via their communication channels represents a sensible strategy, though leveraging cost-effective digital marketing techniques can help spread awareness more broadly. Finally, affordability remains achievable through a freemium model, but open-source technology for development and strategic maintenance partnerships can help minimize expenses long-term.

Conclusion

The digital platform connects homeowners, entrepreneurs, and municipalities with vacant homes in Japan, and would offer property matching, renovation support, legal guidance, and low-cost access options. It will be developed through partnerships with local governments and technical experts, offered via an e-commerce model targeting urban and rural markets, and marketed through digital campaigns and municipal collaborations.

The platform aims to assist residents, entrepreneurs, and municipalities in addressing varied necessities such as reasonably priced housing and revitalization. It achieves this through an intuitive approach and all-inclusive aid delivered utilizing a user-friendly design accessible online. To support older users who may struggle with digital tools, the platform could include educational resources and assistance to help them learn how to use it effectively. Affordability is realized through an innovative freemium model, maintaining modest subscription rates.

The platform could be adapted to disaster recovery housing in other countries or serve migrant populations in aging societies like South Korea. Additionally, AI assistance could be integrated into the app, featuring a chatbot that guides users by answering questions and directing them to relevant sections, such as where to find property matching or legal support.

A next step would be to pilot the platform in one urban ward and one rural city, measuring indicators such as registration rates, contact conversion, legal cases, renovation starts, and completed reuses over 6–12 months. The platform aims to revitalize communities by transforming vacant properties into functional spaces, promoting economic and social sustainability.

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■ References

1. Mitsubishi UFJ Research and Consulting. 空き家バンクの運用に関するアンケート調査結果報告; Mitsubishi UFJ Research and Consulting, 2020. https://www.sumaimachi-center-rengoukai.or.jp/zenkokuakiya-ikou/wp-content/uploads/2020/03/%E7%A9%BA%E3%81%8D%E5%AE%B6%E3%83%90%E3%83%B3%E3%82%AF%E3%81%AE%E9%81%8B%E7%94%A8%E3%81%AB%E9%96%A2%E3%81%99%E3%82%8B%E3%82%A2%E3%83%B3%E3%82%B1%E2%80%95%E3%83%88%E8%AA%BF%E6%9F%BB%E7%B5%90%E6%9E%9C%E5%A0%B1%E5%91%8A.pdf accessed Nov 6, 2025.
2. Ministry of Internal Affairs and Communications. 令和5年住宅・土地統計調査　住宅及び世帯に関する基本集計（確報集計）結果; Sept 25, 2024. https://www.stat.go.jp/data/jyutaku/2023/pdf/kihon_gaiyou.pdf accessed Nov 6, 2025.
3. Nozawa, C. Land and Homes and the Japanese: The Issue of Vacant Houses and Land with Unknown Owners Today: What Progress with Preparations for Closing Houses? Discuss Japan. https://www.japanpolicyforum.jp/society/pt20220126165808118 41.html accessed Nov 6, 2025.
4. Blair, G. Akiya Houses: Why Japan Has Nine Million Empty Homes. The Guardian, May 1, 2024. https://www.theguardian.com/world/2024/may/01/akiya houses why japan has nine million empty homes accessed Nov 6, 2025.
5. Traphagan, J. W. Empty Houses, Abandoned Graves: Negative Population Growth and New Ideas in Neo Rural Japan. Brown J. World Aff. 2017 to 2018, 24, 161.
6. Chris, L.; Maruyama, M. Super Aged Japan Now Has 9 Million Vacant Homes. And That's a Problem. Yahoo News, May 8, 2024. https://www.yahoo.com/news/why too many homes not 013641783.html accessed Nov 6, 2025.
7. Akiya Banks in Japan: Links to Vacant House Databases by Prefecture. 2021. https://resources.realestate.co.jp/buy/akiya-banks-in-japan-links-to-vacant-house-databases-by-prefecture/ accessed Nov 6, 2025.
8. 03Hakusyo_part1_chap4_web.pdf. https://www.chusho.meti.go.jp/pamflet/hakusyo/2024/PDF/chusho/03Hakusyo_part1_chap4_web.pdf accessed Nov 6, 2025.
9. 260th_Special_Article_01.pdf. https://www.jef.or.jp/journal/pdf/260th_Special_Article_01.pdf accessed Nov 6, 2025.

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