IJHSR
ijhighschoolresearch.org
REVIEW ARTICLE

The Gene Editing Controversy: Scientific Breakthroughs and Ethical Boundaries

Katrina Leung

Cardiff Sixth Form College, 1-3 Trinity Court, Cardiff, Wales, CF24 0AA, UK; katkatbb1@gmail.com
Mentor: Katharina S. Bochtler

ABSTRACT: Gene editing has gained widespread attention due to its potential applications in agriculture, medicine, and biotechnology. While media coverage has made great contributions in raising public awareness in recent years, it has also sparked ethical debates concerning the risks and implications of modifying the genetic material of living organisms. This review explores various applications of gene editing, from disease-resistant livestock to biomedical research using animal models. Additionally, we examine the controversial case of the CRISPR babies and the ethical concerns it raised. We highlight key findings such as the potential benefits of gene editing in combating genetic diseases, its role in agricultural advancements, as well as the ethical dilemmas surrounding human applications. By providing a broad perspective on the topic, this paper aims to present both the scientific promise and the ethical complexities of gene editing, encouraging further discussion on its responsible use. Suggestions for further studies involve investigations on unknown effects that one gene may have upon alterations, as well as surveys to study public attitudes.

KEYWORDS: Cellular and Molecular Biology, Genetics, Gene Editing, Ethics, CRISPR, CRISPR Babies.

Introduction

Gene editing has increasingly captured public attention, with media coverage playing a significant role in shaping awareness of this scientific advancement. While such reporting informs the public, it can also introduce bias, influencing readers' perceptions whether in favour of or against gene editing. As media discussions grow, so too does public awareness of the potential risks and ethical concerns associated with applying gene editing to animals and humans.[1] This has sparked intense ethical debates, with some arguing that the technology is not yet suitable for widespread implementation. Gene editing refers to processes that permanently alter the DNA sequences of cells to introduce a desired change in DNA, also called a mutation.[2] For example, researchers are able to use gene editing to create a mouse model that replicates human-like symptoms of COVID-19. This means that scientists can better understand disease progression, develop drugs, and test the efficacy and safety of treatments.[3] While it has served as a core research topic for the biomedical field for the past years, there is a rapid advancement of gene editing technologies, particularly using CRISPR-Cas9, with great potential for treatments of hereditary diseases and cancers.[4]

While many review articles focus on specific applications of gene editing, this paper provides a comprehensive overview of its diverse uses across various fields, including agriculture, medicine, and biotechnology. Additionally, we examine the controversial case of the CRISPR babies, an experiment conducted by a Chinese scientist, critically analysing its ethical implications, scientific shortcomings, and the broader controversies it has generated.

Discussion

Genetic Engineering in Farming:

There are various reasons to genetically engineer animals as well as plants, which benefit our consumption of these products. Animals can be genetically modified to be disease-resistant, which has already been adopted by farmers. For example, the first gene-edited calf was produced to be much less susceptible to the Bovine Viral Diarrhoea Virus (BVDV), which is one of the most common pathogens worldwide among the bovine species, associated with gastrointestinal diseases, respiratory problems, infertility, and congenital malformations.[5] Therefore, being able to greatly reduce susceptibility has a major impact on the health of farmed species. Despite the presence of vaccines for BVDV, vaccination does not seem to effectively prevent transmission, as it does not lead to complete immunity and fails to eliminate viral shedding among infected animals.[6,7] Gene editing offers a potential solution to enhance cattle's resistance to BVDV by directly modifying their genetic makeup, which not only reduces the transmission rates but also alleviates the economic burden associated with disease management. BVDV is one of the costliest diseases in cattle farming, with losses in the U.S. cow-calf herds reaching up to $278 per bred cow due to decreased milk production, reproductive losses, and increased veterinary costs. In Australia, BVDV ranks as the second most costly disease in the beef industry, with estimated annual expenses of AUD 114 million.[8] Research conducted together with the USDA demonstrated that gene-edited cattle with enhanced resistance to BVDV could significantly reduce disease prevalence, potentially decreasing associated economic losses and reducing the need for costly vaccination programs.[5] Furthermore, their findings indicated that these gene-edited cattle exhibited lower transmission rates, leading to improved

DOI: 10.36838/IJHSR84.62

herd health and productivity. Such advancements demonstrate the potential of gene editing to offer a long-term solution for mitigating the financial and health burdens associated with BVDV.

In addition to disease prevention, it is possible to genetically boost the growth rate of animals for faster production of food. For example, research on promoting the growth of livestock has been conducted in pigs to increase muscle mass and body weight. A study conducted by Xie *et al*. and another by Zhu *et al*. demonstrated that gene-edited pigs with myostatin (MSTN) gene knockouts exhibited increased muscle mass and improved growth rates.[9,10] However, concerns remain regarding potential side effects such as altered metabolism and mobility issues, and commercial viability remains a challenge. Furthermore, success rates are low due to technical challenges in achieving consistent genetic modifications, such as unintended mutations and insertion variability.[11] Ethical concerns regarding the welfare of genetically modified animals, particularly in relation to public acceptance and regulatory scrutiny, also contribute to the limitations.[12] Additionally, economic barriers, including high production costs and complex regulatory approval processes, make commercial viability challenging.[13] As a result, it is not yet commercially viable. On the other hand, a successful example is the AquAdvantage Salmon by AquaBounty Technologies. The Atlantic salmon selected are genetically modified to express a 'rapid growing' phenotype, and they are claimed to have the capability to grow from eyed-egg stage to a market-sized salmon in 16-20 months, which is on average 40% quicker than other salmon that are conventionally farmed and require 28-32 months for growth.[14] Despite AquAdvantage Salmon gaining U.S. Food and Drug Administration (FDA) approval in 2015, there are still many existing concerns relating to its consumption, including ethical concerns about genetically modifying animals for human consumption, potential environmental risks if genetically modified salmon escape into wild populations, and health-related worries regarding the long-term effects of consuming genetically modified organisms.[15]

Gene editing works similarly in plants as well. Crops can be genetically modified (GM) for the insertion of abilities such as herbicide tolerance or insect resistance. A meta-analysis of the impacts of GM crops included a total of 147 studies and concluded that the benefits are significant.[16] The study found that genetically modified crops led to an average increase in crop yields by 22%, a reduction in chemical pesticide use by 37%, and an increase in farmer profits by 68% due to improved resistance to pests and environmental conditions. With the application of GM technology in agriculture, fewer chemical pesticides are needed, while crop yields are proven to increase due to better control of the conditions of crops. Additionally, plants can be modified for enhancement in nutritional value. A typical example is golden rice, engineered to contain beta carotene, which can be converted into vitamin A in humans. Vitamin A is an essential micronutrient for healthy skin and hair, as well as for good light vision.[17] Moreover, it plays a role in maintaining a healthy immune system by regulating the immune responses of cells like neutrophils and macrophages.[18] Vitamin A is a vital component in the growth and development stages of humans, yet there are over 124 million children worldwide suffering from Vitamin A deficiency (VAD), with a high prevalence in developing countries such as Africa and Southeast Asia.[19] Therefore, using biotechnology to enrich staple foods (rice) with vitamin A helps meet the nutritional needs of people in developing countries, and may also hint at the great potential in modifying other crops for nutritional purposes in the future.[20] However, Golden Rice has faced challenges related to accessibility, cost, and public perception.[21] Critics argue that regulatory hurdles and high production expenses limit its widespread adoption, while public skepticism toward genetically modified foods has slowed acceptance in some regions.[22] Additionally, concerns about whether the rice provides sufficient bioavailable vitamin A remain debated among researchers.[23]

Biomedical Applications of Gene Editing:

The largest application of gene editing is in biomedical research and its applications in therapeutic methods. Animal models that have been genetically modified can resemble human diseases, such as Alzheimer's disease, cancer, and cystic fibrosis, in much more detail than we could in patients alone.[24,25] These models help researchers understand disease progression and test potential treatments before human trials. They are also useful for the observation of any post-effects after certain genes are modified.

Common animal models are zebrafish, mice, and rats. They are all easy to reproduce, small, and convenient. Zebrafish are a vertebrate species with high physiological and genetic homology to humans. They have a relatively long lifespan, which makes them an accessible organism for biomedical studies. Zebrafish also share common organs and 71.4% of the same genes as humans, making them a great choice for human-related research, such as the development of treatments for rare genetic disorders and brain disorders.[26,27] Similarly, mice and rats are commonly used in medical research. What makes them a better model over zebrafish when studying human diseases is that mice are mammals, while zebrafish are not. Despite the fact that they both share parts of the human genome, mice and rats have a more similar biological body structure to humans. This means they can be genetically manipulated more easily to mimic human diseases and conditions. For example, some mice are genetically modified to have a shorter lifespan, and so they can be used in studies that are related to ageing or chronic diseases.[28]

Because zebrafish have a much higher tolerance of dense chemical mutagens than rodents do, zebrafish are still widely used as practical animal models for genetic research.[29] An example of the use of zebrafish is to study human bone diseases. There are existing zebrafish mutant lines that can successfully model human skeletal dysplasia and forms of osteogenesis imperfecta (OI), also called 'brittle bone disease'.[30] One of the identified zebrafish mutant models for classical dominant OI is the *Chihuahua* (*Chi/+*).[31] Adult zebrafish display typical OI characters that are seen in humans, such as having brittle bones that can fracture easily (especially the fracturing of

ribs), reduced bone elasticity, and uneven mineralisation within bones.[32] As animal models for human diseases, such as OI, rely on gene editing tools, without them, our understanding of medicine would be greatly limited. While zebrafish provide rapid and affordable testing for drug discovery, there are obvious differences between the morphology of zebrafish and humans.[33] Therefore, after zebrafish are used for primary testing, further investigations should be done on mammals to test for efficacy. There is a gradual increase in the availability and use of genetically engineered mouse models (GEMMs), and one of the uses of GEMMs is in the preclinical testing of therapeutics.[34] Traditionally, in cancer research, xenografts are used, which is the subcutaneous insertion of human tumour cells into immunodeficient mice.[35] GEMMs, on the other hand, use immunocompetent mice, meaning they have a normally functioning immune system. This sets up a more realistic microenvironment for modelling tumour development or disease progression, providing more predictive data than traditional cell culture or xenograft models. Subsequently, it obtains higher accuracies in predicting drug efficacy against certain human cancers.[36] One of the examples of GEMMs is drug testing in transgenic models of acute promyelocytic leukaemia (APL).[37] APL is associated with defective hematopoiesis in which the promyelocytes do not fully develop and turn into cancerous cells. Researchers have identified that APL is caused by chromosomal translocations in chromosome 17, producing a fusion of the promyelocytic leukaemia (PML) and retinoic acid receptor alpha (RARα) genes.[38] Studies using transgenic mice with equivalent chromosomal translocations have proven that treatment with a combination of retinoic acid (RA) and arsenic led to a much faster decrease in leukemic population than using the agents separately.[39] After 8 days of treatment, erythroblasts and megakaryocytes were visible in the bone marrow, and normal hematopoiesis was restored.[40]

Despite the production of transgenic animals being time-consuming, they play an important role in drug discovery and testing, which can further our understanding of human diseases. However, their use also raises ethical concerns regarding animal welfare and regulatory challenges related to approval for biomedical research. Public perception plays a significant role in these debates, as concerns about the treatment of genetically modified animals and the potential long-term effects of genetic interventions influence regulatory policies and funding decisions. Studies indicate that public skepticism about transgenic animal research stems from ethical considerations regarding animal rights and the fear of unintended consequences of genetic modifications.[41] Ensuring that these models are used responsibly while balancing scientific progress and ethical considerations remains a critical aspect of their application. Conceptualized in the United Kingdom, the so-called 3Rs of animal research are widely applied by many research institutions. They propose that, wherever possible, animals should be replaced with cell cultures, computer modelling, or other non-animal alternatives for testing ("Replacement"). If animal use is essential, researchers should aim to reduce the number of animals needed ("Reduction"), as well as minimise their pain and suffering to reduce harm ("Refinement").[42] These international guidelines provide a clear and structured framework for performing more humane and ethical animal research.

Human Gene Editing:

The successful cases of gene editing in animals have given scientists hope to further develop this technology and to apply it to humans. Gene therapies do not involve germline editing, as only faulty cells in a certain area are to be replaced, meaning the edited effect will not be passed on to future generations. With an increase in the number of successes alongside positive promotion to the public, there seems to be an inclining trend towards society gradually accepting the use of gene editing. For example, a study published in 2019 found that public attitudes towards gene editing are becoming more favorable, particularly for therapeutic applications that address serious diseases.[43] The most recent advancement is a cure for sickle cell disease (SCD) and β-thalassemia.[44] Both are inherited disorders that affect the haemoglobin in red blood cells: SCD is caused by a mutation in the β-globin gene, producing abnormally-shaped and sticky red blood cells that cannot flow smoothly in blood vessels, while β-thalassemia is caused by the decreased or absent synthesis of β-globin.[45,46] The imbalance of β-chains in both cases forms insoluble hemichromes, which lead to severe apoptosis or cell death. On 8th December 2023, the FDA approved two sickle cell disease gene therapies: Casgevy, made by Vertex Pharmaceuticals and CRISPR Therapeutics, and Lyfgenia by Bluebird Bio.[47]

Casgevy is currently the only CRISPR-based therapy, which aims to treat SCD by reintroducing the production of fetal hemoglobin so that red blood cells return to normal. Fetal hemoglobin is a protein that is normally shut off shortly after birth. It helps red blood cells retain their biconcave shape so that they can function healthily. By manipulating the patient's own stem cells, scientists are able to reactivate the production of fetal hemoglobin. The hematopoietic stem cells (HSCs) are collected from the patient's bone marrow. CRISPR is then used to 'knock out' the regulator that prevents HSCs from producing foetal haemoglobin.[44] In preparation for the treatment, patients have to take a chemotherapy drug called busulfan to wipe out any native stem cells that remain in the bone marrow, allowing space for the edited stem cells to grow after infusion. The use of busulfan chemotherapy can trigger severe side effects such as low levels of infection-fighting leukocytes and cytopenia, so patients have to be hospitalised under sterile conditions until their immune systems recover.[48] Despite this process being several months long, Casgevy is the only treatment available that targets the root cause rather than merely treating symptoms. Unlike symptom management, which only alleviates the effects of SCD, Casgevy addresses the genetic mutation responsible for the disorder. By restoring normal hemoglobin production, this therapy provides a long-term solution, potentially eliminating the need for continuous treatment. A patient confirmed it was worth doing as he "escaped from the clutch of fear that comes from thinking every occasion could be [his] last."[49] While this represents a massive

DOI: 10.36838/IJHSR84.62

scientific breakthrough, its application is still limited by the large 2.2 million USD price tag.[50]

On the same day, Lyfgenia was also approved to serve as a treatment for SCD, with a different editing mechanism from Casgevy. Lyfgenia works by adding a functional β-globin gene to patients' own HSCs, allowing the production of adult haemoglobin with antisickling properties, thus reducing the sickling of red blood cells.[51] However, a 'black box warning' was also given to Lyfgenia, as the process may potentially increase the risk of haematological malignancies in the patient. A 'black box warning' is the most serious warning issued by the FDA, indicating that a medication carries a significant risk of severe or life-threatening adverse effects. This warning serves to inform healthcare providers and patients of potential dangers, requiring careful monitoring and consideration before undergoing treatment. Although this may put Lyfgenia in a less beneficial position due to potential comparisons between the two treatments by the public, the risk of Casgevy should also not be neglected. Potential concerns include unforeseen long-term effects such as immune responses, off-target genetic modifications, and the possibility of haematological complications. As only a theoretical estimation of risks is currently available, further long-term studies are necessary to fully understand its safety profile.[52]

The World's First CRISPR Babies:

CRISPR has given scientists high hopes that it can not only be used as an effective treatment for genetic disorders during a person's life, but also, in the future, to potentially eliminate certain genetic disorders, such as sickle cell disease, cystic fibrosis, and Huntington's disease, from a human being before birth. Chinese biophysicist He Jiankui attempted to genetically engineer two embryos using CRISPR. His idea was to provide them with lifelong immunity against Human Immunodeficiency Virus (HIV). His approach involved a 32-base-pair deletion in the CCR5 gene on chromosome 3 of the embryos. This deletion is thought to lead to the production of non-functional copies of the CCR5 protein. When these proteins cannot function, HIV is unable to infect a cell, effectively preventing the patient from contracting HIV.[53] The project was only made public after the two CRISPR-edited babies were born in November of 2018, just before the Second International Summit on Human Genome Editing (ISHGE).

He Jiankui's announcement drew immediate global attention and widespread condemnation for breaching ethical and regulatory standards. Amongst the most serious concerns was his failure to follow the guidelines established by the First International Summit on Human Genome Editing, which recommended that germline editing not proceed without robust safety data and broad societal consensus.[54] He provided no preclinical evidence from studies in rodents or non-human primates to demonstrate the safety or efficacy of his method. Nor did he register the study with China's official clinical trial registry, in violation of requirements for prospective registration and documented ethics approval.[55] He Jiankui also falsely claimed to have received ethical clearance from the Shenzhen HarMoniCare Women and Children's Hospital, whose ethics committee was not officially registered; subsequent investigations revealed that the approval documents had been forged.[56] Furthermore, his home institution, the Southern University of Science and Technology, stated that the research had been conducted without their knowledge or approval. These violations, including the implantation of gene-edited embryos, which is explicitly prohibited under Chinese regulations, underscore the absence of legitimate oversight throughout the project.[57]

In addition to the regulatory violations surrounding the trial itself, He Jiankui's decision to target the *CCR5* gene was also criticised. He justified the intervention by pointing to the high number of HIV cases in some developing countries and aimed to make the embryos resistant to the virus by mimicking a naturally occurring mutation in the *CCR5* gene.[58] However, this mutation is rare in the Chinese population, and its protective effect is neither universal nor without risk.[59] There are insufficient published pre-clinical testing reports to certify whether the manipulation is safe, but editing *CCR5* has been linked to unintended consequences, including increased susceptibility to West Nile virus and higher mortality from influenza.[60,61] Moreover, his intervention was not intended to treat a life-threatening genetic disorder, but to grant a speculative health advantage. Existing treatments, such as antiretroviral therapies, are already effective, accessible, and far less invasive.[62,63] The case has since become a widely cited example of how scientific ambition, when unchecked by ethical and regulatory oversight, can undermine both public trust and future research.[64]

The long-term consequences of the experiment remain unknown. He Jiankui pledged to monitor the children's health for 18 years, assessing HIV resistance and potential off-target effects.[58] However, continued medical follow-up would not be able to resolve the fundamental concerns about safety and regulatory failure. Unpublished data from his manuscript revealed signs of genetic mosaicism in the twins, suggesting that the edits were not consistently incorporated across all cells. In one child, only one copy of the *CCR5* gene was successfully modified, meaning she may still be susceptible to infection.[65] While this experiment raises serious ethical concerns, it does not negate CRISPR's broader potential in medicine. Notably, since this study, the U.S. FDA has approved Casgevy, a CRISPR-based therapy for sickle cell disease, though crucially, this application does not involve embryo editing.

The CRISPR baby controversy catalysed widespread debate about the ethics of germline editing and the readiness of society to confront its implications. It highlighted concerns about unintended genetic consequences, intergenerational effects, and the potential for increased genetic inequality.[66,67] Some bioethicists have cautioned that access to genetic enhancement technologies may be limited to those with greater financial resources, potentially deepening existing social and economic inequalities. This concern is already visible in the case of CRISPR-based treatments such as Casgevy for sickle cell disease, a condition that primarily affects people of African descent. Although this therapy represents a major medical advance, its extremely high cost may limit access to wealthier patients and nations, raising questions about who will benefit

from future gene-editing innovations.[68–71] These disparities raise important questions about who will benefit from future gene-editing innovations and how to ensure equitable access as the technology advances.

At the same time, growing acceptance of preimplantation genetic testing (PGT) suggests a societal shift toward selecting embryos with preferred genetic traits.[69] While PGT does not involve gene editing, it reflects the increasing comfort with using technology to influence offspring characteristics. PGT is usually used in combination with *in vitro* fertilization, enabling parents to select the best combination of genetic characteristics among a batch of their pre-implanted embryos. If this trend continues, demand for more direct genetic modification, particularly among those who can afford it, may follow, raising concerns about fairness and equity in future reproductive technologies. This would ultimately lead to an era where reproduction will become "a highly commercial enterprise", as described by a bioethicist, Laura Hercher.[72]

These developments have renewed debate over the ethics of so-called "designer babies." For some, concerns about misuse are seen as barriers to scientific progress; for others, they serve as necessary guardrails to ensure technologies are introduced responsibly. While editing to prevent serious genetic diseases may seem justifiable, selecting for non-medical traits, such as appearance or cognitive ability, poses deeper ethical challenges.[70]

These concerns are closely linked to broader issues of access and fairness. Gene editing is an emerging novel therapeutic, and as seen with other costly therapies, problems such as health inequity may arise: individuals with higher social statuses could have easier access to these cutting-edge treatments.[68,71] Beyond cost barriers, minority patients are also much less likely to be aware of these therapies upon their availability.

Gene editing holds enormous potential to improve human health, but its application must be governed by clear ethical guidelines and equitable access. Without these safeguards, the benefits of genetic technologies may be unequally distributed, and their misuse could entrench, rather than reduce, existing forms of inequality.

Conclusion

Gene editing represents a powerful tool with significant potential benefits in medicine, agriculture, and biotechnology, and may also be beneficial to many other fields of work. However, its rapid advancement also raises ethical concerns that must be addressed. Where should the boundary be drawn between utilising such a phenomenal tool to treat a genetic disease and to enhance a specific trait? Is there a grey area in between, demonstrated by He Jiankui and his 'HIV-resistant' babies? When will this boundary be set and recognised by society? Many experts agree that therapeutic gene editing is ethically acceptable to prevent or treat severe genetic conditions, but using the same tools to enhance traits such as intelligence or appearance remains highly controversial and lacks international consensus.[73–76] The higher acceptability for using gene editing for therapeutics over trait enhancement mainly lies in its not involving any germline intervention (i.e., at the embryonic stage). Yet, given the acute ethical concerns surrounding the current and developing gene editing therapies, it is unlikely that genetic enhancement will become a reality anytime soon.[73]

Current gaps in knowledge need to be addressed in future research, especially the lack of long-term safety data. For instance, the cascade effects of editing even a single gene are still unknown, due to the pleiotropic nature of some genes, meaning that a single gene can influence the expression of multiple phenotypes.[77] Intergenerational effects should also be monitored for a more thorough understanding. Future research could examine and track the effects of genome editing in animal models, starting with simple organisms such as *C. elegans*, and ultimately moving to non-human primates, which are the most genetically and physiologically similar to humans.[78,79]

Another area that future studies should address is the presence of misconceptions surrounding gene therapy and gene editing among the public. These misconceptions may have psychological and societal impacts, creating ethical controversies, fear, and potential discontentment among those who cannot receive treatment. It is essential for the scientific community to understand and address public attitudes when designing new studies and to choose the most pertinent diseases to target. The main limitation of such investigations is that they cannot directly measure the societal impacts gene editing may have. Complementary studies using hypothetical scenarios and surveys could be used to identify global trends and make such predictions, hence helping guide the development of responsible innovations before clinical use becomes possible.

While gene editing has already demonstrated success in disease-resistant crops and biomedical research, issues such as equitable access, unforeseen genetic consequences, and ethical considerations regarding human applications remain unresolved.

Designer babies may become a viable option for future generations. However, we are still ethically, socially, and economically unprepared to incorporate it into our daily lives. As society continues to navigate this evolving field, it is essential to balance innovation with responsibility, to prioritise transparency, public trust, and equitable access at every stage of development, ensuring that the ethical implications are carefully considered before widespread implementation.

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DOI: 10.36838/IJHSR84.62

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Author

Katrina Leung is an upper-sixth form student who will pursue medicine in the coming years. She has been enjoying studying Biology in her A-levels, and in particular, she is interested in topics that raise ethical debates. She is motivated to become a doctor to help those who are medically challenged.