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REVIEW ARTICLE

Engineering Approaches to Combat Air Pollution: A Cross-Disciplinary Review on Respiratory Health

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ABSTRACT: Air pollution is a major environmental risk affecting billions of people worldwide, contributing to respiratory diseases such as asthma, bronchitis, and chronic obstructive pulmonary disease (COPD). While many studies focus on medical treatments and policy interventions, only a few explore how engineering can directly help reduce pollution-related health risks. This review introduces three promising technological approaches: wearable air quality monitors, which allow individuals to track real-time exposure to harmful pollutants; air-filtering materials, including HEPA and nanofiber filters that block fine particles before they enter the lungs; and lung-targeted therapies, such as inhalable drug delivery systems using nanoparticles. Additionally, we explore how integrating these technologies with public health initiatives, such as educational campaigns and environmental regulations, can enhance their accessibility and effectiveness. Through this cross-disciplinary lens, the paper highlights the critical role of bioengineering in addressing one of the most urgent environmental health challenges of our time. It encourages student researchers to pursue innovative, science-based solutions.
KEYWORDS: Biomedical Engineering, Biomedical Devices, Air Pollution, Respiratory Health, Nanotechnology.

Introduction

In today's world, air pollution has become a pervasive part of life for billions of people. Whether in bustling cities or rural areas near factories and farms, harmful particles and gases are constantly released into the atmosphere. According to the World Health Organization (WHO), over 90% of the world's population breathes air that exceeds safety limits, leading to more than 7 million premature deaths every year.[1] This makes air pollution not only an environmental concern but also a critical public health issue.

The lungs are among the organs most affected by air pollution. With every breath, people may inhale pollutants such as particulate matter (PM2.5 and PM10), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3). These substances can irritate or inflame the airways, reduce lung function, and increase the risk of chronic diseases such as asthma, bronchitis, and chronic obstructive pulmonary disease (COPD).[2,3,8] Children are especially vulnerable because their lungs are still developing[4-6] and the elderly often have pre-existing conditions that make them more sensitive to environmental stressors.[7,9]

In recent decades, public health researchers have made great progress in understanding the health effects of air pollution. Many review articles and reports have examined the epidemiology of pollution-related diseases, healthcare costs, and policy responses such as emission limits or clean air zones. However, despite these valuable insights, relatively few studies have focused on how engineering and technology can actively contribute to preventing or reducing the harm caused by air pollution.[10]

In particular, the role of bioengineering – a field that combines biology, medicine, and engineering –remains underexplored in this context. Engineering tools such as wearable sensors, smart air filters, and targeted drug delivery systems have the potential to reduce individual exposure, monitor real-time air quality, and even deliver treatments directly to affected lung tissues.[11-14] However, these technological solutions are rarely emphasized in traditional health-focused literature. Figure 1 illustrates this intersection between environmental risks and bioengineering interventions.

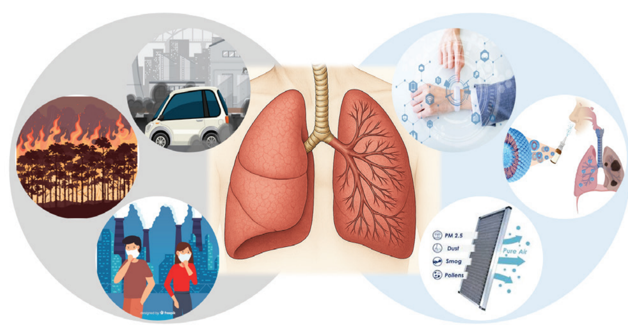

Figure 1: Sources of air pollution and corresponding bioengineering-based solutions for respiratory health. The left side of the figure shows common sources of air pollution, such as wildfires, vehicles, and urban smog, which can harm the lungs and cause serious health problems. The right side presents examples of engineering-based solutions – like wearable air quality monitors, advanced air filters, and inhalable drug delivery systems – that aim to reduce exposure and support respiratory health.

This review aims to highlight the importance of engineering-based solutions to the health problems caused by air pollution, especially in the area of respiratory health. While medical treatments and public health policies are essential, technology can add an important layer of protection and innovation. In particular, we focus on three promising areas of development:

1. Wearable Air Quality Monitors – Small, portable devices that track pollution exposure in real time.

2. Air-Filtering Materials – Advanced filters and masks that block harmful particles, including those enhanced by nanotechnology.

3. Lung-Targeted Therapies – Innovative drug delivery systems that treat pollution-induced lung conditions more efficiently.

By exploring these cross-disciplinary solutions, this paper encourages a broader view of how different fields – engineering, biology, and public health – can collaborate to address one of the most pressing environmental health issues of our time, and aims to promote further exploration of interdisciplinary solutions.

Discussion

Air Pollution and Lung Health: The Basics:

The U.S. Environmental Protection Agency (EPA) defines air pollution as the presence of harmful substances in the atmosphere that negatively affect human health and the environment. These pollutants include PM2.5 and PM10, NO_2, SO_2, O_3, and more.[15] PM2.5 is a serious air pollutant that affects physical and mental health as well as human productivity, primarily due to its small size and widespread sources.[16] Fine particles such as PM2.5 are especially dangerous, as they can penetrate deep into the lungs and even enter the bloodstream.[17] These pollutants originate from both human activities and natural sources, with major contributors being energy production, industrial processes, agriculture, and transportation.[18] The burning of fossil fuels, primarily for electricity production, industrial manufacturing, and transportation, is the largest contributor. In urban areas, vehicle exhaust is a significant source of NO_2, CO, and black carbon, which contribute to the formation of ground-level ozone and photochemical smog.[19] In addition, agriculture contributes through emissions of methane

(CH_4) from livestock and ammonia (NH3) from fertilizer. These chemicals combine in the atmosphere to form secondary pollutants like PM and tropospheric ozone.[20] Natural sources include wildfires, dust storms, and volcanic activity, which can release large volumes of smoke, ash, and chemical gases. Table 1 summarizes the major air pollutants, their sources, and associated health or climate effects.

Table 1: Sources of major air pollutants and their environmental impacts. Pollutants such as PM, NO_2, and O_3 primarily originate from human activities, including transportation, industrial processes, and agriculture. These substances are associated with serious health effects – such as asthma, cardiovascular disease, and lung inflammation – and also contribute significantly to climate change.

Pollutant	Primary Source	Key Health/Climate Effect
PM2.5 / PM10	Combustion, traffic, dust	Respiratory disease, cardiovascular impact
NO_2	Vehicles, power plants	Asthma, ozone formation
SO_2	Coal combustion, industry	Acid rain, bronchitis
O_3 (ground-level)	Secondary pollutant from NOx + VOCs	Lung inflammation, smog
CO	Incomplete fuel combustion	Headache, impaired oxygen delivery
CH_4 / NH_3	Agriculture, livestock	Climate warming, secondary PM formation

Air pollution is becoming increasingly severe, and this trend is closely tied to the worsening of global climate change. Although they are often treated as separate environmental issues, air pollution and climate change share a major common cause: the combustion of fossil fuels such as coal, oil, and natural gas. These fuels are burned to generate electricity, power vehicles, and support industrial activities. In the process, they release large amounts of greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), into the atmosphere, all of which contribute to global warming by trapping heat. At the same time, fossil fuel combustion emits harmful air pollutants, including SO_2, NO_2, and PM. These pollutants not only damage the ecosystem but also pose significant threats to human health, especially to the respiratory system.[21] The continued use of fossil fuels, especially in high-urban areas, is causing the Earth's climate to warm and the air to become increasingly toxic. Exposure to polluted air can trigger or worsen a wide range of diseases, including respiratory infections, asthma, allergic rhinitis, lung cancer, and COPD. Numerous studies have shown that as levels of pollutants like PM2.5 and NO_2 rise, the incidence of asthma and COPD also increases.[22] In polluted regions, hospital admissions for respiratory illnesses tend to spike, especially during extreme weather events like heatwaves or heavy smog.

Children and the elderly are particularly vulnerable to the effects of air pollution. For children, early exposure to toxic air can disrupt lung development and lead to long-term respiratory problems. Their immune systems are still developing, making it harder for their bodies to fight off airborne irritants. Older adults, on the other hand, experience a natural decline in lung function as they age, making them more susceptible to the effects of pollutants. People with pre-existing conditions, such as asthma, cardiovascular disease, or diabetes, are also at higher risk because air pollution can trigger inflammation, reduce lung capacity, and worsen existing symptoms. Therefore, it is crucial to minimize exposure to air pollution as much as possible to reduce the risk of further respiratory damage caused by it.[23-25]

Engineering-Based Solutions to Air Pollution:

Recent advancements in bioengineering and environmental technology have opened up new ways to reduce the health impacts of air pollution. While policies and healthcare systems are essential, engineering innovations can help detect, block, and even treat pollution-related health problems. This section explores three key types of engineering-based solutions: wearable monitors, air-filtering materials, and lung-targeted therapies.

Wearable air quality monitors measure real-time personal exposure and are available as wristbands, keychains, or clip-ons—especially useful in urban areas. These monitors typically utilize sensors that detect common pollutants, including PM2.5, NO_2, O_3, and volatile organic compounds (VOCs). The collected data is transmitted via Bluetooth or Wi-Fi to smartphone applications that display pollution levels, issue alerts, and offer recommendations, such as avoiding outdoor activities or wearing a mask when air quality is poor.[11,26,27]

Figure 2 illustrates two representative wearable monitors and their paired smartphone interfaces, demonstrating the practical application of this technology. These devices are small and lightweight, allowing users to clip them onto bags or wear them on the body. They offer continuous, real-time monitoring of airborne pollutants and sync seamlessly with mobile apps to provide actionable health guidance throughout the day.

Figure 2: Illustration of two representative wearable monitors. They are designed to be clipped onto backpacks or worn as personal accessories. These compact devices detect pollutants such as PM2.5, VOCs, and NO_2 in real-time and send data to smartphones, enabling users to manage their exposure effectively. By tracking air quality, individuals—especially those with asthma or COPD—can take preventive steps, such as avoiding high-exposure areas or wearing protective masks, which reduces the risk of symptom flare-ups and promotes better respiratory health awareness.

Air filters are designed to capture airborne pollutants before they enter the body. Different physical and chemical mechanisms are used to trap particles, depending on their size and properties. One basic mechanism is sieving, which blocks larger particles that are too big to pass through the pores of the filter material. Gravity settling removes particles heavier than air, which naturally fall out of the airflow before reaching the filter. In cases where particles are too small to be caught by gravity or sieving, inertial impaction becomes effective by forcing heavier particles to deviate from the airstream and collide with filter fibers. Meanwhile, interception captures particles that follow airflow but come into direct contact with fibers and adhere to them. Diffusion targets ultra-fine particles, typically smaller than 0.5 micrometers, that move randomly due to Brownian motion and are thus more likely to hit the filter surface. Lastly, electrostatic attraction enhances filtration by pulling charged or polar particles toward oppositely charged fibers, increasing the capture rate without reducing airflow. Table 2 provides an overview of the major filtration mechanisms used in air filters, including their targeted particle sizes and representative technologies.[28]

Table 2: Overview of air filtering mechanisms and technologies. Six major filtration methods are used, each designed to capture particles of different sizes based on physical or electrostatic principles. Technologies such as HEPA, N95, and nanofiber filters apply these mechanisms to improve air quality and protect respiratory health.

Filtration Mechanism	Description	Effective Particle Size	Example Technologies
Sieving	Blocks particle larger than the filter pores	Large particles (>1 μm)	Basic fiber filters, coarse pre-filters
Gravity Settling	Heavy particles naturally fall out of the airstream due to gravity	Heavier/larger particles	Used in industrial or pre-filter systems
Inertial Impaction	Particles deviate from the airflow and collide with the filter fibers due to inertia.	Mid-size particles (~0.3 - 10 μm)	HEPA, N95 filters
Interception	Particles following the airstream stick to fibers when they come close enough	Small to medium particles	HEPA, multilayer respirators
Diffusion	Very small particles move randomly (Brownian motion) and eventually hit and stick to filter surfaces.	Ultrafine particles (<0.5 μm)	Nanofiber filters, HEPA
Electrostatic Attraction	Changed fibers attract and trap oppositely charged or polar particles	Wide range (especially fine particles)	Electrospun filters, N95, Electrostatic cloth masks

HEPA (High Efficiency Particulate Air) filters combine many of these mechanisms and are widely used in air purifiers and high-grade masks. They are capable of removing at least 99.97% of airborne particles as small as 0.3 microns. Recent innovations include nanofiber membranes and electrospun filter materials, which maintain high filtration efficiency while allowing for improved breathability. Additionally, some advanced filters are enhanced with graphene oxide, silver nanoparticles, or activated carbon, which provide antimicrobial and deodorizing properties. These features are especially beneficial in environments that are exposed to both chemical pollutants and biological threats, such as viruses or bacteria.[29] Masks, such as N95 and KN95 respirators, employ multilayer filtration systems that incorporate many of the mechanisms described above.[30] They are commonly recommended during wildfire events, high-smog conditions, or public health emergencies. Similarly, modern household air purifiers equipped with smart sensors can automatically adjust filtration settings in response to real-time air quality data, providing more efficient protection indoors.

For individuals already affected by air pollution-induced diseases, especially those suffering from chronic conditions like asthma, COPD, or pulmonary fibrosis, advanced drug delivery systems targeting the lungs offer a transformative approach to treatment. Conventional systemic medications often suffer from poor targeting, leading to lower therapeutic efficacy and increased side effects. In contrast, inhalable drug delivery systems deliver therapeutic agents directly to the lungs, resulting in targeted drug delivery, precisely where the damage from airborne pollutants occurs.[31,32] These systems typically use aerosols or dry powder formulations engineered with optimized particle sizes (1-5 μm) for effective deposition in the lower respiratory tract. Traditionally, inhaled corticosteroids have been the mainstay of treatment for asthma and

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COPD; however, recent innovations are pushing boundaries by enabling the pulmonary delivery of more complex drugs, including antioxidants, anti-inflammatory compounds, and even genetic materials like siRNA and mRNA.[33,34] The significance of this innovation is particularly evident in the context of chronic exposure to PM2.5, which can cause persistent inflammation, oxidative stress, and even DNA damage in lung epithelial cells. In such cases, generalized treatments may fall short, whereas targeted and sustained-release therapies can mitigate damage more effectively. Nanotechnology plays a critical role in these systems. Lipid nanoparticles (LNPs), polymeric micelles, dendrimers, and hybrid nanoparticles are being developed not only to protect therapeutic agents during delivery but also to facilitate mucus penetration and site-specific release in diseased lung regions. Figure 3 illustrates a range of these advanced nanocarrier structures. Some nanoparticles are now engineered to bypass mucus barriers and target alveolar macrophages or inflamed bronchioles, allowing deep lung penetration and enhanced bioavailability.[35-37]

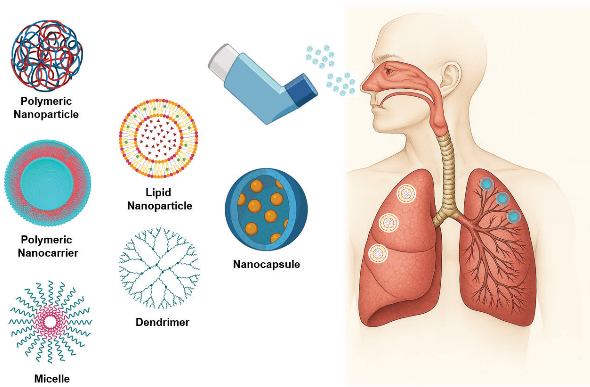

Figure 3: Illustration of various nanocarrier systems used for inhalable lung-targeted drug delivery. Examples include micelles, dendrimers, nanocapsules, polymeric nanoparticles, lipid nanoparticles, and polymeric nanocarriers, which are delivered via aerosol inhalers to inflamed or diseased lung tissue. These systems enable localized, sustained, and mucus-penetrating drug delivery for treating respiratory conditions caused by air pollution. By directly targeting the site of injury in the lungs, these nanocarrier-based therapies can improve treatment efficacy while reducing systemic side effects, offering significant benefits for patients with chronic respiratory diseases and potentially lowering healthcare burdens in polluted regions.

Emerging technologies are also combining drug delivery with real-time environmental sensing, such as smart inhalers that monitor air quality and adjust drug doses accordingly.[38] These devices may include pollutant sensors, GPS tracking, and AI-based dosage algorithms – empowering patients to manage symptoms based on exposure risk proactively.[39] For example, the "Propeller Health" platform in the United States has conducted multi-city pilot programs using sensor-equipped inhalers linked to mobile apps, which reduced asthma-related hospital visits by up to 35% over 12 months. Similarly, a clinical trial in the UK tested an AI-driven inhaler system that adjusted bronchodilator dosing based on daily air quality index (AQI) readings, leading to improved symptom control and reduced medication overuse. These examples demonstrate the practical feasibility and measurable health benefits of integrating engineering innovation with respiratory care. Looking forward, the convergence of inhalable drug delivery systems and precision medicine offers exciting new frontiers. Future systems may incorporate biosensors that detect biomarkers of inflammation, oxidative stress, or airway constriction, allowing for real-time, personalized therapeutic responses. Such integration could revolutionize the way we manage chronic respiratory diseases in the face of escalating air pollution, turning passive treatment into active disease prevention.

While wearable air quality monitors, air-filtering materials, and lung-targeted therapies each offer unique benefits, they differ in cost, accessibility, and optimal application environments. Wearable monitors provide real-time exposure data and empower preventive actions, but they require user engagement and may have accuracy limitations under extreme weather conditions. Air-filtering materials, such as HEPA or nanofiber filters, are relatively low-cost and effective in removing pollutants before inhalation, yet their efficiency depends on proper maintenance, and they may not address gaseous pollutants. Lung-targeted therapies directly treat pollution-induced damage with high precision, making them invaluable for patients with chronic respiratory diseases; however, they are often more expensive and require healthcare access and prescription, limiting widespread preventive use. In urban settings with frequent pollution spikes, a combination of wearable monitoring and portable filtration may offer the best preventive protection, whereas in clinical contexts, lung-targeted therapies can be critical for patient recovery. Recognizing these distinctions can guide policymakers, healthcare providers, and engineers in designing integrated, cost-effective interventions for diverse populations.

The Importance of Combining Engineering and Public Health:

Engineering-based technologies, such as air-filtering materials, wearable monitors, and lung-targeted drug delivery systems, offer promising tools to reduce the health burden of air pollution. However, their true impacts are maximized when integrated into public health frameworks that consider accessibility, education, and policy support. For example, wearable air quality monitors may help individuals avoid high-exposure areas, but their effectiveness depends on whether users know how to interpret the data and take appropriate actions. Public health campaigns can bridge this gap by educating communities on how to utilize these tools and what steps to take when pollution levels are high. In schools, real-time air monitoring systems combined with asthma awareness programs have been shown to reduce respiratory symptoms and absenteeism among students.[40] Policy also plays a critical role. Governments can mandate air quality standards in public spaces, provide funding for schools and clinics to install HEPA filters, or promote clean transportation systems. Engineering innovations such as smart air purifiers and low-cost sensors are more likely to benefit the public when supported by large-scale infrastructure and funding mechanisms. A well-documented example is the "Clean Air for Schools" program in parts of the United States and Europe, where schools located near highways or factories are equipped with air filtration systems and air quality sensors, and students receive education on environmental health. Such programs show how combining technological solutions with public awareness and institutional support can effectively reduce pollution-related health risks.[41]

Despite their potential, several challenges remain when combining engineering and public health strategies. One of the biggest barriers is cost. High-quality filters, wearable monitors, and smart devices can be expensive, limiting access for low-income families or under-resourced schools. Without proper subsidies or government support, the benefits of these technologies may not reach those most at risk. Another challenge is user engagement and digital literacy. Even when tools are available, people may not use them effectively due to a lack of awareness or misunderstanding. For example, studies show that many users misinterpret air quality index (AQI) values or fail to change filters in purifiers regularly, reducing the protective effect. Finally, there are technological limitations. Some wearable devices still have accuracy issues under certain environmental conditions. Filters may clog quickly in areas with high pollution, and smart sensors may require frequent calibration. Public health professionals and engineers must collaborate to enhance the usability, affordability, and reliability of devices. Addressing these challenges requires interdisciplinary collaboration, not only among engineers and doctors, but also with policymakers, educators, and communities. Only through such cooperation can we ensure that innovative technologies make a meaningful contribution to reducing the health impacts of air pollution.

Conclusion

Air pollution remains one of the most urgent environmental threats to human health, particularly affecting the lungs. While medical research and public health policies have advanced our understanding of its impact, engineering-based solutions offer new tools to monitor, prevent, and even treat the damage caused by polluted air. This review has explored three promising technological approaches: wearable air quality devices, which help individuals track and respond to pollution exposure in real time; air-filtering materials, such as HEPA and nanofiber filters, which physically block harmful particles before they reach the body; and lung-targeted therapies, which deliver medications directly to affected tissues for more effective treatment. The integration of these engineering innovations with public health efforts can greatly enhance their effectiveness. Schools, governments, and communities must work together to ensure these tools are accessible, affordable, and easy to use. At the same time, interdisciplinary collaboration between engineers, health professionals, and educators will be essential to overcome barriers such as cost, awareness, and usability.

Engineering solutions to air pollution represent not only technical innovation but also a critical pathway toward environmental equity and improved public health. These technologies can be particularly beneficial for vulnerable individuals, including young children, seniors, and those with underlying health conditions. Moving forward, interdisciplinary research efforts that bridge engineering, biomedical science, and public health policy will be crucial in developing scalable and inclusive solutions. In particular, the advancement of personalized air quality monitoring and responsive therapeutic systems, such as smart inhalers that detect pollutants and automatically adjust drug dosing, represents a highly promising direction.

This review underscores the importance of early engagement in cross-disciplinary research and calls on young researchers to take part in tackling this global challenge through STEM. From designing wearable sensors and optimizing filter materials to leading educational outreach, student-led innovation has the power to significantly advance respiratory health and contribute to cleaner air and healthier communities worldwide.

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