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# Different methods and technologies of air pollution mitigation: An overview

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## Abstract

Air pollution represents a critical dimension of environmental contamination and poses severe risks to human health and ecological systems. While environmental pollution can manifest in various forms—such as air, water, and soil pollution—air pollution remains the most pervasive and damaging. Rapid industrialization and the proliferation of pollution-intensive technologies have significantly contributed to the degradation of air quality. This review provides an overview of existing research focused on strategies for controlling and mitigating air pollution. Emphasis is placed on technological interventions, regulatory measures, and innovative approaches being explored to reduce airborne pollutants. The study also addresses current research gaps and proposes future approaches for air pollution mitigation measures.

***Keywords:*** Air pollution; Air pollution control; Environment pollution; Carbon monoxide; Particulate matter; Volatile organic compounds; Electrification

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## 1. Introduction

Air pollution remains one of the most concerning environmental issues in modern society, contributing considerably to worldwide illness loads and environmental degradation. According to the World Health Organization, air pollution causes approximately 7 million premature deaths each year, with low- or middle-income countries bearing the greatest burden due to rising urbanization and insufficient regulatory restrictions.[1] Pollutants, including particulate matter $(PM)_{2.5}$ and $PM_{10}$, nitrogen oxides $(NO_x)$, sulfur dioxide $(SO_2)$, and volatile organic compounds (VOCs), are increasingly prevalent due to both anthropogenic and natural sources. $PM_{2.5}$ (PM with a diameter of <2.5 μm) can carry hazardous chemicals deep into the lungs, where they may enter the human bloodstream and cause significant health issues.[2]

A defining challenge of the Anthropocene is the catastrophic impact of air pollution on both health and economic growth.[2] According to the Global Burden of Disease research, various kinds of pollution caused 9 million deaths in 2015, with air pollution accounting for 6.5 million of them.[2] Furthermore, air pollution reduces gross domestic product in low- and middle-income nations by 2% every year.[2] If air pollutants are not effectively managed, they will continue to endanger human health.[2]

One of the most effective strategies for mitigating air pollution is reducing emissions.[3] The effectiveness of air pollution control primarily depends on the political climate, governmental transparency, and the nation's economic standing.[3] Local issues can be addressed more effectively when there is a targeted approach supported by flexible policies.[3] In developed nations such as the United States (US), industrialization has contributed to deteriorating air quality. In China, rapid technological advancement and urbanization have driven recent initiatives to reduce air pollution. Several studies indicate that technological improvements remain the most effective approach. Additional mitigation techniques include photocatalysis, strict enforcement of environmental regulations, smart city planning, the use of alternative vehicle fuels, radical-induced oxidation, renewable energy adoption, stainless steel catalysts, green infrastructure, and energy-based biofiltration. In particular, biofiltration, a technique in which off-gases containing inorganic air toxics or biodegradable VOCs are vented through a biologically active medium, has proven effective in controlling air pollution.[4]

As expected, coal continues to serve as a major source of electricity worldwide. Improving air quality requires better emission management, which can be supported by technological solutions.[5] Photocatalysis, for example, has been demonstrated as an effective strategy for removing environmental contaminants from the atmosphere.[6] In this process, powerful oxidizing and reducing agents are photochemically generated on a catalyst's surface, leading to the degradation of contaminants, particularly organic compounds.[6] When treating air pollution in indoor or semi-enclosed spaces, photolysis, also known as visible light-driven photocatalysis, is recommended.[7] However, nitrate compounds have been less responsive to efforts aiming at lowering $NO_x$ emissions, which often increase during wintertime pollution episodes that cause haze.[8] Weak deposition has been identified as the primary factor contributing to this seasonal rise in nitrate.[8]

Urban design also plays a significant role in reducing air pollution, as hotspots are not always directly associated with high traffic density.[9] The Google ranking-inspired General Information Report approach can assist in ranking cities based on their environmental conditions.[10] In addition, sensor modules are valuable tools for mitigating air pollution.[9] These devices continuously monitor air pollutants such as PM, nitrogen dioxide ($NO_2$), $SO_2$, carbon monoxide (CO), ozone, and VOCs. By providing real-time data, they facilitate early detection of hazardous air quality conditions. Sensor modules can be strategically installed near traffic signals or toll booths.[9] Furthermore, plant leaves can absorb PM, thereby lowering ambient concentrations.[11] Improving energy efficiency in the non-power sector can further reduce $SO_2$, $NO_x$, PM, and carbon dioxide ($CO_2$) emissions.[12]

The shipping industry is another contributor to air pollution, as oil combustion produces black smoke and emits high concentrations of $NO_x$, CO, $CO_2$, and other pollutants.[13] In response, the global maritime and port sectors are developing new technologies, such as advanced engine systems and improved fuel quality.[13] Biofuels, derived from organic matter, offer a promising alternative to conventional fossil fuels. They can reduce overall energy consumption and emissions.[14] Different types of biofuels each offer specific advantages, such as enhanced atomization and low viscosity. Moreover, various renewable energy resources have the potential to replace fossil fuels, whereas hybrid power systems integrating multiple renewable sources can supply electricity more efficiently and significantly reduce carbon emissions.

This study aims to examine the technologies and techniques currently employed for air pollution mitigation, analyzing their mechanisms, applications, and overall effectiveness. It also seeks to identify research gaps and limitations in current air pollution control strategies, highlighting critical areas that require further investigation. In addition, the study assesses the effectiveness of various mitigation solutions across diverse environmental and socioeconomic contexts to understand their adaptability and real-world impact. Based on these findings, recommendations for future research are proposed to support the development of more effective and sustainable air quality management strategies.

## 2. Methodology

This study adopts a qualitative research approach through a comprehensive literature review to examine various methods and technologies for mitigating air pollution. The methodology involves collecting, analyzing, and synthesizing data from previously published research articles, industrial reports, environmental assessments, and relevant case studies. Sources were selected from peer-reviewed journals, reports by governmental and non-governmental organizations, and recognized environmental databases.

The literature review specifically focused on identifying the types and mechanisms of air pollution control, as well as distinguishing between active and passive control methods and technologies. Data collection was conducted through searches of electronic databases such as Google Scholar, ScienceDirect, ResearchGate, and other academic repositories, using keywords including "air pollution," "air pollution control," "environment pollution," "CO," "PM," "VOCs," and "electrification." Articles published between 2000 and 2023 were prioritized to ensure relevance and currency of information.

The findings were thematically categorized to highlight key concerns related to air pollution control technologies. Where applicable, comparative data and statistics were tabulated or referenced to support critical analysis.

## 3. Technical strategies

Effective air pollution control requires an integrated combination of technological, regulatory, and societal approaches. These strategies aim either to prevent pollutant formation at the source or to capture and treat emissions before they are released into the atmosphere. Control measures vary depending on the type of pollutant, source characteristics, and applicable environmental regulations. This section provides an overview of key methods and technologies for air pollution control, drawing on data from previous research.

Electrostatic precipitators (ESPs) are widely used in power plants and industrial facilities to remove PM, dust, and smoke. They operate by applying high-voltage electric fields to charge airborne particles, which are then attracted to oppositely charged collector plates. The particles accumulate on the plates and are periodically removed. Baghouse filters, also known as fabric filters, are highly effective in capturing fine particulates such as $PM_{2.5}$ and $PM_{10}$, as well as heavy metals. Contaminated air passes through fabric filter bags that trap particles, allowing clean air to exit. Accumulated dust is periodically removed, making this system particularly efficient in industries such as cement, steel, and chemicals. Cyclone separators are typically used to eliminate coarse particle debris. In a cylindrical chamber, centrifugal force drives heavier particles toward the walls, separating them from the air stream. Cyclones are often used as pre-cleaners before more efficient filtration systems. Wet scrubbers are versatile devices capable of removing PM, $SO_2$, ammonia ($NH_3$), and certain VOCs. In these systems, polluted gas comes into contact with a scrubbing liquid—usually water ($H_2O$) or a chemical solution—that absorbs or reacts with the pollutants. The cleaned gas is released into the atmosphere, and the resulting liquid waste is treated separately. Activated carbon adsorption is widely used for removing VOCs, odors, and mercury. The high surface area and porosity of activated carbon granules enable pollutants to adhere to their surfaces. Spent carbon can be regenerated or replaced, making this method suitable for both indoor air purification and industrial exhaust treatment. Selective catalytic reduction (SCR) is commonly used to control $NO_x$ emissions, especially in power plants and heavy-duty vehicles. In this process, $NO_x$ gases react with $NH_3$ in the presence of a catalyst, producing harmless nitrogen and $H_2O$. Biofiltration is an environmentally friendly technique for treating air containing VOCs, hydrogen sulfide ($H_2S$), and other odorous compounds. Polluted air is passed through a biologically active medium, such as compost or soil, where microorganisms degrade the organic pollutants. This method is particularly useful in wastewater treatment plants and food-processing industries. Finally, low-$NO_x$ burners and combustion modification techniques aim to minimize $NO_x$ formation during combustion. By altering conditions such as temperature, air-to-fuel ratio, and burner design, these approaches reduce $NO_x$ emissions and are commonly applied in industrial boilers and furnaces.

Numerous methods and technologies are available for controlling air pollution. The most effective approaches, along with supporting data, are presented in the subsequent subsections.

### 3.1. Emission control technology improvements

Coal remains the primary fuel source for many power stations. While combustion of coal generates power, it also releases substantial amounts of pollutants, including $SO_2$, nitrous oxide ($N_2O$), PM, and mercury. Coal-fired power plants are major emitters of $SO_2$ and $NO_2$.[5] PM is primarily released from coal ash generated during combustion.[5] The quality of the coal plays a significant role in determining emission levels.[5] Advancements in pollution control technologies can substantially reduce the concentration of pollutants emitted into the atmosphere. These technologies must be both cost-effective and efficient in removing pollutants. Table 1 summarizes findings from previous studies on various air pollution control techniques, including their pollutant removal efficiencies, costs, and applicability.

### 3.2. Photocatalyst immobilization methods

Photocatalysis, especially using semiconductor materials such as titanium dioxide ($TiO_2$), offers a sustainable approach to air pollution mitigation by degrading pollutants such as $NO_x$, VOCs, and other hazardous air contaminants under ultraviolet or visible light. However, practical deployment of photocatalysts requires immobilization onto a substrate to prevent catalyst loss and facilitate continuous operation.[6] Free (powdered) photocatalysts possess high surface area and reactivity but are impractical for large-scale, real-world applications due to challenges in recovery, particle agglomeration, and the risk of secondary pollution. Immobilization overcomes these limitations by anchoring the photocatalyst to a solid matrix or support, thereby improving durability and reusability.

The main photocatalyst immobilization techniques include (Table 2):

- Sol–gel method: A solution of metal alkoxides is hydrolyzed and polymerized to form a gel that

**Table 1. Summary of techniques for air pollution control[5]**

| Techniques | $SO_2$ (%) | $NO_2$ (%) | Mercury (%) | Particulate matter (%) | Cost ($/kW) | Applicability |
|---|---|---|---|---|---|---|
| Advanced dry scrubber | 90–95 | – | 0–90 | – | 50–150 | Pilot to commercial scale; it depends on the type of coal |
| Activated carbon injection with an electrostatic spray adsorption process | – | – | 50–90 | 99 | 3–8 | Pilot scale; retrofit and new plants with FF and ESP |
| Combined mercury and $SO_2$ sorbents | 40–85 | – | Up to 90 | – | 30–60 | Pilot scale; integrated with ESP or FF unit |
| WFGD with mercury oxidation process | 95 | – | >80 | 90% for>10 μm (up to 39.6% for $PM_{2.5}$) | 160–275 | Pilot scale testing |
| Wet scrubbers with a wet electrostatic precipitator | 99 | – | 80 | 90–99 | 10–20 | Commercial level; integrated with existing wet scrubbers |
| Activated coke | 90–98 | 15–80 | 90–99 | 80–85 | 150–200 | New plants and retrofits |
| SCR with WFGD | 95 | 90–95 | 40–90 | 90% for>10 μm (up to 39.6% for $PM_{2.5}$) | SCR: 50–140; WFGD: 160–275 | Commercial level |
| Electrocatalytic oxidation | 98 | 90 | 90 | 86 | 200 (for 500 MW) | Demonstration level: new plants and retrofits |

Abbreviations: $SO_2$: Sulfur dioxide; $NO_2$: Nitrogen dioxide; WFGD: Wet flue gas desulfurization; SCR: Selective catalytic reduction; FF: Fabric filter; ESP: Electrostatic precipitator; PM: Particulate matter.

**Table 2. Factors influencing photocatalyst immobilization method selection[6]**

| Criteria | Consideration |
|---|---|
| Substrate type | Porous ceramics, glass, metals |
| Operating environment | Indoor versus outdoor, ultraviolet versus visible light |
| Pollutant target | Nitrogen oxides, volatile organic compounds, and particulate matter |
| Durability requirements | Resistance to weathering, abrasion |
| Reactor design | Batch versus continuous flow |

embeds the photocatalyst onto a substrate (e.g., glass or ceramics). Advantages include excellent coating uniformity, strong substrate adhesion, and pore structure control that enables high surface area. The highest reported $NO_x$ removal rate using this method is 16 mg/m$^2$ min.[6] Limitations include the potential for cracking during drying and the complexity of its multi-step process
- Thermal spraying: The photocatalyst is deposited onto a surface by spraying at high temperatures, causing partial melting and strong adhesion. Variants include plasma spraying, flame spraying, and high-velocity oxy-fuel. Advantages are high durability and suitability for coating large and irregular surfaces. The highest reported VOCs removal rate is 107 mg/m$^2$•min. Limitations include possible thermal degradation of photocatalyst (especially $TiO_2$) and reduced surface area and porosity
- Dip coating: The substrate is immersed in a suspension of photocatalyst, then withdrawn, dried, and calcined. Advantages include simplicity, scalability, and potential good adhesion depending on the substrate. Limitations are the difficulty in controlling coating thickness and the need for multiple application cycles
- Spin coating: A small amount of catalyst suspension is dropped onto a substrate, which is then rapidly spun to distribute the liquid uniformly. Advantages include high uniformity and production of thin films ideal for optical applications. Limitations are its restriction to flat, small substrates and the poor mechanical strength of the resulting film
- Chemical vapor deposition: Volatile precursors decompose or react on a heated substrate to form a thin film. Advantages include strong adhesion, high purity, and good crystallinity. Limitations are high cost, operational complexity, and potential substrate damage from elevated temperatures
- Electrophoretic deposition: Charged photocatalyst particles are deposited onto a conductive substrate under an electric field. Advantages are rapid, efficient deposition and suitability for complex geometries. Limitations include the requirement for a conductive substrate and the need for post-deposition sintering.

### 3.3. Radical-induced oxidation

To remediate air pollutants present in flue gas, additional oxidants can be introduced as radical precursors. Various types of reactive radicals are used in this process, such as hydroxyl radicals, sulfate radicals, chlorine radicals, and ozone. These radicals can be generated and applied through different catalytic and photochemical pathways, such as homogeneous catalysis, heterogeneous catalysis, thermal catalysis, photolysis, photocatalysis, and electrical catalysis. For sulfate radical-based processes, both single-catalyst and synergistic-catalyst approaches are possible, with the latter often achieving higher removal efficiencies due to enhanced reaction pathways. Table 3 summarizes the reported pollutant removal efficiencies for $SO_2$, $NO_x$, and mercury using different types of radicals.

### 3.4. Expansion of renewable energy use

The primary source of $CO_2$ emissions is the combustion of fossil fuels. Reducing fossil fuel use is therefore essential for mitigating air pollution. Transitioning to renewable energy offers multiple benefits, including lowering the demand for fossil fuels, ensuring a sustainable clean fuel resource, and reducing greenhouse gas emissions.

Previous research has examined hybrid power systems, such as one combining a lead–acid battery with renewable regeneration, and another applied in coastal regions of Bangladesh. Both systems demonstrated effective results in achieving sustainable electrification.[1] From these studies, it was observed that $CO_2$ emissions decreased from 67% to 64%. For instance, while a 1% increase in renewable energy can reduce air pollution management costs in China by 17–35%, the same increase yields a reduction of more than two-thirds in India. Increasing renewable energy capacity not only lowers $CO_2$ emissions but also contributes to controlling $NO_x$ and PM levels in China; however, it is less effective in reducing $SO_2$ emissions.[15]

### 3.5. Catalytic methods for air pollution control

Catalysis, which encompasses catalytic oxidation and catalytic reduction, is an effective and energy-efficient approach to air pollution mitigation that produces no secondary pollutants.[16] It has substantial emission-reduction potential, making it an essential component of global air pollution control strategies.[16] Stainless steel catalysts have properties that make them suitable for installation near diesel engines to control emissions. For example, Co–Ba–K/$ZrO_2$/AISI 314 foam catalysts can be manufactured and utilized to remove both soot and $NO_x$.[16] Catalytic combustion is particularly effective[16] for oxidizing VOCs into $CO_2$ and $H_2O$ at relatively lower temperatures (200–500°C). Stainless steel is affordable, widely available, and its elemental compositions make it an effective support for VOC oxidation.

**Table 3. Summary of multi-pollutant removal efficiencies using different radicals[7]**

| Radical type | $SO_2$ removal efficiency (%) | $NO_x$ removal efficiency (%) | Mercury removal efficiency (%) |
|---|---|---|---|
| Hydroxyl radical | 99–100 | 75–100 | 75–98 |
| Sulfate radical | 99–100 | 72–100 | 85–99 |
| Chlorine radical | 99–100 | 77–98 | 90–95 |
| Ozone | 97–100 | 91–97 | 82–91 |

For $NO_x$ control, SCR with $NH_3$ is the most effective method for tail gas denitrification. $N_2O$, which has a global warming potential approximately 300 times greater than $CO_2$ can be decomposed using monolithic stainless-steel supports, which have been widely applied in $N_2O$ abatement.[16]

### 3.6. Biofiltration

Biofiltration is a low-cost biological process for air pollution control that requires minimal maintenance[17] and produces fewer hazardous byproducts compared to many physicochemical techniques.[17] It is also recognized for its potential to reduce atmospheric $CO_2$ levels. It entails passing polluted air through a bed of solid media, often maintained at a specific moisture level, where microorganisms degrade methanotrophs, ammonia-oxidizing bacteria, oligotrophic bacteria, fungi, and algae. Bacteria play the primary role in contaminant removal during biofiltration, whereas fungi aid in the degradation of complex compounds.[17]

Biofiltration can remove $H_2S$, odor, and VOCs, as well as carbon disulfide, when combined with biotrickling filtration.[17] The efficiency of the process depends largely on the concentration and activity of microorganisms, as well as environmental factors such as temperature, pH, and moisture content.[17]

### 3.7. $NH_3$ emission reduction strategies

According to the GEOS-Chem model, decreasing VOCs and $NO_x$ by 30% during winter leads to only an 8.6% reduction in PM levels. In contrast, $NH_3$ reduction is the most effective strategy for lowering $PM_{2.5}$ nitrate concentrations, especially during winter haze events. Even small reductions in $NH_3$ emissions are beneficial.

A 50% reduction in $NH_3$ emissions can lower nitrate-containing $PM_{2.5}$ by 25% and decrease haze days by 31%. Such a reduction also lowers total $PM_{2.5}$ by 13% in winter, 18% on winter haze days, and 14% annually 8. Agriculture is a major source of $NH_3$ emissions, which can be reduced through measures such as optimized fertilizer application and improved manure management practices.

### 3.8. Traffic management and urban planning

Two primary strategies can be applied to mitigate urban air pollution: improving traffic systems and enhancing urban planning efficiency.

Traffic systems can be improved by establishing low-emission zones and enforcing strict penalties for traffic law violations, which can moderately reduce air pollution.[9] Studies show that heavy-duty diesel vehicles are responsible for 40–60% of $NO_x$ emissions and 70–90% of $CO_2$ emissions from black smoke.[9] One-way traffic flow has been found to be more effective in reducing emissions.[9] Reducing the number of heavy diesel vehicles and improving road pavement quality can further limit air pollution.[9]

The adoption of electric vehicles and advancements in engine technology can mitigate transport-related emissions.[9] Between these two options, electric vehicles are considered the most effective;[9] VOC emissions are reduced by 98% and $NO_x$ emissions by 34% compared to conventional vehicles.[9] Strict regulatory enforcement remains critical to further reduce transportation-related pollution.[9]

Urban planning also plays a significant role in air quality management. Effective city layouts should facilitate natural ventilation into open spaces. Building height is an important factor in dispersing pollutants.[9] Weather conditions, such as wind speed, sunlight, temperature, and humidity, should be considered in planning. Urban greenery, such as roadside tree planting, promotes pollutant deposition and can facilitate beneficial chemical reactions that further reduce air pollution.[9]

### 3.9. XGBoost and grid ranking for pollution source identification

Research on XGBoost and grid ranking methods has not adequately captured air quality dynamics across entire regions, despite broad geographic coverage. The General Information Report approach is comparable to the Google PageRank algorithm, which ranks web pages based on their impact.[10] XGBoost, a non-linear machine learning algorithm, incorporates variable relevance mechanisms to enhance predictive performance.[10,11] This approach can identify the pollution sources that have the greatest influence on other areas, enabling targeted interventions to mitigate air pollution.[10] For example, studies have shown that XGBoost can be applied in various fields, including environmental monitoring, and can guide governments to prioritize air pollution prevention in high-impact regions, such as southern Oregon, which has been identified as significantly affecting air quality in northern parts of the US.[10]

### 3.10. Cloud computing-based air pollution monitoring systems

Cloud-based air pollution monitoring systems store air pollution data in a centralized database. In this approach,[9] sensor modules are installed at toll collection centers and traffic light intersections. When a vehicle passes these points, the system measures its emissions and uploads the data to the cloud. If emissions exceed permissible limits, both the local police and the vehicle owner are notified. The system can also verify inspection compliance, such as insurance expiry dates and smoke test results.[9]

High traffic volumes in street canyons can significantly elevate pollution concentrations. Green infrastructure can help improve air quality in areas where planting space is limited. Options include green walls, green screens, and green roofs. The effectiveness of green infrastructure interventions depends on the design of the street canyon.[9] Roadside vegetation can reduce PM concentrations by up to 60% and $NO_2$ levels by up to 40%.[9] Where planting space is available, trees are an excellent long-term solution; in more constrained areas, smaller potted plants and rooftop gardens can also contribute to localized air quality improvements.

### 3.11. Energy intensity improvements and electrification

Improving energy intensity can reduce $SO_2$ emissions by 26–44%, $NO_x$ emissions by 19–44%, PM emissions by 25–46%, and $CO_2$ emissions by 18–50%. Electrification can lower $SO_2$ emissions by 19–25%, $NO_x$ emissions by 4–28%, PM emissions by 20–29%, and $CO_2$ emissions by 11–12%.[14]

Among industrial sub-sectors, the non-ferrous industry demonstrates the largest spectrum of co-benefits, with reduction rates ranging from 20.9% to 55.8% for $SO_2$ emissions, 17.5% to 44.6% for $NO_x$ emissions, 24.5% to 47.8% for PM emissions, and 24.0% to 58.3% for $CO_2$ emissions 15. The paper sector achieves substantial reductions in $NO_x$ (7.9–38.1%) and $CO_{2\,(}$9.6–41.3%), but lower reductions in $SO_2$ and PM emissions.[12] According to Qian *et al.*,[12] the average direct co-benefits are highest in the non-ferrous industry and lowest in the non-power sector. In the non-ferrous industry, average reduction rates are 43.7% for $SO_2$, 44.2% for $NO_x$, 46.4% for PM, and 49.6% for $CO_2$.[12] In contrast, the non-power sector achieves reductions of 25.5% for $SO_2$, 24.1% for $NO_x$, 32.5% for PM, and 18.5% for $CO_2$, which remain significant.

Coal power plants, due to their higher energy intensity, provide smaller co-benefits to the non-power sector,[12] with reductions of 6.1% for $SO_2$, 3.6% for $NO_x$, 6.0% for PM, and 2.5% for $CO_2$. $NO_x$ reduction rates vary the most across industries.[12] Petroleum and non-metallic sectors achieve the highest $NO_x$ reductions[12]—19.3% and 27.6%, respectively—when 30% of fossil fuels are replaced with electricity.[12] In other industries, $NO_x$ reductions are below 12% under the same conditions.[12] $CO_2$ reduction rates are relatively similar across sectors when electricity substitutes 12–30% of fossil fuel use.[12]

### 3.12. Plastic waste disposal and recycling

Plastic is recognized as a significant contributor to air pollution. Most plastic products are single-use and cannot be reused. While biodegradable plastics have been developed as eco-friendly alternatives, their limited availability reduces their overall impact. Several strategies exist for plastic waste disposal. At present, a large proportion of plastic waste is sent to landfills, which has negative environmental impacts. Thermal treatment offers an alternative, as the heat generated during waste incineration can be utilized for other purposes.[13] Recycling is another viable option; however, it is constrained by factors such as polymer impurities and economic feasibility. Contamination of the plastic stream can disrupt the recycling process, and when economic returns are minimal, recycling becomes impractical.[13]

### 3.13. Air pollution predictor system development

Air pollution affects regions worldwide, and the ability to predict pollutant concentrations is essential for timely countermeasures. Several predictive systems have been developed, with advanced models increasingly built on deep learning frameworks.[18] One such approach employs recurrent neural networks in combination with particle swarm optimization algorithms.[18] The prediction process generally involves several steps. First, air quality data are collected from multiple monitoring stations. Second, the data are processed and prepared for analysis. Third, the dataset is divided into training and testing subsets according to established principles. The predictive model is then trained to interpret patterns from the collected data and generate forecasts.[18] Although data are typically collected over 30 days, using 25 days of data for model input has been demonstrated to yield optimal results.[18]

### 3.14. Fuel quality improvements

China produces the largest number of automobiles globally and is also among the world's most heavily polluted countries.[19] Faulty vehicles and low-quality gasoline are major contributors to urban air pollution.[19] Implementing strict fuel standards is a viable strategy for reducing pollutant emissions. For example, improvements in gasoline quality in China have resulted in a 12.9% reduction in pollutant emissions and an estimated financial benefit of USD 26 billion.[19] Under the new standards, the sulfur content of fuel is significantly reduced.[9] Biofuels also offer a promising solution for reducing air pollution.[14] Each type of biofuel provides specific benefits; for instance, oils derived from lemon peel and orange peel have been identified as suitable biofuel feedstocks.[14] Research indicates that blending 20% biofuel with conventional diesel can be used effectively in traditional diesel engines without major modifications.[14]

### 3.15. Sensor and monitoring systems

Low-cost sensors provide a practical approach for evaluating air pollutants in urban settings. However, they can sometimes produce inaccurate readings due to environmental factors. The integration of machine learning and advanced computational techniques can help overcome these limitations. In addition, calibration methods can be used to ensure accurate operation under extreme weather conditions. Intelligent calibration systems allow sensors to function reliably even in challenging environments, such as those with heavy smoke.[20] Calibration results have shown that these sensors can measure aerosol mass accurately. Two primary types of calibrators are used: (i) White-box calibrators and (ii) black-box calibrators.[20]

Black-box calibrators generally outperform white-box calibrators, although their performance may vary depending on environmental conditions.[20] Advanced monitoring systems can be developed by integrating wireless sensor network technology with building information modeling.[21] Previous research has demonstrated that the integration of these two technologies provides accurate monitoring, as shown in tests conducted over distances of up to 250 m.[21] However, signal strength was decreased by 15–20% when the receiver was rotated by 90° 23 and by 30–40% when penetrating thick walls.[21]

## 4. Non-technical strategies

### 4.1. Public awareness and education

Public awareness campaigns play an important role in encouraging behaviors that reduce air pollution, such as reducing private vehicle use, promoting public transportation, preventing open burning, and supporting clean energy initiatives. These campaigns should focus on educating individuals about the sources and health effects of air pollution while fostering community-level action.

Several case studies illustrate the impact of awareness initiatives. For example, Mahajan *et al.*[22] reported that involving approximately 400 citizens in air quality monitoring increased awareness of $PM_{2.5}$ and $NO_2$ exposure risks and led to a 21% reduction in car usage among participants in European urban areas. Similarly, a survey of 800 citizens in Isfahan by Jokar *et al.*[23] found that higher environmental awareness significantly predicted pro-environmental behavior ($p$<0.01), with educational interventions improving willingness to adopt cleaner practices by 30%. In Spain, Sánchez-García *et al.*[24] found that among 1200 respondents, 68% were willing to pay for policies aimed at reducing traffic-related air pollution. The average willingness to pay was EUR 3.95/month per person, highlighting the connection between awareness and economic support for pollution control policies.

### 4.2. Government policy and regulation

Governments can implement regulatory frameworks that set emission limits, monitor air quality, enforce pollution control standards, and promote cleaner technologies. Examples include establishing ambient air quality standards, incentivizing the installation of pollution control equipment, phasing out high-emission vehicles, and promoting renewable energy adoption. Successful policy implementation typically requires a combination of legal enforcement, financial incentives, and regular monitoring. Selected case studies are outlined below.

In a study by Jin *et al.*,[25] implementation of the 2013 Air Pollution Action Plan led to a 33–47% reduction in $PM_{2.5}$ concentrations in key Chinese cities, resulting in an average life expectancy gain of 0.4 years in urban areas. Industrial regulations and vehicle emissions control policies achieved 30–60% reductions in $SO_2$ and $NO_x$ emissions over 5 years. Amann *et al.*[26] reported that integrating air pollution and climate policies (e.g., EURO vehicle standards, low-emission zones) reduced premature deaths by approximately 500,000 annually across European nations. Nasir *et al.*[27] demonstrated that regulatory enforcement in the cement and textile sectors reduced PM emissions by 15–25% in pilot cities, with industries receiving incentives for pollution control equipment demonstrating 50% higher compliance than non-incentivized facilities. According to Mir *et al.*,[28] integrated strategies combining cleaner transportation and renewable energy promotion could yield a 16% reduction in $CO_2$ emissions, an 18% decrease in $PM_{2.5}$, and annual health cost savings of approximately USD 800 million. Meanwhile, Li *et al.*[20] reported that upgrading fuel standards (2010–2015) reduced $PM_{2.5}$ levels in urban centers by an average of 12.5 $\mu g/m^3$.

## 5. Discussion

The increasing threat of air pollution, as outlined in earlier sections, underscores the urgent and growing need for integrated, multidimensional control strategies. The comprehensive analysis of existing technologies and non-technical approaches reveals a wide spectrum of methods that are currently applied worldwide to mitigate the impacts of air pollutants—ranging from traditional engineering-based solutions to innovative, sustainable, and community-driven practices. The effectiveness of these strategies, however, is not uniform. Success depends largely on a region's geographical, climatic, socioeconomic, and regulatory context. For instance, countries with robust regulatory frameworks and strong economies can often deploy high-cost, technologically advanced solutions, while developing regions may need to rely on cost-effective, scalable alternatives.

Recent studies emphasize the critical importance of integrated approaches that combine PM control technologies—such as ESPs, baghouse filters, and cyclone separators—with advanced gaseous pollutant treatment systems such as SCR, wet scrubbers, and chemical absorbers.[28-32] Evidence supports that no single technology, regardless of sophistication, can adequately address the complex and multifaceted nature of air pollution. Instead, hybrid strategies that merge end-of-pipe control (targeting pollutants after formation) with preventive measures (minimizing pollutant formation at the source) have proven more effective in achieving significant reductions in air pollutant concentrations across urban, industrial, and rural settings.

Furthermore, sustainable and low-cost alternatives such as biofiltration systems and activated carbon adsorption show significant promise. These methods are not only effective in pollutant removal but also align with environmental sustainability goals, owing to their low energy consumption and minimal secondary pollution. For example, biofilters, which use microorganisms to degrade VOCs and odorous substances, have been successfully deployed in multiple industrial zones across Southeast Asia. Previous studies[9] have demonstrated that biofilters can significantly reduce VOC levels and odor emissions, making them particularly appealing for application in regions with limited financial and technical resources.

In addition to technological interventions, non-technical strategies play a crucial role in comprehensive air quality management. This review reinforces the findings of past research,[31] who argue that public awareness campaigns, community education programs, and behavioral change initiatives can meaningfully contribute to emission reductions at the community level. These efforts foster a sense of environmental responsibility among citizens, which in turn supports broader pollution control objectives. However, the long-term effectiveness of such initiatives hinges on several key factors, including consistent enforcement of environmental regulations, the availability of institutional support, and public perceptions of both the seriousness of air pollution and the benefits of mitigation.

Moreover, the regulatory and policy frameworks discussed earlier in this review align with key international environmental governance instruments, such as the World Health Organization's Air Quality Guidelines, the United Nations Sustainable Development Goals, and various regional climate action plans. These frameworks advocate the use of adaptive policy tools, market-based economic incentives, and the integration of technological innovation into national and local governance systems. The importance of aligning national efforts with international best practices emerges as a recurrent theme in the reviewed literature, further supporting the call for cohesive and harmonized policy actions.

In summary, the evidence presented in this discussion demonstrates that while a wide array of air pollution control technologies and strategies is currently available, their ultimate success is largely dependent on thoughtful integration, strong policy support, active public engagement, and a nuanced understanding of the local context. The findings of this review not only corroborate previous research but also extend it by offering a synthesized, holistic perspective that bridges conventional engineering solutions with emerging sustainable practices. In addition, it identifies critical areas where further research, policy innovation, and cross-sector collaboration are necessary to address existing gaps and enhance the overall effectiveness of air pollution mitigation efforts.

## 6. Conclusion

Air pollution remains an important environmental and public health concern, with multiple factors contributing to degraded air quality in both urban and industrial settings. This study has reviewed several key technologies for air pollution control, including ESPs, wet scrubbers, bag filters, and SCR systems, as well as alternative methods such as biofiltration and activated carbon adsorption. In addition, non-technical strategies, such as public awareness and regulatory policies, were highlighted as essential complements to technological interventions. Despite these developments, significant gaps remain. Many existing technologies are either cost-prohibitive or limited in scope, particularly when addressing mixed pollutant loads. The impact of public awareness campaigns is often hampered by inadequate educational outreach and inconsistent implementation. Similarly, regulatory policies, while in place in many regions, frequently lack the enforcement mechanisms necessary to achieve meaningful results. Future progress should focus on improving the efficiency and affordability of control technologies to facilitate broader adoption, especially in developing countries. There is also a pressing need for integrative frameworks that combine technological, behavioral, and policy-based approaches in a context-sensitive manner. Strengthening monitoring systems, promoting community participation, and reinforcing regulatory compliance mechanisms can amplify the overall impact of air pollution control measures.

Overall, this study underscores the importance of a multidimensional approach to air quality management and emphasizes the importance of continual innovation and adaptation, guided by environmental, economic, and social considerations.

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The authors declare they have no competing interests.

## Author contributions

*Conceptualization:* All authors
*Writing–original draft:* All authors
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Not applicable.

## Consent for publication

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Not applicable.

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