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(Review Article)

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Air pollution as a global health risk: Emerging evidence, interventions and policy insights

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Abstract

Air pollution continues to be a major global health threat, causing around seven million early deaths each year and ranking as the fourth leading cause of illness and death worldwide. Fine particulate matter ($PM_{2.5}$) and gaseous pollutants such as ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO) penetrate deeply into the respiratory and cardiovascular systems, causing oxidative stress, inflammation, and a range of chronic diseases. This burden disproportionately impacts low and middle-income countries, but high-income nations are not immune, with the United States reporting 100,000 to 200,000 air pollution-related deaths each year. Economically, air pollution results in trillions of dollars in healthcare costs and lost productivity worldwide. Recognizing the extent of this crisis, interventions have been developed at policy, technological, and household levels. Policies like the U.S. Clean Air Act and the EU Ambient Air Quality Directive have led to significant reductions in pollutant levels and related health burdens. Household interventions in low resource settings aim to cut indoor air pollution from traditional cooking methods, though their health benefits vary. Technological advances, including cleaner fuels and emission controls, show promise but require widespread adoption and cultural integration. This article assesses recent evidence on how air pollution affects biological mechanisms linked to disease, evaluates the effectiveness of interventions, and identifies critical gaps and future directions. Tackling air pollution demands coordinated global efforts that integrate health, environmental, and equity considerations to protect populations and achieve sustainable development goals.

Keywords: Air Pollution; Public Health; Particulate Matter; Policy Interventions; Household Air Pollution; Environmental Health; Cardiovascular Disease; Respiratory Disease; Global Health

1. Introduction

Air pollution has always been a threat to global public health, causing millions of premature deaths and chronic illnesses each year. Air pollution is currently the fourth leading risk factor for global disease and death, only after hypertension, smoking, and dietary issues. Economically, the worldwide health-related external costs were estimated at US$ 5 trillion in 2013, with an additional US$ 225 billion lost due to reduced labor productivity and in the European Region, the total annual economic impact of air pollution-related health issues and mortality, including morbidity costs, is about US$ 1.575 trillion [1]. According to the World Health Organization (WHO), combined exposure to outdoor and household air pollution results in approximately 7 million premature deaths annually, with the majority occurring in low- and middle-income countries. Even in high income countries, the burden of disease remains high. For example in the US, exposure to air pollution is associated with 100,000 to 200,000 deaths annually [2]. By conservative limits, air pollution reduces the average life expectancy in Europe by about a year [3].

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This burden of mortality is primarily driven by non-communicable diseases: fine particulate matter ($PM_{2.5}$) and gaseous pollutants (O_3, NO_2, SO_2) penetrate deep into the lungs and bloodstream, provoking cardiovascular events (heart attacks, strokes) and chronic respiratory disorders (COPD, asthma, lung cancer). Air pollutants are able to induce oxidative stress and airway inflammation [4,5]. Recent research has identified air pollution as one of the leading environmental health risk factors worldwide [6,7]. In children, air pollution is shown to be the most significant environmental risk factor [8].

Given this scale, interventions that improve air quality through policy, technology, or behavioral change are crucial for reducing the burden of chronic respiratory and cardiovascular diseases.

1.1. Purpose and Scope of Review Article

This review compiles the latest evidence on how different air quality improvement strategies lead to better health outcomes. It explores the biological mechanisms connecting pollution to disease, the global patterns of pollution-related illness, and various interventions at policy, household, and technological levels. We review case studies and articles showing the effectiveness of air quality measures and analyze policy frameworks for implementation. Finally, we discuss future directions, focusing on emerging research, integrating policy with climate action, and addressing equity concerns. Throughout, we emphasize the public health implications and policy lessons: cleaner air not only saves lives today but also aligns with economic development and climate goals.

2. Air Pollutants

The World Health Organization (WHO) reports on six major air pollutants [9]. These substances include ground-level ozone, particulate matter, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. Air pollution has a pervasive effect on all components of the environment, including groundwater, soil, and air as it can also permeate these areas.

2.1. Particulate Matter

Particulate matter (PM) is formed in the atmosphere when there are chemical reactions between different pollutants. The penetration of particles is closely dependent on their size. The United States Environmental Protection Agency defined the term as a term for particles. Particulate matter (PM) pollution encompasses particles with diameters of 10 micrometers (μm) or smaller, referred to as PM10, and extremely fine particles with diameters generally 2.5 micrometers (μm) or smaller. These substances contain tiny liquid or solid droplets that can be inhaled, resulting in health impacts [10]. Small-sized particulate matter is more dangerous because they are able to enter the lungs as well as the bloodstream [11,12]. Also, long-lasting suspension in the atmosphere and even their transfer and spread to distant destinations where people and the environment may be exposed to the same magnitude of pollution is another insidious way particulate matter impacts health [13].

2.2. Ozone

Ozone (O_3) is a gas formed from oxygen under high voltage electric discharge. It arises in the stratosphere, but it could also arise following chain reactions of photochemical smog in the troposphere [14]. Ground-level ozone (GLO) is generated through a chemical reaction between oxides of nitrogen and VOCs emitted from natural sources and human activities.

Ozone uptake usually occurs by inhalation. Due to the low water-solubility of ozone, inhaled ozone can penetrate deeply into the lungs [15]. Research has shown that ozone causes biochemical, immunological and skin diseases by interfering with the skin barrier function [16,17].

2.3. Lead

Lead is a naturally occurring toxic metal found in Earth's crust. Key sources of environmental contamination include activities like mining, smelting, manufacturing, and recycling, as well as lead used in various products. Most of the worldwide lead consumption goes toward making lead-acid batteries for cars. Lead also appears in many items, such as pigments, paints, solder, stained glass, lead crystal glassware, ammunition, ceramic glazes, jewelry, toys, certain traditional cosmetics, and some traditional medicines [18].

In terms of air pollution, exposure to lead occurs through the inhalation of lead particles generated by burning materials containing lead, for example, during smelting, recycling, stripping leaded paint, and plastic cables. When lead enters the body, it is distributed to organs such as the brain, kidneys, liver, and bones [19]. Lead accumulates in the teeth and bones over time, and bone-stored lead can be released into the bloodstream during pregnancy, potentially exposing the fetus. Malnourished children are at higher risk of lead poisoning because they absorb more lead when lacking nutrients like calcium or iron [19]. In pregnant women, lead can cause them to miscarry [18].

2.4. Nitrogen dioxide

Nitrogen oxide is a pollutant linked to traffic, emitted by automobile engines through the combustion of fossil fuels [20]. It is formed in processes where nitrogen reacts with oxygen at high temperatures, e.g., through lightning and the combustion of fuels [21]. Additionally, it is the precursor gas for the formation of ambient O_3 and NO_x further reacts with organic chemicals or ozone to form a variety of toxic products including nitrate radicals and nitroarenes [21]. It irritates the respiratory system by reaching deep into the lungs, leading to respiratory diseases, coughing, wheezing, dyspnea, bronchospasm, and even pulmonary edema at high inhalation levels [22,23]. Long-term exposure to high nitrogen dioxide levels has been linked to chronic lung disease and can impair the sense of smell [24]. Additionally, effects are not limited to the respiratory system, as symptoms such as eye, throat, and nose irritation have also been reported [24].

2.5. Carbon Monoxide

Carbon Monoxide is a tasteless, odorless, and colorless gas that results from the incomplete combustion of fossil fuels [25]. Poisoning from inhaling carbon monoxide can cause symptoms such as headache, dizziness, weakness, nausea, vomiting, and eventually unconsciousness. Carbon monoxide binds to hemoglobin much more strongly than oxygen does, and as a result, prolonged exposure to high levels of carbon monoxide can lead to severe poisoning [25,26]. This competitive binding reduces oxygen delivery, causing hypoxia, ischemia, and cardiovascular problems. Recently, carbon monoxide pollution has also been linked with neurocognitive impairment in children [27].

2.6. Sulphur dioxide

Sulfur dioxide is a hazardous gas mainly released during the burning of fossil fuels and industrial processes [13]. It affects the health of humans, animals, and plants. Vulnerable populations, including those with lung diseases, the elderly, and children, are at greater risk. Key health problems associated with sulfur dioxide exposure in industrial areas include respiratory irritation, bronchitis, increased mucus production, and bronchospasm. As a sensory irritant, it deeply penetrates the lungs, transforms into bisulfite, and activates sensory receptors, causing bronchoconstriction. Exposure can also lead to skin redness, eye issues such as tearing and corneal opacity, mucous membrane irritation, and exacerbating existing cardiovascular conditions [27].

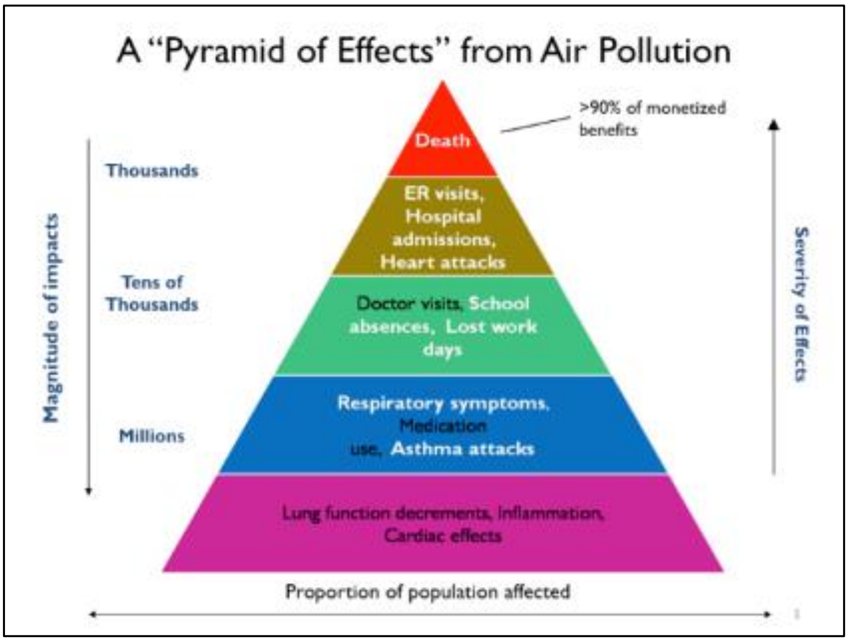

Figure 1 Economic impacts of air pollution [28]

3. Intervention Strategies

3.1. WHO Guidelines

After years of intensive research and deliberations with experts across the globe, the World Health Organization (WHO) updated its 2005 Global Air Quality Guidelines (AQG) in September 2021 [1]. The new air quality guidelines (WHO AQG) are ambitious and reflect the significant impact that air pollution has on global health. They recommend aiming for annual mean concentrations of $PM_{2.5}$ not exceeding 5 μg/m^3 and NO_2 not exceeding 10 μg/m^3, and the peak season mean 8-hr ozone concentration not exceeding 60 μg/m^3 [1]. For reference, the corresponding 2005 WHO guideline values for $PM_{2.5}$ and NO_2 were, respectively, 10 μg/m^3 and 40 μg/m^3 with no recommendation issued for long-term ozone concentrations.

The most important message of the updated WHO AQG is that each reduction in the outdoor concentrations of key air pollutants brings health benefits to the surrounding population, even in places which already have low pollution concentrations. Moreover, linear exposure-response relationships down to the lowest observable concentrations show that every individual will benefit from cleaner air [29–31]. These findings provide critical input into clean air policies and regulation around the world. They also are key to estimating the potential health and economic benefits from policies that reduce exposure to air pollution. While the guidelines are not legally binding, there is an expectation that they will influence air quality policy across the globe for many years to come.

3.2. United States of America Policy Interventions

Legislative and regulatory policies are fundamental to ongoing improvements in air quality. Examples include emission standards, fuel quality regulations, urban planning, and national air quality laws. For example, the U.S. Clean Air Act (CAA) and its 1970 and 1990 amendments established strict limits for industrial stacks, vehicle emissions, and ozone precursors [32]. Furthermore, this law authorizes EPA to establish National Ambient Air Quality Standards (NAAQS) to protect public health and public welfare and to regulate emissions of hazardous air pollutants.

Since its inception in 1970, the Clean Air Act has demonstrated a strong track record of progress. A 1997 EPA Report to Congress highlights that the first two decades of the Act's programs, covering 1970 to 1990, prevented numerous serious health problems in 1990 alone. These included 205,000 premature deaths, 672,000 cases of chronic bronchitis, 21,000 instances of heart disease, 843,000 asthma attacks, 189,000 cardiovascular hospitalizations, a reduction of 10.4 million I.Q. points in children caused by lead decreases, and 18 million cases of respiratory illnesses among children. These results emphasize the significant positive impact the Clean Air Act has had on public health across the United States [33].

Between 2006 and 2008, air quality improvements became clear, with 95 out of 126 areas previously failing to meet ozone standards now achieving the targets. Almost the entire country now complies with air quality standards for carbon monoxide, nitrogen oxides, and sulfur dioxide, showing significant progress in reducing pollutants. Lead levels in ambient air have decreased by 92% since 1980, leading to a noticeable decline in the number of children with IQs below 70 caused by lead exposure, thus highlighting the public health benefits of the Clean Air Act. A preliminary EPA analysis for 2010 estimates that the Act's programs for fine particles and ozone, enacted since the 1990 Amendments, will prevent over 160,000 early deaths. The economic benefits from these air quality improvements are projected to reach nearly $2 trillion by 2020, far surpassing the costs of the Act and related initiatives. These results underscore not only the success of the Act in enhancing public health but also the considerable economic advantages of investing in cleaner air [33].

3.3. Europe's Legislative Control

Since the 1980s, the European Union has taken significant steps to address air pollution, resulting in a marked decrease in most air pollutants over the past few decades. These efforts have undoubtedly improved public health and environmental conditions across Europe. However, the issue of air quality remains a pressing challenge. Despite the reduction in the number of people exposed to harmful levels of air pollution, several regions still experience air quality levels that exceed the World Health Organization's (WHO) guidelines.

The EU standards for health protection outlined in the AAQ Directive address both short-term and long-term health effects. They restrict the number of instances where pollutant concentrations can surpass short-term (daily and hourly) limits and mandate that annual averages remain below specified thresholds. In reality, EU ambient air quality limits are much weaker than the WHO guidelines for $PM_{2.5}$ and SO_2, and weaker for PM_{10} (annual average) and for ozone [34]. For

PM_{10} (daily value) and NO_2, EU standards are aligned with WHO guidelines that sometimes allow for limits to be exceeded on certain occasions.

3.4. Europe's Legislative Control for Automotive Emissions

The European Commission has always been dedicated to safeguarding air quality and reducing greenhouse gas emissions. The EU has set very strict standards for emissions from light-duty vehicles like cars and vans, as well as heavy-duty trucks and buses, along with regulations for non-road mobile machinery. These steps help cut down air pollution and lessen health risks, all while encouraging technological progress to protect our environment. Over time, Europe has rolled out a series of rules and standards to limit harmful vehicle emissions, gradually tightening these limits to achieve cleaner air and meet climate goals. The Euro 7 rules are meant to support the EU Green Deal's ambitious goal of zero pollution and will cover vehicles over a longer lifespan than before. For the first time ever, Euro 7 will also regulate emissions from tyres and brakes. Plus, it includes new requirements for battery durability, helping accelerate the switch to electric vehicles. Alongside the Euro 7 proposal, there are several legislative documents that set emission limits for different vehicle types and improve testing procedures, such as the Real Driving Emissions (RDE) test and the World Harmonized Light Vehicle Test Procedure (WLTP).

Regarding light-duty vehicles, the EU has already established strict emission standards under Euro 5 and Euro 6, aiming to reduce CO2 emissions from new fleets of cars and vans. Since September 2017, new car models are required to undergo more accurate emissions testing based on real-world driving conditions. For heavy-duty vehicles, the Euro VI standard, which has been in place since 2013, introduced tighter emission limits for trucks and buses. Furthermore, starting January 1, 2019, the CO2 emissions and fuel use of new lorries must be measured and reported using the VECTO simulation tool. The EU also created a verification testing process (VTP) to ensure these standards are met. Through these combined efforts, Europe continues to push for technological innovations and aims to significantly reduce the environmental impact of transportation, moving towards a cleaner and more sustainable future [35].

3.5. EU Ambient Air Quality Directive: A Crucial Step Towards Healthier Air

The persistent failures to meet WHO standards underline the need for updated policies and more rigorous measures to protect both human health and the environment. The revised EU Ambient Air Quality Directive, which entered into force on 10 December 2024, addresses these ongoing challenges by refining and strengthening the previous regulatory framework, ensuring that Europe's air quality standards align more closely with the latest scientific recommendations and the EU's long-term environmental goals [36]. The revised Directive sets out several key objectives to enhance air quality and safeguard public health. First, it aims to define common methods for monitoring and assessing air quality across the EU. This will enable a more uniform approach to air quality management, ensuring that member states adhere to consistent standards and reporting practices. One of the Directive's central goals is to provide a framework for assessing emerging pollutants, which could pose new risks to human health and the environment in the future. To achieve this, the Directive calls for the creation of a robust and high-quality monitoring network across Europe, supported by more than 4,000 air quality monitoring stations and an enhanced use of air quality modeling techniques. These efforts will not only improve the accuracy and comprehensiveness of air quality data but will also enable governments and the public to better understand the health risks associated with air pollution [36].

3.6. Household Interventions

In countless homes across low- and middle-income countries (LMICs), the simple act of preparing a family meal comes with a heavy cost. The smoke rising from open fires and traditional stoves contains fine particulate matter (PM2.5) and carbon monoxide (CO)—invisible yet deadly hazards linked to respiratory illnesses, poor pregnancy outcomes, and cardiovascular disease. This quiet crisis of household air pollution (HAP) disproportionately impacts women and children, who spend the most time near the stove. For decades, researchers and policymakers have worked to break this cycle, introducing improved cookstoves, liquefied petroleum gas (LPG) systems, ethanol stoves, and even solar ovens. These technologies promise cleaner air and healthier lives, but do they truly deliver? Do they reduce exposures enough to change health trajectories for millions living in these conditions? This synthesis brings together findings from rigorous randomized controlled trials (RCTs) across Africa, Asia, and Latin America to explore a critical question which is how effective are these interventions in reducing harmful exposures and improving health? The results reveal both progress and persistent challenges.

3.7. Effectiveness of Interventions on Reducing Household Air Pollution

At the core of household efforts is a simple goal to reduce the smoke and toxic pollutants that fill kitchens and damage lungs. However, the success of these efforts varies greatly depending on technology and the situation. In rural Guatemala, where families use open indoor wood fires for cooking, they received improved biomass-burning cookstoves with chimneys designed to vent smoke outside. Children in these homes breathed air with much less carbon monoxide and $PM_{2.5}$ compared to those in homes still using open fires [37]. Another study, RESPIRE, a randomized trial of an improved cookstove, was conducted in Guatemala to assess health effects of long-term reductions in wood smoke exposure. The between-group comparisons provide evidence that chimney stove reduces blood pressure, and the before-and-after comparisons are consistent with this evidence [38]. Nepal's experience reflected this mixed outcome. A step-wedge trial of improved biomass cookstoves achieved modest reductions in indoor air pollution, but when families switched to LPG stoves, the air quality improved significantly. Enhanced biomass stoves might not lower indoor air pollution enough to significantly affect adverse birth outcomes [39,40] Other settings uncovered deeper challenges. In Malawi, a fan-assisted biomass stove designed to burn fuel more efficiently did not notably decrease household CO levels [41]. Families often continued using their traditional stoves alongside the new ones, a practice called stove stacking, reducing the potential benefits. In contrast, multicountry LPG interventions showed consistent success. Trials in Guatemala, India, Peru, and Rwanda provided not only LPG stoves but also dependable fuel supply and behavior-change support. These programs achieved significant and lasting reductions in both PM2.5 and CO exposures for pregnant women and children [42,43]. However, not all innovative technologies succeeded. In Nigeria, ethanol stoves failed to meaningfully reduce personal exposures, while solar ovens in Senegal were limited by cultural preferences and inconsistent sunlight [44,45]. The lesson from these diverse experiences is that interventions providing clean fuels and targeting user behavior are much more effective than relying solely on improved biomass stoves.

3.8. Effectiveness of Interventions on Child Health

Children under five are especially vulnerable to the dangers of household air pollution [46]. However, even as some interventions have improved air quality, translating these improvements into clear health benefits has been challenging. In Guatemala, improved cookstoves did not significantly reduce overall pneumonia rates in young children, although there was some indication of protection against severe pneumonia [37]. In Malawi, despite the introduction of cleaner-burning stoves, there was no observable change in pneumonia incidence [41]. Trials in Nepal and various other countries found no impact on birthweight, growth, or respiratory infections in infants and toddlers, even when mothers experienced significantly lower exposure to $PM_{2.5}$ and CO during pregnancy [39,42]. These results underline an important reality that reducing household air pollution is essential, but it alone may not be enough to improve child health outcomes. Other factors, such as ambient air pollution, poor nutrition, and limited access to healthcare, continue to impact children's health in these communities.

3.9. Effectiveness of Interventions on Adult Health

For women who spend long hours preparing food over smoky fires, clean cooking technologies offer hope for healthier lungs and hearts. In Mexico, that hope was partly realized. Women using improved biomass stoves reported fewer respiratory symptoms such as coughing, wheezing, and eye irritation, and their lung function declined more slowly over time [47]. Elsewhere, the picture was less encouraging. Studies in Malawi, India, and Peru found no significant improvements in women's lung function, blood pressure, or reported respiratory symptoms after adopting cleaner technologies [41,48,49]. Even LPG interventions, despite achieving dramatic reductions in exposure, did not lead to clear health benefits for adult women in some trials. These inconsistencies suggest that for women with years of prior exposure, the damage may already be done, or that health improvements take longer to become apparent than most studies' timeframes allow.

The evidence indicates that clean cooking initiatives can reduce household air pollution, with LPG technologies surpassing improved biomass stoves. However, the impact on health outcomes is more complex. Factors such as households using old stoves alongside new ones or other environmental and social influences can lessen the health benefits of exposure reductions. Future strategies should focus not only on deploying cleaner stoves but also on ensuring their consistent use, cultural acceptance, and comprehensive approaches covering nutrition, healthcare, and outdoor air quality. Transitioning to truly clean fuels like LPG, electricity, or renewables requires reliable supply systems to ensure continuous use. While the outlook for cleaner cooking is promising, achieving their full health potential will require bold, integrated strategies that go beyond just the stove.

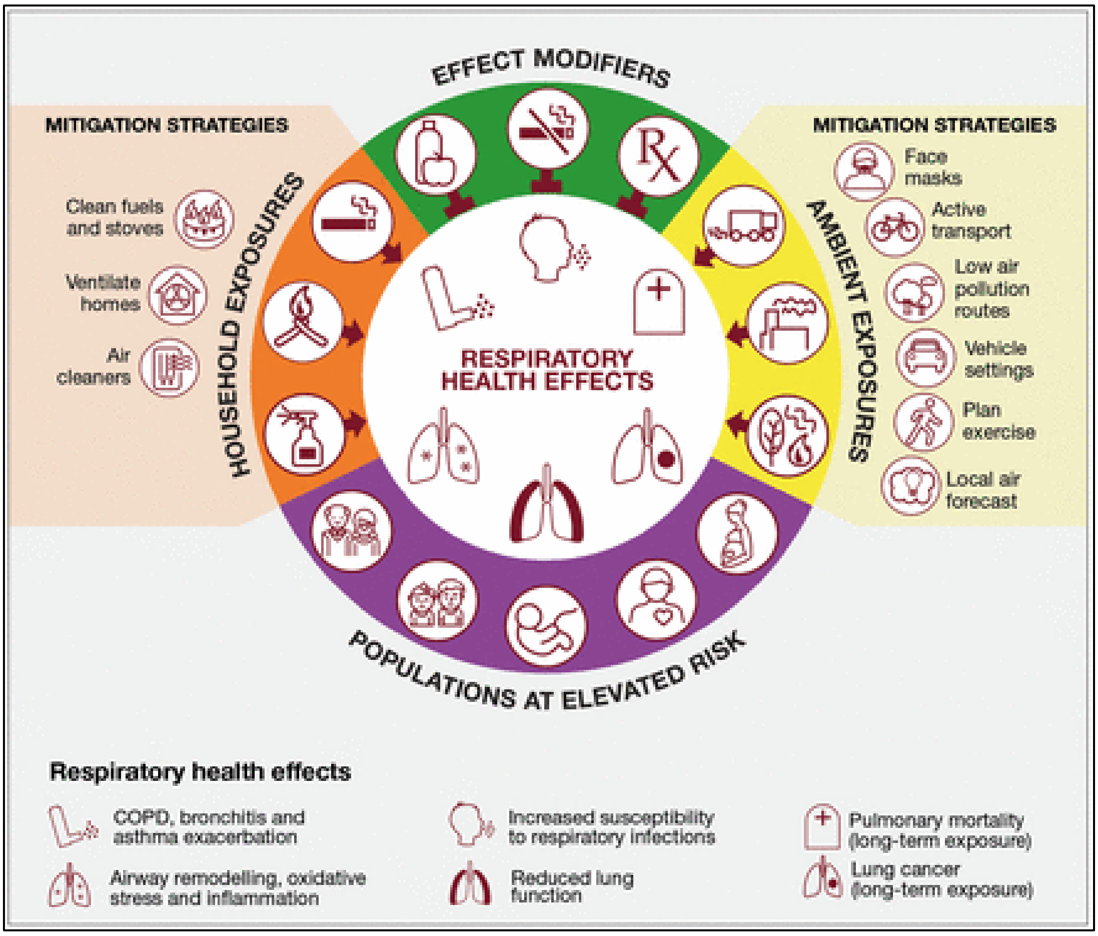

Figure 2 Air Pollution Effects and Mitigation Strategies [50]

4. Technological Interventions

4.1. Air Pollution Monitors

Direct measurements are considered the gold standard for assessing air pollution exposure, especially when high-quality, validated instruments are used over extended periods [51]. However, collecting such data for large populations is quite challenging due to costs and logistical hurdles. As a result, most studies have involved smaller groups or shorter monitoring times. The way air pollution is monitored is changing from large regulatory sites to smaller sensors [52]. The approach to air pollution monitoring is rapidly changing due to recent advances in portable, affordable sensors that deliver near-real-time data with high temporal resolution, along with improved computational tools, visualization methods, and wireless communication infrastructure [52].

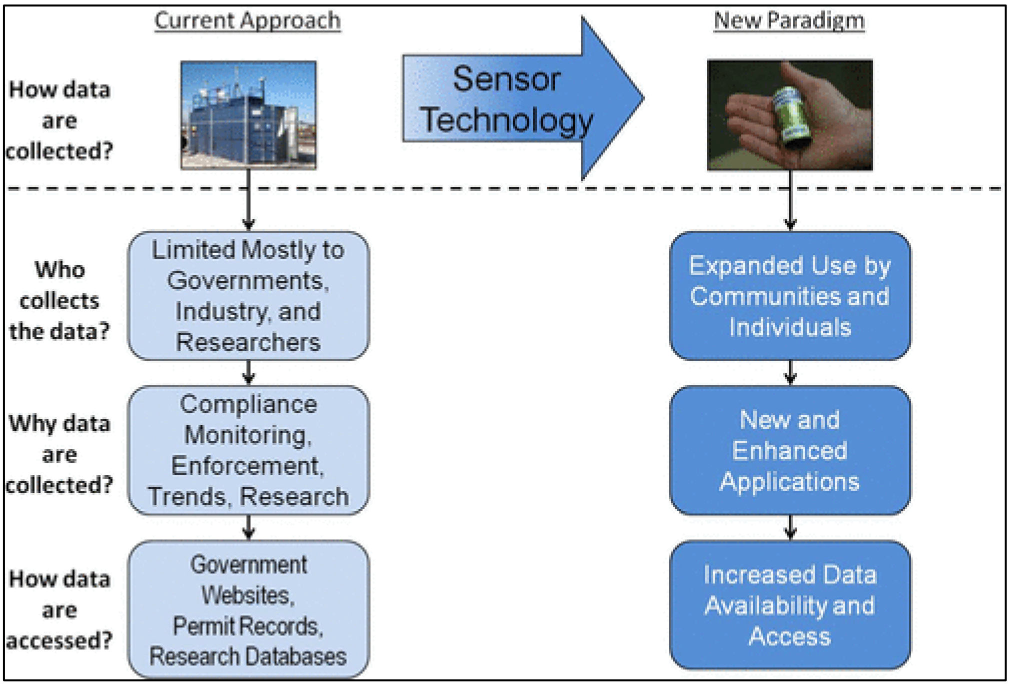

Figure 3 Paradigm of air pollution exposure data collection [52]

Modern air pollution monitoring techniques extend beyond traditional networks, including satellite remote sensing, affordable portable sensors, nonregulatory networks, and air quality models. Each method has advantages and disadvantages for health research and public health communication. These limitations encompass technical issues such as data accuracy, coverage, and resolution, as well as practical challenges like cost, awareness of data access, and ease of use [53].

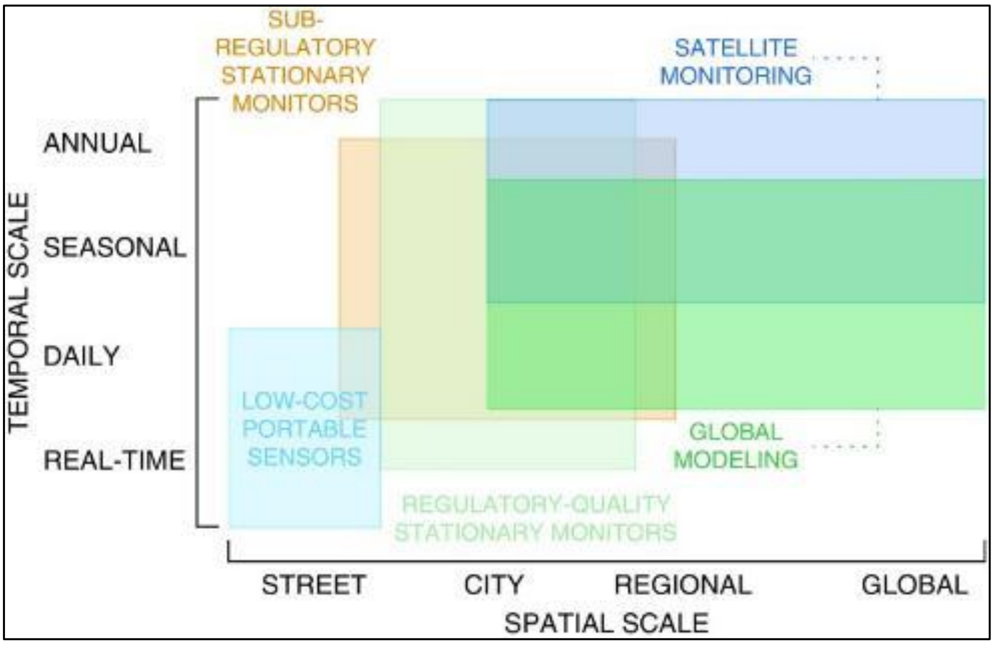

Figure 4 Temporal and spatial scale methods of air pollution data collection [53]

Satellite data offers unmatched spatial coverage, a key advantage over other technologies. Although earlier, resolution limits restricted this benefit, advancements in satellite technology have continuously improved it. Agencies like NASA and the European Space Agency operate a vast network of satellites providing global data. This data underpins scientific research and initiatives in environmental and public health, such as monitoring air pollution, evaluating exposure risks, and predicting air quality. [54–57]

Low-cost sensors are an emerging technology with great potential for air quality monitoring. For under resourced settings and developing nations such as South Asian countries and Pakistan where monitoring infrastructure is limited, low cost sensors present a valuable solution for managing air quality. Research has been able to show that low cost sensors can be effective in measuring air pollutants in the bid to control emissions. For example, the TSI BlueSky low-cost sensor data, validated against a co-located BAM reference monitor at DG Cement Chakwal was shown to be reliable and robust [58]. Again, low-cost sensors due to their compact design, ease of replacement and deployment at various locations, high resolution, ease of operation and lower capital cost than the conventional/reference instruments, are highly recommended to be incorporated into hybrid monitoring networks for widescale monitoring [58]. With rapid urbanization, a lot of low cost sensors have shown promise in addressing the pressing challenges of urban air pollution [59]. Additionally, an added advantage is that these low-cost sensors are also used with existing networks, have better spatial coverage and improved data granularity [60].

Recent years have seen substantial progress in developing and deploying air quality sensors for pollution monitoring. However, the swift progress in sensor technologies creates both challenges and opportunities, shaping research priorities and business expansion. Effective air pollution monitoring requires innovative approaches that promote market growth and tackle environmental and public health issues [61].

4.2. Air Pollution Models

Since personal air measurements and individual GPS data are unlikely to be collected continuously over the time periods necessary to capture long-term air pollution exposures, environmental models are required to estimate these long-term exposures. The primary strengths of air pollution modelling lie in its capacity to leverage diverse data sources. With the rise of “big data,” there are many opportunities to enhance these models. Satellite data related to air pollution are increasingly integrated with detailed land use information, such as emissions sources like roads, population density, and land types, to generate fine-scale spatiotemporal pollution patterns. This approach has helped in understanding and possibly predicting air quality issues. For example, a global model of NO_2 concentrations at a 100m x100m resolution using satellite estimates and land use variables that predicts 54% of the NO_2 variation from 5,220 air monitors in 58 countries [62]. Artificial intelligence approaches are also being used in tandem with air pollution models for air pollution predictions and applications of deep learning to high resolution satellite imagery, combined with other ground-based images [63,64]. Research has shown that pollutant information from nearby stations has a significant effect in predicting the pollutant concentrations [65].

4.3. Smartphones

Smartphones will allow for personal air pollution exposure assessments at scales needed for population research by supporting the use of personal sensors and GPS tracking and offering a platform for innovative air pollution health studies. Currently, there are 3.8 billion smartphone users worldwide, with estimates rising to 6.8 billion by 2022 [66].

The most direct application of smartphones to enhancing air pollution exposure estimates is the collection of time-activity patterns using GPS [51]. The widespread use of smartphones and increasing acceptance of health and research applications enable the collection of time-activity patterns from potentially hundreds of thousands of individuals over extended periods. Research has been able to show the effectiveness of using smartphones through various studies. For example, a study demonstrated this utility by using smartphones to collect personal-level time activity data [67], as well as a high degree of temporal and spatial regularity in time-activity patterns [68]. These findings have shown that continuous GPS monitoring might not be necessary for evaluating long-term activity patterns in health research. For instance, seasonal measurements lasting a week could effectively capture much of the variation in time-activity that influences air pollution exposure.

4.4. Air cleaning infrastructure

Another technological frontier is air cleaning infrastructure. Some cities and buildings experiment with large-scale air filtration and UV systems. Green infrastructure (urban trees and vegetated barriers) can modestly capture dust and scatter pollutants, though their health impact is complex. Innovations like satellite and ground sensor networks provide granular air quality data, enabling targeted alerts and planning (e.g. warning vulnerable people during smog events). In high-risk environments (schools, hospitals), installing HEPA filtration has shown benefits in reducing particulate exposure and improving respiratory symptoms among occupants.

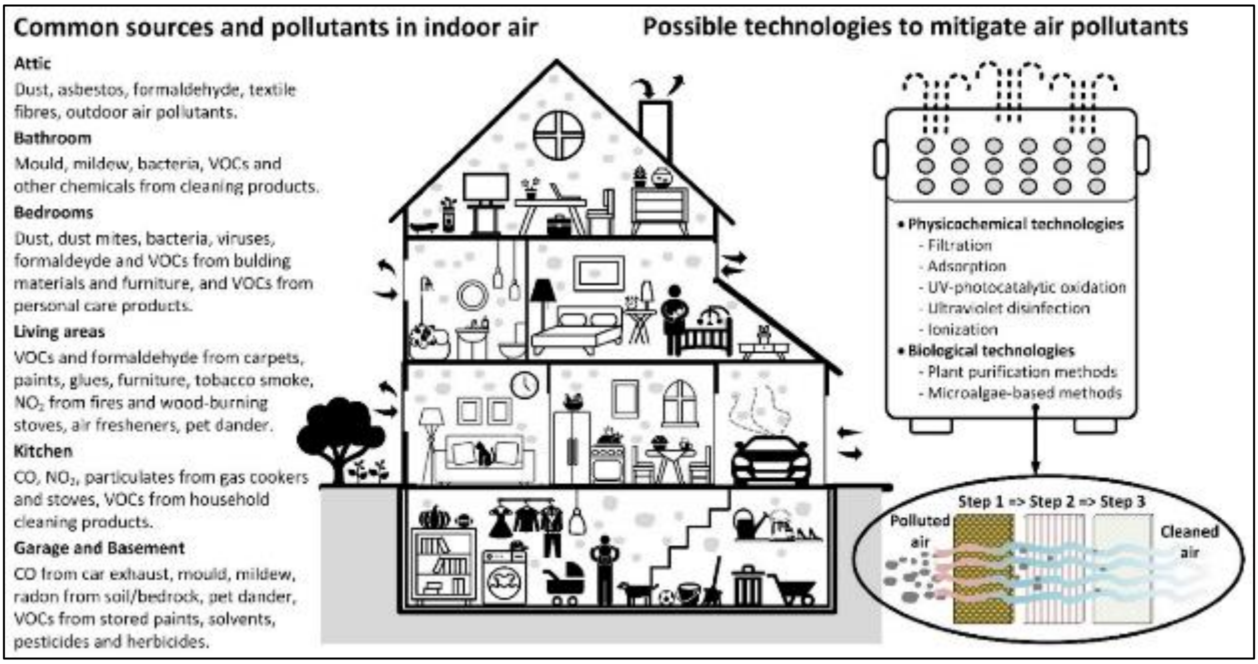

Figure 5 Temporal and spatial scale methods of air pollution data collection [69]

Air purification technologies play a crucial role in enhancing indoor air quality by targeting pollutants such as particulate matter (PM) and gases. Among these methods, filtration and adsorption are the most widely employed, with additional technologies like UV-photocatalytic oxidation and ionization emerging as effective solutions.

4.5. Filtration

Filtration technologies, especially mechanical and electronic filters, are commonly used to eliminate particulate matter from indoor air. Mechanical filters trap particles using porous materials and operate through impaction and diffusion. The most prevalent type is the HEPA filter, which removes 99.97% of particles down to 0.3 µm. These filters are vital in both residential air purifiers and large HVAC systems. Various studies have studied the effect of air filters in improving air quality. For instance, a randomized controlled trial assessed how effective free-standing air filters and window air conditioners (ACs) are in 126 low-income households with children who have asthma. Indoor air quality (IAQ) was tracked over week-long periods across three to four seasons. High levels of particulate matter (PM) and carbon dioxide were often observed [70] When monitoring IAQ, filters cut PM levels in the child's bedroom by about 50% on average. Another study by Du et al. in Detroit, Michigan [71]reported a reduction in PM by roughly 69 to 80%, indicating that although homes with asthmatic children often have high PM levels, these can be significantly lowered with the use of filters. Air filters have been shown to be able to eliminate air pollutants such as lead and particulate matter. For example, to evaluate how portable air filters affect particle exposure and endothelial function in healthy adults living in a community affected by woodsmoke, 45 participants underwent a randomized cross-over study with consecutive 7-day periods of filtered and unfiltered air [72]. In a recent study by Weichenthal et al. [73], the effectiveness of an electrostatic air filter was evaluated in 37 residents across 20 homes. The indoor PM2.5 levels significantly dropped when the air filter was used compared to a placebo (average difference: 37 µg/m3, 95% CI: 10 to 64). Typically, using the air filter was linked to a 7.9 mmHg reduction in systolic blood pressure (95% CI: -17 to 0.82) and a 4.5 mm Hg decrease in diastolic blood pressure (95% CI: -11 to 2.4).

4.6. Adsorption

Adsorption captures gases and VOCs on materials like activated carbon, which has a high surface area for trapping pollutants. Unlike filtration, it can be passive. Adsorbents are easily incorporated into building materials and/or integrated into interior surfaces to remove air pollutants with no additional energy input and minimal byproduct formation; for this reason, they are classified as passive removal materials (PRMs). Passive removal materials enable ozone control, for example, in susceptible populations with health benefits, creating healthy indoor environments [74]. Ao and Lee [75]examined the effect of TiO_2 immobilized on activated carbon under different humidity levels for the removal of air pollutants from indoor air at parts-per-billion (ppb) levels. In this research, NO (200 ppb), BTEX (20 ppb) and SO_2 (200 ppb) were used as target pollutants. Different resident times and relative humidity levels were tested to investigate their mutual effect on TiO_2 and TiO_2 immobilized on activated carbon. The results showed that the effect of TiO_2/AC is more significant with decreasing residence time and increasing levels of humidity.

4.7. UV-Photocatalytic Oxidation

UV-photocatalytic oxidation (PCO) uses UV light to activate photocatalysts such as titanium dioxide (TiO2), decomposing harmful pollutants into less harmful substances like water and carbon dioxide. Although promising, the process may produce harmful byproducts like formaldehyde during partial oxidation, necessitating further investigation and hybrid systems to guarantee safety and effectiveness [76,77]. Despite these issues, PCO remains a valuable component in advanced air purification technologies.

The ongoing development of physicochemical air purification technologies offers various solutions for tackling indoor air pollution. While filtration remains the most reliable method for particulate removal, adsorption, ionization, and UV-photocatalytic oxidation technologies provide valuable supplementary approaches, especially in controlling gases and microorganisms. The future of air purification lies in integrating these technologies into hybrid systems, ensuring both efficiency and safety in diverse indoor environments.

4.8. Future Directions

Looking ahead, achieving cleaner air and improved health depends on innovation, integration, and inclusiveness. Gaps in research remain, particularly regarding combined indoor and outdoor exposures, the long-term impacts of low-dose pollution, and vulnerable groups such as children, the elderly, and those with pre-existing conditions. Advances in affordable, widespread air sensors, including satellite and IoT devices, can generate detailed exposure maps, enabling communities and policymakers to identify hotspots. Interdisciplinary research is essential to convert exposure data into personalized risk alerts or timely interventions, where AI and machine learning in environmental health are especially beneficial [64].

Policy innovation is equally important. Many experts support aligning air quality policies with climate initiatives. As climate change progresses, new challenges emerge, such as increased wildfires and higher ozone levels during hot days. Future solutions should consider these interactions; for instance, urban heatwave plans can also address air pollution surges, and city greening can tackle both issues simultaneously. Investments in sustainable transportation, including electric buses, bike lanes, and pedestrian friendly cities, offer dual benefits for reducing air pollution and carbon emissions. Additionally, there is an increasing focus on One Health approaches, which view pollution as part of overall environmental health, linking air, water, and soil quality policies.

In the global development arena, funding mechanisms must catch up. There is not a lot of global health funding goes to air pollution, yet this risk factor rivals or exceeds better-funded problems. International aid and climate finance could be reoriented to support clean air in the most affected countries. This includes funding clean energy infrastructure, city planning, and health system integration (e.g. screening for pollution-related disease). Along with top-down programs, empowering communities through citizen science and local action plans will be important. For example, community-based programs that install cookstoves or launch urban gardens can complement national policies.

Equity must stay at the core of future efforts. We should ensure that the benefits of clean air are accessible to all levels of society. This involves creating policies that prioritize the most polluted neighborhoods first and offering subsidies or financing to help low-income families switch away from polluting fuels or vehicles. Including vulnerable populations in planning, such as thorough participatory urban design can improve both fairness and effectiveness. Additionally, ongoing monitoring of intervention outcomes is essential. Public health agencies should combine air quality data with health surveillance to conduct regular assessments of the impact on health. Systematically analyzing lessons learned from interventions will help improve strategies in real time. In summary, while the scientific and technological basis for addressing air pollution is solid, future progress relies on comprehensive approaches. By integrating health, environmental, economic, and social policies, the next decade can bring significant reductions in pollution levels and the associated chronic respiratory and cardiovascular diseases.

5. Conclusion

Air pollution remains one of the main preventable causes of chronic respiratory and cardiovascular diseases worldwide. Recent years have reinforced a positive message: well-designed interventions are effective. These range from legislative reforms that transform industries, to city-level transportation policies, household stoves, and filters — all contributing to cleaner air and healthier populations. Evidence from rigorous studies and real-world examples consistently demonstrates that reducing emissions quickly decreases instances of asthma attacks and heart attacks. Enhancing air quality is not only a healthy necessity but also an economic opportunity. Healthier populations are more productive and exert less pressure on healthcare systems; lower pollution levels are often associated with modern, high-tech economies. The challenge is to maintain and accelerate this progress: fully implementing and enforcing WHO standards, expanding access to clean fuels and technologies, and ensuring that vulnerable groups benefit. As countries update their policies based on scientific evidence, every decrease in pollutant levels is an investment in public health. The growing global agreement that air pollution is the top environmental health risk must lead to concrete actions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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