Ecotoxicology and Environmental Safety 280 (2024) 116532

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

Breathing in danger: Understanding the multifaceted impact of air pollution on health impacts

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ARTICLE INFO

Edited by Professor Bing Yan

Keywords:
Air quality monitoring
Environmental health
Pollution control strategies
Sustainable urban planning
Public health policy
Technological innovations in air purification

ABSTRACT

Air pollution, a pervasive environmental threat that spans urban and rural landscapes alike, poses significant risks to human health, exacerbating respiratory conditions, triggering cardiovascular problems, and contributing to a myriad of other health complications across diverse populations worldwide. This article delves into the multifarious impacts of air pollution, utilizing cutting-edge research methodologies and big data analytics to offer a comprehensive overview. It highlights the emergence of new pollutants, their sources, and characteristics, thereby broadening our understanding of contemporary air quality challenges. The detrimental health effects of air pollution are examined thoroughly, emphasizing both short-term and long-term impacts. Particularly vulnerable populations are identified, underscoring the need for targeted health risk assessments and interventions. The article presents an in-depth analysis of the global disease burden attributable to air pollution, offering a comparative perspective that illuminates the varying impacts across different regions. Furthermore, it addresses the economic ramifications of air pollution, quantifying health and economic losses, and discusses the implications for public policy and health care systems. Innovative air pollution intervention measures are explored, including case studies demonstrating their effectiveness. The paper also brings to light recent discoveries and insights in the field, setting the stage for future research directions. It calls for international cooperation in tackling air pollution and underscores the crucial role of public awareness and education in mitigating its impacts. This comprehensive exploration serves not only as a scientific discourse but also as a clarion call for action against the invisible but insidious threat of air pollution, making it a vital read for researchers, policymakers, and the general public.

1. Introduction

Air pollution, a critical environmental issue, has garnered global attention due to its profound impact on public health (Sicard et al., 2023). It is a complex mixture of various gases and particles that originate from both natural sources, such as wildfires and volcanic eruptions, and human activities like vehicle emissions, industrial processes, and the burning of fossil fuels (Al-Kindi et al., 2020). These pollutants not only degrade the quality of the air we breathe but also contribute to a range of health problems (Manisalidis et al., 2020). The health implications of air pollution are extensive, spanning respiratory illnesses, cardiovascular diseases, and even neurological disorders (Simkovich et al., 2019). Children, the elderly, and those with pre-existing health conditions are particularly vulnerable to these adverse effects (Naclerio et al., 2020). As urbanization and industrialization continue to escalate, the issue of air pollution becomes more pressing, making it a topic of paramount importance for researchers, policymakers, and the general public alike (Domingo and Rovira, 2020). Additionally, air pollution

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https://doi.org/10.1016/j.ecoenv.2024.116532
Received 8 December 2023; Received in revised form 25 April 2024; Accepted 29 May 2024
Available online 7 June 2024
0147-6513/

also significantly impacts climate change, influencing both weather patterns and global temperatures (Zhang et al., 2021). This interconnection between air quality and climate systems underscores the urgency of integrating air pollution control in broader environmental policies (Li et al., 2023b). Additionally, the economic costs associated with air pollution are staggering, encompassing healthcare expenditures for treating diseases caused by polluted air, as well as lost labor productivity due to illness (Farooqi et al., 2020). Addressing these issues requires innovative solutions that span policy adjustments, technological advancements in emission control, and increased public awareness (Xu et al., 2013). Engaging communities in air quality monitoring and management can empower individuals to contribute to cleaner air initiatives, thereby enhancing public health and environmental resilience (Bag et al., 2023).

The relevance of this topic extends beyond the immediate health effects. Air pollution has far-reaching consequences that impact societal well-being and economic stability (Urhie et al., 2020). Health care costs associated with treating diseases caused by air pollution place a significant burden on economies, especially in developing countries where air quality regulations may be less stringent (Pandey et al., 2021). Additionally, air pollution doesn't respect geographical boundaries; pollutants can travel long distances, affecting regions far from their sources (Liang et al., 2019). This global nature of air pollution necessitates a collaborative approach to research and policy-making. Understanding the intricate relationship between air pollution and health is essential for developing effective strategies to mitigate its impacts (Ravindra et al., 2019). This includes not only addressing the sources of pollution but also increasing public awareness and promoting lifestyle changes that can reduce individual exposure (Li et al., 2023a). Building on these points, the role of international cooperation becomes crucial in combating air pollution effectively (Kumar et al., 2023). Establishing shared environmental standards and exchanging best practices can help harmonize efforts across borders, creating a more robust response to a problem that affects all nations (Nazir, 2023). Furthermore, advancements in technology, such as satellite monitoring and machine learning for predicting pollution patterns, are enhancing our ability to track and tackle air quality issues more efficiently and with greater precision (Abolhasani et al., 2023). These tools not only aid in regulatory compliance but also facilitate proactive interventions that can pre-emptively reduce pollution levels globally (Laprise, 2023).

This review article aims to shed light on the multifaceted relationship between air pollution and health, with a focus on the latest research and innovative approaches to tackle this challenge. It seeks to go beyond the traditional discourse by exploring emerging pollutants whose health impacts are not yet fully understood. The novelty of this review lies in its comprehensive approach to the subject, integrating insights from various disciplines including environmental science, public health, and economics. It aims to provide a holistic understanding of the issue, encompassing not only the physical health effects but also the broader societal and economic implications. By examining new methods and technologies in air pollution research, the article aims to highlight the potential of big data and advanced analytics in enhancing our understanding of air pollution patterns and their health impacts. The ultimate objective is to inform and guide effective policy interventions, contribute to public health strategies, and foster international cooperation in the fight against air pollution. This article is not just a review of existing knowledge but a call to action, emphasizing the urgent need for a concerted global response to one of the most pressing environmental health challenges of our time.

2. New methods and technologies for air pollution research

The field of air pollution research has witnessed remarkable advancements in methodologies, largely propelled by technological innovation (Cain et al., 2023). These new methods have significantly enhanced our ability to monitor, analyze, and understand the complexities of air pollution (Duan et al., 2023). Satellite remote sensing technology, for instance, has revolutionized the monitoring of air quality on a global scale. It enables the tracking of pollutant dispersion over large areas, providing data that was previously inaccessible. This technology, coupled with ground-based monitoring stations, offers a more comprehensive view of air quality patterns and trends (Zhou et al., 2023). Additionally, the development of sophisticated sensors and air quality models has facilitated more accurate and real-time monitoring of air pollutants (Jońca et al., 2022). These sensors can detect and quantify a wide range of pollutants, from common contaminants like nitrogen dioxide and particulate matter to emerging pollutants that have only recently been identified (Louis et al., 2022). The integration of these advanced sensors into urban infrastructure and personal devices has also led to the development of extensive air quality monitoring networks, providing valuable data for research and public awareness (Li et al., 2022b).

The merits of the advanced air quality monitoring techniques mentioned are numerous. Firstly, the capability to track pollutant dispersion on a large scale enables researchers and policymakers to understand transboundary pollution issues and the effectiveness of air quality regulations (Jońca et al., 2022). Secondly, the integration of satellite and ground-based data allows for a robust and multi-dimensional analysis of air pollution trends (Li et al., 2022b). Sophisticated sensors facilitate the early detection of hazardous pollutants, which is crucial for timely public health interventions. Finally, real-time data availability from these sensors enhances public engagement and empowers individuals to make informed decisions about their daily activities to minimize exposure (Jońca et al., 2022). However, there are also demerits to consider. The high cost of advanced technology can be a barrier to implementation, especially in low-income regions. There can also be issues with data accuracy and calibration of sensors, leading to potential discrepancies in air quality assessments. The complexity of data management and analysis requires specialized expertise, which may not be readily available (Cain et al., 2023). Furthermore, there is a risk of data overload, where the sheer volume of information becomes challenging to interpret and use effectively for policy-making. Lastly, privacy concerns may arise with the widespread deployment of sensors, especially those integrated into personal devices (Louis et al., 2022).

Furthermore, the impact of technology on air quality assessment has been transformative. The advent of big data analytics and machine learning techniques has enabled researchers to analyze vast amounts of air quality data, leading to more nuanced and precise insights (Zhang et al., 2022a). These tools allow for the identification of pollution sources and trends, and the assessment of the effectiveness of air pollution control strategies (Gonzalez-Martin et al., 2021). Machine learning algorithms, in particular, have been used to predict air pollution levels, aiding in the formulation of timely public health advisories and policy decisions (Madan et al., 2020). Computational models have also become increasingly sophisticated, incorporating meteorological data and emission inventories to simulate air quality under various scenarios. This predictive capability is crucial for planning and implementing effective air quality management strategies (Zavala et al., 2020). Additionally, the use of citizen science and mobile applications in air quality research has democratized data collection, engaging the public in monitoring and raising awareness about air pollution (Rawat and Kumar, 2023). These technological advancements are not only enhancing our understanding of air pollution but are also playing a pivotal role in shaping policies and interventions aimed at improving air quality and protecting public health (Khreis et al., 2023). These innovations highlight the potential for a more integrated and comprehensive approach to managing air quality, where technology empowers both policymakers and the public. By leveraging these advanced tools, communities can more actively participate in the fight against air pollution, contributing to more sustainable and better urban environments. Fig. 1 outlines the advanced methodologies employed in air

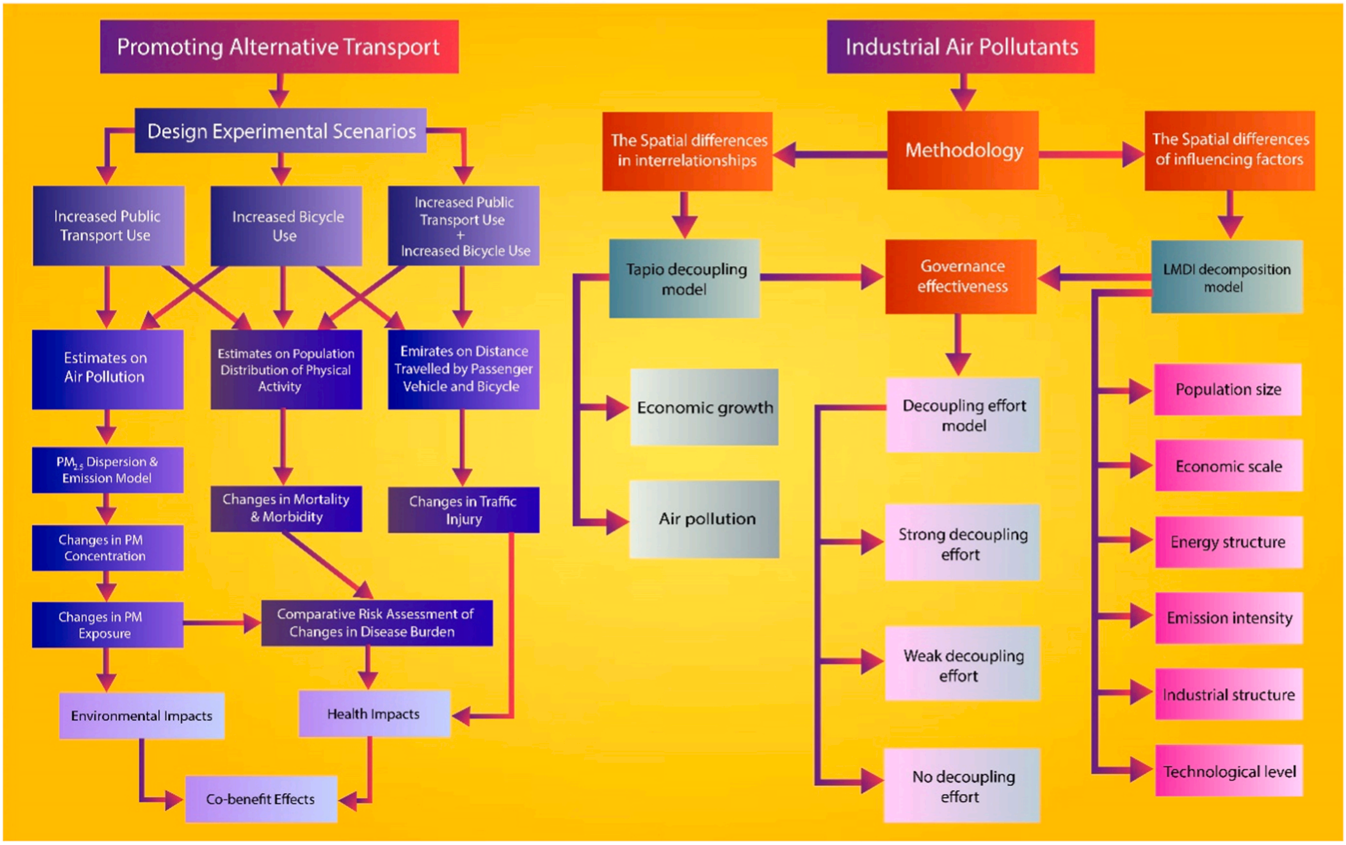

Fig. 1. Presents a conceptual framework outlining new methods and technologies for air pollution research, divided into two main branches: Promoting alternative transport and industrial air pollutants. On the left, "Promoting Alternative Transport" is detailed, starting with "Design Experimental Scenarios," which includes increasing the use of public transport and bicycles. These scenarios are evaluated to estimate their impact on air pollution, which is assessed through models of particulate matter dispersion and emissions. The changes in PM concentration and exposure lead to two principal outcomes: environmental impacts and health impacts. Environmental impacts are direct results of changes in particulate matter concentration, whereas health impacts are assessed through changes in mortality, morbidity, and a comparative risk assessment of changes in disease burden. The section concludes with the identification of "Co-benefit Effects," which likely refer to positive outcomes that affect both environmental and health sectors due to alternative transportation. On the right, "Industrial Air Pollutants" is explored, beginning with "Methodology," which references three analytical models: the Tapio decoupling model, the governance effectiveness model, and the LMDI decomposition model. These models study the relationship between economic growth and air pollution, assess governance effectiveness, and decompose the influencing factors of air pollution, respectively. Central to this branch is the "Decoupling effort model," which classifies the effort to decouple economic growth from air pollution into three categories: strong, weak, and no decoupling effort.

pollution research, including experimental designs and their implications for health and environmental policy.

3. Exploring the intersection of big data, air pollution, and human health

The role of big data in air pollution and health research has become increasingly pivotal, offering profound insights that were previously unattainable (Shahbaz et al., 2021). Big data encompasses vast datasets gathered from various sources such as satellite observations, air quality monitors, meteorological stations, and even social media platforms (Zhai and Cheng, 2020). This extensive collection of data, characterized by its volume, variety, and velocity, enables researchers to draw more comprehensive and accurate conclusions about the nature, causes, and effects of air pollution (Sadheesh et al., 2022). By analyzing trends and patterns within this data, scientists can better understand the distribution and concentration of air pollutants, their sources, and how they interact with environmental and meteorological factors (Kumar et al., 2022). This holistic view is crucial for assessing the impact of air pollution on human health, as it allows for the correlation of pollution levels with health outcomes in different populations and regions (Dominski et al., 2021). Several case studies exemplify the application of big data in air pollution research. One notable example is the use of satellite data combined with ground-based observations to map global exposure to fine particulate matter (PM2.5) (Sahu et al., 2021). This research has provided invaluable insights into the global distribution of this harmful pollutant, identifying regions with high exposure levels and aiding in the assessment of associated health risks (Ramon et al., 2023). Another case study involves the use of mobile sensor networks, where citizens contribute to air quality monitoring using portable devices (Park et al., 2023). This participatory approach has not only expanded the spatial coverage of air quality data but has also increased public engagement and awareness (Healy and Booth, 2023). Additionally, machine learning algorithms applied to large air quality datasets have been used to predict pollution levels, offering a powerful tool for urban planning and public health interventions (Méndez et al., 2023).

These applications underscore the transformative potential of big data in enhancing our understanding of air pollution and its health implications. By leveraging the power of big data, researchers and policymakers can devise more targeted and effective strategies to combat air pollution, ultimately leading to improved public health outcomes and a better quality of life (Gulan et al., 2023). Moreover, big data facilitates the personalization of health advisories, enabling individuals to take timely action to minimize exposure during high-pollution events. It also assists in identifying at-risk populations and areas with consistently poor air quality, directing resources and interventions where they are most needed (Dominski et al., 2021). The predictive power of big data analytics can foresee pollution trends and potential health crises, thereby aiding in preventative healthcare planning (Rawat and Kumar, 2023). With continuous advancements in data processing and analytics, the granularity of data available for research can significantly enhance the accuracy of air quality models (Al-Kindi et al., 2020). Ultimately, big data stands as a cornerstone in the development of smart cities, where real-time air quality monitoring integrates with urban infrastructure to create adaptive and responsive environments that promote public well-being (Domingo and Rovira, 2020). Fig. 2 illustrating the journey of air pollutants from emission to health effects, this figure emphasizes the transformation processes and the resultant health risks.

4. New pollutants in the air

In recent years, the identification and understanding of new pollutants in the air have become a crucial aspect of environmental research (Huang et al., 2023). These emerging contaminants, often a result of modern industrial and technological activities, add another layer of complexity to the already intricate issue of air pollution (Chen et al., 2023a). Unlike traditional pollutants like carbon monoxide or sulfur dioxide, whose sources and effects are well-known, these new pollutants often present unique challenges in terms of identification, measurement, and understanding their health impacts (Jung and El Samanoudy, 2023). One significant group of these new pollutants includes volatile organic compounds (VOCs), which are emitted from a variety of sources including industrial processes, vehicle emissions, and consumer products like paints and cleaning agents. VOCs are particularly concerning because they can react in the atmosphere to form ozone and fine particulate matter, both of which are harmful to human health (Bai et al., 2023). Another emerging concern is microscopic plastic particles, or microplastics, which are now being found in the air. These tiny particles, often originating from the breakdown of larger plastic debris, can be inhaled and potentially cause respiratory issues (Cao and Cai, 2023). Additionally, pharmaceuticals and personal care products are now being detected in the air, raising concerns about their long-term effects on health (Veiga et al., 2023).

The sources of these new pollutants are diverse and often interconnected with global economic and industrial activities (Xi and Zhai, 2023). For instance, the increasing use of synthetic chemicals in agriculture and industry leads to the release of novel compounds into the atmosphere (Chaudhary et al., 2023). Urbanization and the rise in vehicular traffic contribute to higher emissions of VOCs and other harmful compounds. The global proliferation of plastic materials has resulted in the release of microplastics into the environment, including the air we breathe (Wu et al., 2023). These pollutants interact with

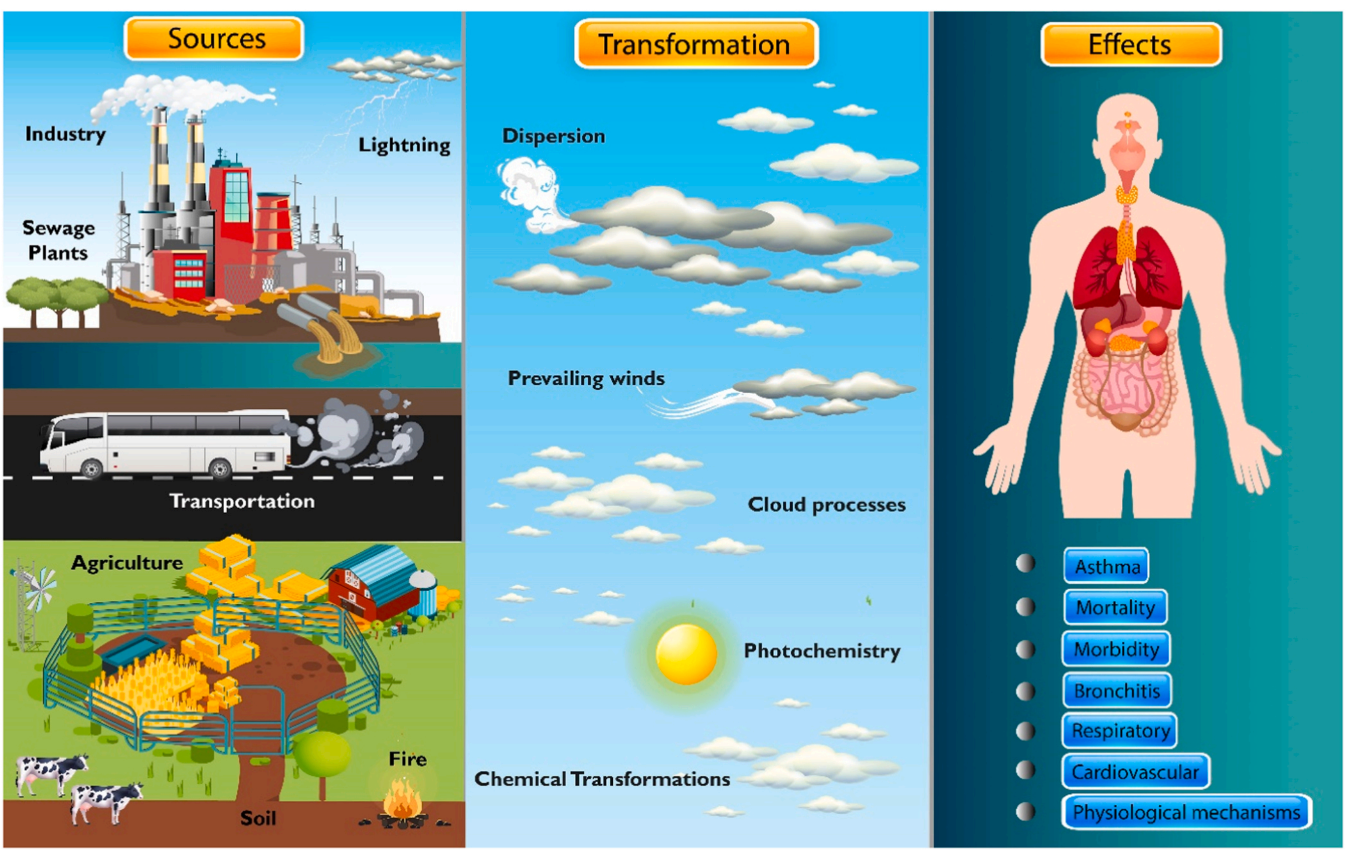

Fig. 2. Provides a visual representation of the journey of air pollutants from their sources through transformation processes in the atmosphere to their eventual health effects on humans. The leftmost section labeled "Sources" depicts common origins of air pollutants. It illustrates four sources: "Industry" with smokestacks emitting pollutants, "Sewage Plants" releasing gases, "Transportation" represented by a bus emitting exhaust fume, and "Agriculture" which includes crop burning, livestock, and treated soils releasing pollutants. Additionally, "Lightning" and "Fire" are natural sources that contribute to the release of pollutants into the atmosphere. The central section titled "Transformation" shows how pollutants undergo various processes once they are in the atmosphere. "Dispersion" demonstrates how pollutants spread out, influenced by "Prevailing winds" which can carry them over long distances. "Cloud processes" depict the interaction of pollutants with cloud formation and precipitation, while "Photochemistry" at the bottom indicates the chemical reactions that pollutants undergo in the presence of sunlight, leading to the creation of secondary pollutants like ozone. On the right, "Effects" illustrates the human health impacts of air pollution. A human figure with highlighted respiratory and cardiovascular systems indicates the organs most affected by poor air quality. Next to it, a list of health effects includes "Asthma," "Mortality," "Morbidity," "Bronchitis," "Respiratory" issues, and "Cardiovascular" problems, all of which are known to be exacerbated by air pollution. At the bottom of this list, "Physiological mechanisms" suggests that the diagram considers not just the diseases but also the underlying biological processes affected by air pollution.

natural atmospheric processes, leading to complex chemical reactions that may give rise to secondary pollutants, which can be more harmful than their precursors (Jung and El Samanoudy, 2023). Energy production and consumption, critical to economic development, also emit significant amounts of particulate matter and greenhouse gases, further exacerbating air pollution (Chaudhary et al., 2023). The transboundary nature of these pollutants necessitates international policy frameworks and collaborative efforts for effective regulation and mitigation (Huang et al., 2023). Additionally, the rapid pace of technological innovation, while providing potential solutions, can also introduce new types of pollutants, thus challenging researchers and policymakers to constantly adapt and respond to evolving air quality issues (Méndez et al., 2023).

The distribution of these pollutants is also a matter of concern. Unlike traditional air pollutants, which tend to be concentrated in urban and industrial areas, new pollutants can be found in a variety of environments. VOCs, for example, can be transported long distances by wind and weather patterns, affecting areas far from their source (Xu et al., 2023). Microplastics have been found in remote locations, indicating that they can be carried great distances through the atmosphere. This widespread distribution makes it challenging to monitor and control these pollutants and to assess their full impact on health and the environment (Khanjani et al., 2023). In summary, the identification and analysis of new pollutants in the air is a rapidly evolving field that is critical to our understanding of air quality and public health (Siddiqua et al., 2022). As industrial and technological activities continue to evolve, so too will the nature of the pollutants we emit into the atmosphere. It is essential that research in this area keeps pace with these changes, to ensure that we can effectively monitor, regulate, and mitigate the impacts of these new contaminants (Ji et al., 2022).

5. Health effects of air pollution

The health effects of air pollution are extensive and multifaceted, impacting individuals in both the short-term and long-term (Chen et al., 2022a). In the short-term, exposure to air pollutants can cause immediate health problems such as respiratory irritation, coughing, and shortness of breath. These symptoms are particularly noticeable during episodes of high pollution, such as smog events in urban areas (Aguilar-Gomez et al., 2022). Individuals with pre-existing respiratory conditions, like asthma, are especially susceptible to these acute effects. Moreover, short-term exposure to elevated levels of air pollutants has been linked to increased hospital admissions and emergency room visits for respiratory and cardiovascular problems. For instance, spikes in particulate matter and ozone levels are associated with higher rates of heart attacks and strokes. These acute effects underscore the immediate risks that air pollution poses to public health (Dzushupov et al., 2022).

In the long-term, the impacts of air pollution can be even more severe and life-altering. Prolonged exposure to polluted air has been linked to the development of chronic respiratory diseases, including asthma, chronic obstructive pulmonary disease (COPD), and lung cancer. The risk of cardiovascular diseases, such as hypertension and heart disease, also increases with long-term exposure to air pollutants (Jo, 2022). There's growing evidence that air pollution may have detrimental effects on the brain, contributing to the development of neurodegenerative diseases like Alzheimer's and Parkinson's. Moreover, recent studies suggest that long-term exposure to air pollution may affect mental health, leading to an increased risk of depression and anxiety (Hautekiet et al., 2022). Certain populations are particularly vulnerable to the health effects of air pollution. Children and the elderly are at higher risk due to their developing or weakened respiratory systems. Pregnant women exposed to polluted air may face a higher risk of complications, including preterm birth and low birth weight in newborns (Muttoo et al., 2022). People with pre-existing health conditions, such as asthma, heart disease, and diabetes, are more susceptible to the effects of air pollution. Additionally, socioeconomic factors play a crucial role in vulnerability (So et al., 2022). Individuals in low-income communities often face higher levels of exposure due to proximity to pollution sources such as factories and heavy traffic, and they may have less access to healthcare and resources to mitigate exposure. This disparity highlights the need for targeted interventions and policies to protect the most vulnerable groups from the harmful effects of air pollution (Castellani et al., 2022). The pervasive nature of air pollution underscores the importance of environmental justice, as the burden of poor air quality disproportionately affects marginalized communities. Implementing clean air policies not only serves public health but also advances social equity by ensuring all populations can breathe safer, cleaner air (Hautekiet et al., 2022). Furthermore, the economic burden that arises from the healthcare costs associated with treating long-term effects of air pollution calls for urgent action to prevent these diseases at the source. Global initiatives aimed at reducing emissions from industries and investing in cleaner, renewable energy sources are critical steps toward mitigating the impact of air pollution and safeguarding future generations (Aguilar-Gomez et al., 2022).

In conclusion, the health effects of air pollution are far-reaching and impact individuals and communities in both the short and long term. Understanding these effects is crucial for public health planning and policy-making, particularly in protecting vulnerable populations. Continued research and public health efforts are essential to mitigate the health risks associated with air pollution and to ensure a healthier future for all. To this end, investment in pollution monitoring and control technologies is vital for providing accurate data that can inform policy decisions. Public awareness campaigns and education can also play a significant role in reducing personal exposure and prompting community action against local sources of pollution. Internationally, there is a pressing need for stricter global emissions standards and collaborative efforts to address the transboundary nature of air pollution. Ultimately, a commitment to sustainable development that prioritizes clean air will be a decisive factor in improving public health outcomes and achieving environmental resilience.

6. Air pollution health risk assessment

6.1. Methodologies and approaches

The assessment of health risks due to air pollution is a critical aspect of environmental health science, requiring a multidisciplinary approach to accurately measure and interpret the impacts (Yan et al., 2022). Various methodologies are employed to evaluate the risk, each offering unique insights and presenting different challenges (Zhang et al., 2022c). One common approach is the use of epidemiological studies, which investigate the correlations between exposure to air pollutants and health outcomes in populations (Monoson et al., 2023). These studies often utilize large datasets, including air quality measurements and health records, to identify trends and associations (Sidell et al., 2022). Another methodology is exposure assessment, which seeks to estimate the amount of pollutants individuals are exposed to over time (Arregocés et al., 2023b). This can involve direct monitoring of air quality in different environments or the use of models to estimate exposure based on pollutant concentrations and population activities (Cheng et al., 2022).

Toxicological studies are also vital in understanding the health risks of air pollution. These studies, often conducted in laboratories using animal models or cell cultures, help determine the mechanisms by which pollutants cause harm to the body (Asha et al., 2022). This research is essential for identifying which pollutants pose the greatest risk and understanding how they interact with the body to cause disease (Wang et al., 2022). Risk characterization, another key aspect of health risk assessment, combines information from exposure and toxicological studies to estimate the likelihood and severity of health outcomes due to pollution exposure. This process often involves the use of mathematical models to integrate data and provide risk estimates (Zhu et al., 2022). Incorporating epidemiological data into these models enhances their real-world applicability, allowing for more precise public health recommendations and regulatory standards (Wang et al., 2022). Advances in biomonitoring and bioinformatics further refine risk assessments by providing individual exposure profiles and identifying genetic factors that may influence susceptibility to air pollution. Public health interventions and policy initiatives can be better tailored with this detailed understanding of risk factors, ensuring more effective protection for at-risk groups (Zhang et al., 2022c). Additionally, continuous monitoring and updating of risk characterizations are necessary as new pollutants emerge and as our understanding of their impacts evolves (Yan et al., 2022).

6.2. Case studies

Several case studies highlight the application and importance of these methodologies in assessing health risks from air pollution. One notable example is the assessment of particulate matter (PM) pollution in major cities worldwide (Li et al., 2022a). Epidemiological studies in these areas have consistently shown associations between PM exposure and increased rates of respiratory and cardiovascular diseases (Adinarayanappa and District, 2022). Exposure assessments in these studies often involve both fixed-site air monitoring stations and personal monitoring devices, providing a detailed picture of the pollution levels that individuals are exposed to in their daily lives (Narayana et al., 2022). These case studies also underscore the importance of spatial analysis in understanding air pollution exposure, revealing how geographical factors can influence the distribution of pollutants and health outcomes (Li et al., 2022a). The implementation of geographic information systems (GIS) and other spatial data tools has been instrumental in pinpointing pollution hotspots and identifying communities that are most at risk (Wang et al., 2022). Furthermore, the integration of time-activity patterns into exposure assessment helps clarify the nuances of when and where individuals are most vulnerable to the effects of air pollution. The data derived from these comprehensive assessments are crucial for developing targeted intervention strategies, such as urban planning initiatives that reduce pollution exposure in high-risk areas (Zhu et al., 2022).

Another case study involves the assessment of health risks from traffic-related air pollution in urban areas. This research often employs a combination of exposure modeling, using traffic and meteorological data, and epidemiological analysis of health outcomes in populations living near major roadways (Cheng et al., 2022). These studies have been instrumental in demonstrating the health risks associated with living in close proximity to heavy traffic, leading to policy changes aimed at reducing exposure in these areas (Bai et al., 2022). This field of research has also catalyzed the development of green infrastructure in urban planning, such as the creation of buffer zones with trees and vegetation between roadways and residential areas to absorb pollutants.

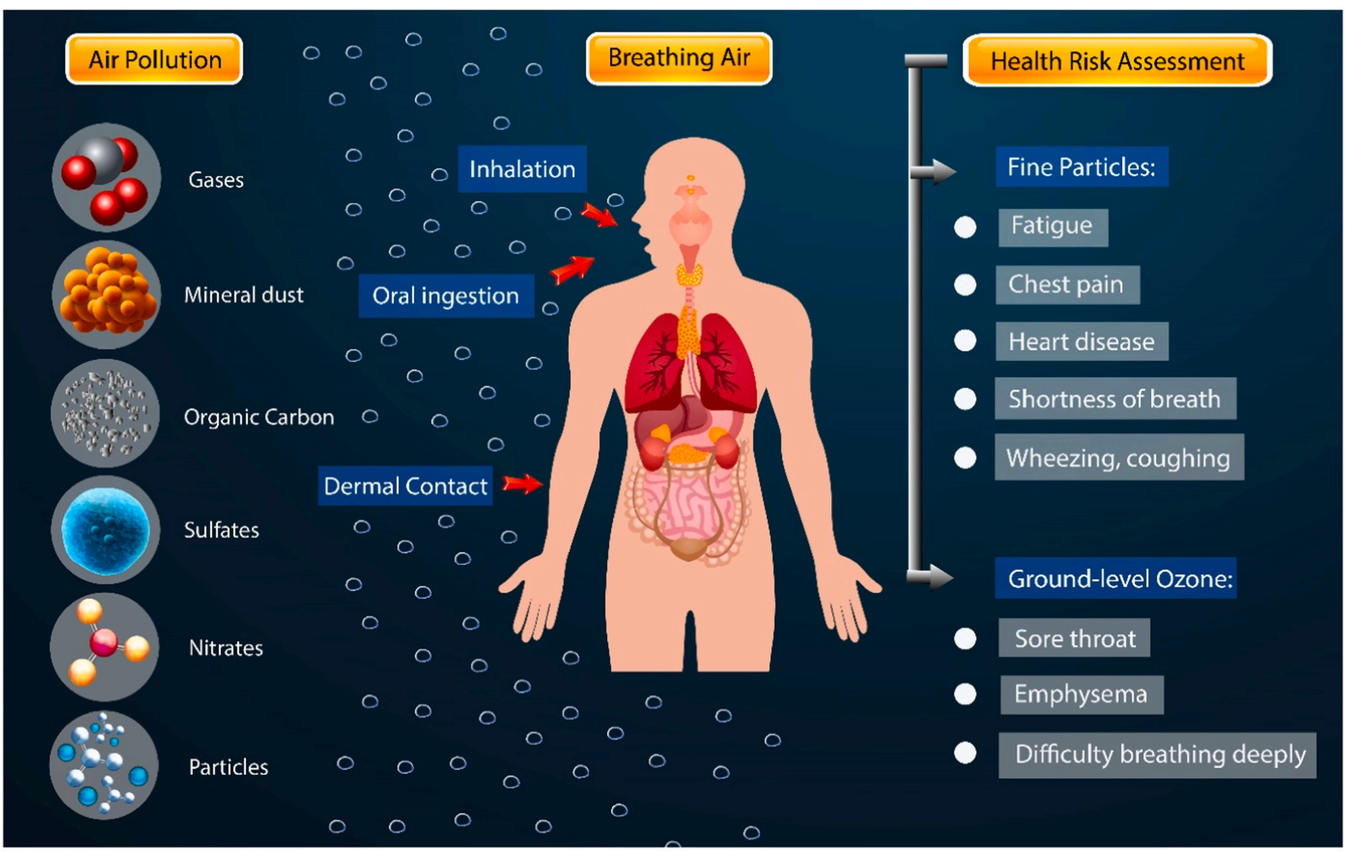

Fig. 3. Illustrates a health risk assessment model that connects various forms of air pollution to their modes of human exposure and subsequent health risks. The left section of the diagram, labeled "Air Pollution," displays a variety of common air pollutants, including gases, mineral dust, organic carbon, sulfates, nitrates, and other particulate matter. Each pollutant is represented by a colorful molecular structure or particle cluster, visually differentiating the types of contaminants found in the air. In the center, the "Breathing Air" portion shows a human figure, with arrows pointing from the air pollution molecules to the respiratory and digestive systems, indicating the routes of exposure. There are three main pathways identified: inhalation, oral ingestion, and dermal contact. This suggests that air pollution affects not only the lungs but can also enter the body through the skin and through ingestion of contaminated food or water. On the right side, the "Health Risk Assessment" section connects specific pollutants to their potential health impacts. For fine particles, the listed effects include fatigue, chest pain, heart disease, shortness of breath, and wheezing or coughing. Below that, ground-level ozone is linked to health issues such as a sore throat, emphysema, and difficulty breathing deeply. This figure succinctly conveys the critical pathways through which air pollutants cause harm to humans and underscores the importance of understanding and managing air quality to prevent these health outcomes.

Public transportation policies have been re-evaluated to promote low-emission vehicles and reduce overall traffic congestion (Li et al., 2022b). There is also an increasing focus on the development of pedestrian- and cyclist-friendly zones, which can contribute to reduced vehicle emissions and improved population health. The lessons learned from these case studies are shaping a global discourse on the necessity of integrating health considerations into urban design and transportation policy to create healthier living environments (Sadheesh et al., 2022). In summary, health risk assessment for air pollution is a complex field that requires a variety of methodologies and approaches to accurately quantify and understand the risks. These assessments are crucial for informing public health policies and interventions to reduce the health impacts of air pollution. The case studies discussed highlight the practical application of these methodologies and their importance in protecting public health (Bodor et al., 2022). Fig. 3 demonstrates the different routes of human exposure to air pollution and the associated health risks, highlighting the need for effective risk assessments.

7. Disease burden due to air pollution

The disease burden due to air pollution is a significant global health concern, with impacts that vary greatly across different regions (Xu et al., 2022a). From a global perspective, air pollution is one of the leading risk factors for premature death and disability (Ritchie and Roser, 2023). It contributes to a range of diseases, including respiratory infections, chronic obstructive pulmonary disease (COPD), lung cancer, heart disease, and stroke (Aghapour et al., 2022). According to the World Health Organization (WHO), millions of premature deaths each year can be attributed to outdoor and indoor air pollution, making it a critical public health issue worldwide (Zikirillo and Ataboyev, 2023). The impact of air pollution extends into economic domains, with increased healthcare costs and lost productivity due to illness placing a heavy financial burden on societies. Addressing this issue is not just a health imperative but also an economic one, as improving air quality can lead to significant savings and better quality of life (Xu et al., 2022a). Efforts to reduce air pollution also align with climate change mitigation, as many air pollutants contribute to global warming. Therefore, policies aimed at reducing emissions have the dual benefit of improving public health and slowing climate change, highlighting the interconnectedness of environmental and health governance (Bai et al., 2022).

Regionally, the burden of disease due to air pollution exhibits considerable variation, influenced by factors such as industrialization, urbanization, environmental policies, and socioeconomic status (Fuller et al., 2022). In many developing countries, particularly in parts of Asia and Africa, high levels of air pollution are often the result of rapid industrialization, urban sprawl, and reliance on biomass fuels for cooking and heating. These regions tend to have higher rates of respiratory and cardiovascular diseases linked to pollution (Maung et al., 2022). In contrast, more developed regions like Europe and North America, while still facing challenges, generally have lower levels of air pollution due to stricter environmental regulations and advanced technology for emissions control. However, even in these regions, there are disparities at the local level, often influenced by economic and social factors (Zhang et al., 2022b). A comparative analysis between regions reveals these disparities. For example, in South Asia, air pollution is a major health risk, largely due to the widespread use of solid fuels for domestic purposes and high levels of vehicular emissions (Krishna et al., 2017). In contrast, in many Western European countries, efforts to reduce emissions from transport and industry have led to improvements in air quality and associated health outcomes. However, even within these regions, there are areas where air pollution levels remain high, often in economically disadvantaged or industrialized areas (Oyebanji and Kirikkaleli, 2023).

These regional differences in the disease burden due to air pollution highlight the need for tailored approaches to tackle this global health issue. Policies and interventions need to be context-specific, addressing the unique sources and impacts of air pollution in each region (Alahmad et al., 2023). This requires not only a commitment to reducing emissions and exposure but also a focus on equity, ensuring that all populations, regardless of economic status or geography, have access to clean air (Alam et al., 2023). The assignation of local communities in air quality monitoring and intervention strategies can enhance the effectiveness and acceptance of policies. Educational programs that raise awareness about the sources of air pollution and its health effects are also essential in driving behavioral changes that support cleaner air initiatives (Maung et al., 2022). Furthermore, international cooperation and support are crucial, particularly in assisting lower-income countries to develop and implement air quality standards. Investments in renewable energy sources and sustainable urban planning are long-term strategies that can help reduce the reliance on polluting fuels and decrease air pollution globally (Krishna et al., 2017). Fig. 4 visually details the extensive effects of air pollution on various organs within the human body, underlining the pervasive impact on overall health.

8. Health and economic losses from air pollution

8.1. Quantifying the impact

The health and economic losses from air pollution are profound and multifaceted, affecting individuals, communities, and nations at large (Pandey et al., 2021). Quantifying these impacts is essential for understanding the full scope of the problem and for developing effective policies to address it (Zhang et al., 2022e). Health losses are typically measured in terms of morbidity and mortality (Sun et al., 1922). Air pollution is a leading risk factor for a number of chronic diseases, including respiratory infections, COPD, lung cancer, and cardiovascular diseases (Beulens et al., 2022). The Global Burden of Disease Study has consistently highlighted air pollution as a major global health risk, attributing millions of premature deaths to it annually. In addition to mortality, air pollution contributes significantly to illness and disability, reducing the quality of life for countless individuals (Burkart et al., 2022). The economic losses are equally staggering, encompassing healthcare costs for treating diseases caused by air pollution and indirect costs from lost productivity due to illness. This not only strains healthcare systems but also impedes economic growth as a significant portion of the workforce is affected (Zhang et al., 2022e). Furthermore, there are costs associated with environmental damage, including impacts on agriculture and ecosystems, which can further exacerbate food security and biodiversity issues. To combat these issues, it is crucial to invest in renewable energy sources, enforce stricter emissions standards, and promote public transportation, which can collectively reduce pollution levels and mitigate its harmful effects (Sun et al., 1922).

Economic losses due to air pollution are equally substantial, though they can be more challenging to quantify. These losses manifest in several ways, including direct costs such as healthcare expenditures for treating diseases caused by air pollution, and indirect costs like lost productivity due to illness and premature death (Xu et al., 2022c). Additionally, air pollution can lead to broader economic impacts, such as reduced agricultural yields due to pollution damage to crops and the degradation of natural ecosystems, which can have long-term economic consequences (Ramzan et al., 2022). Quantifying these impacts requires comprehensive economic analysis that considers both direct and indirect costs, as well as the less tangible impacts on well-being and quality of life. Incorporating the valuation of ecosystem services into economic analyses can reveal the hidden costs of air pollution on natural capital, emphasizing the need for sustainable practices. Investments in clean air technologies and green infrastructure present opportunities for economic growth and job creation, offsetting some of the losses due to air pollution (Pandey et al., 2021). Moreover, the implementation of green policies can improve public health, resulting in a healthier workforce and reduced spending on medical care. Ultimately, the transition to a low-pollution economy can provide a pathway to both environmental

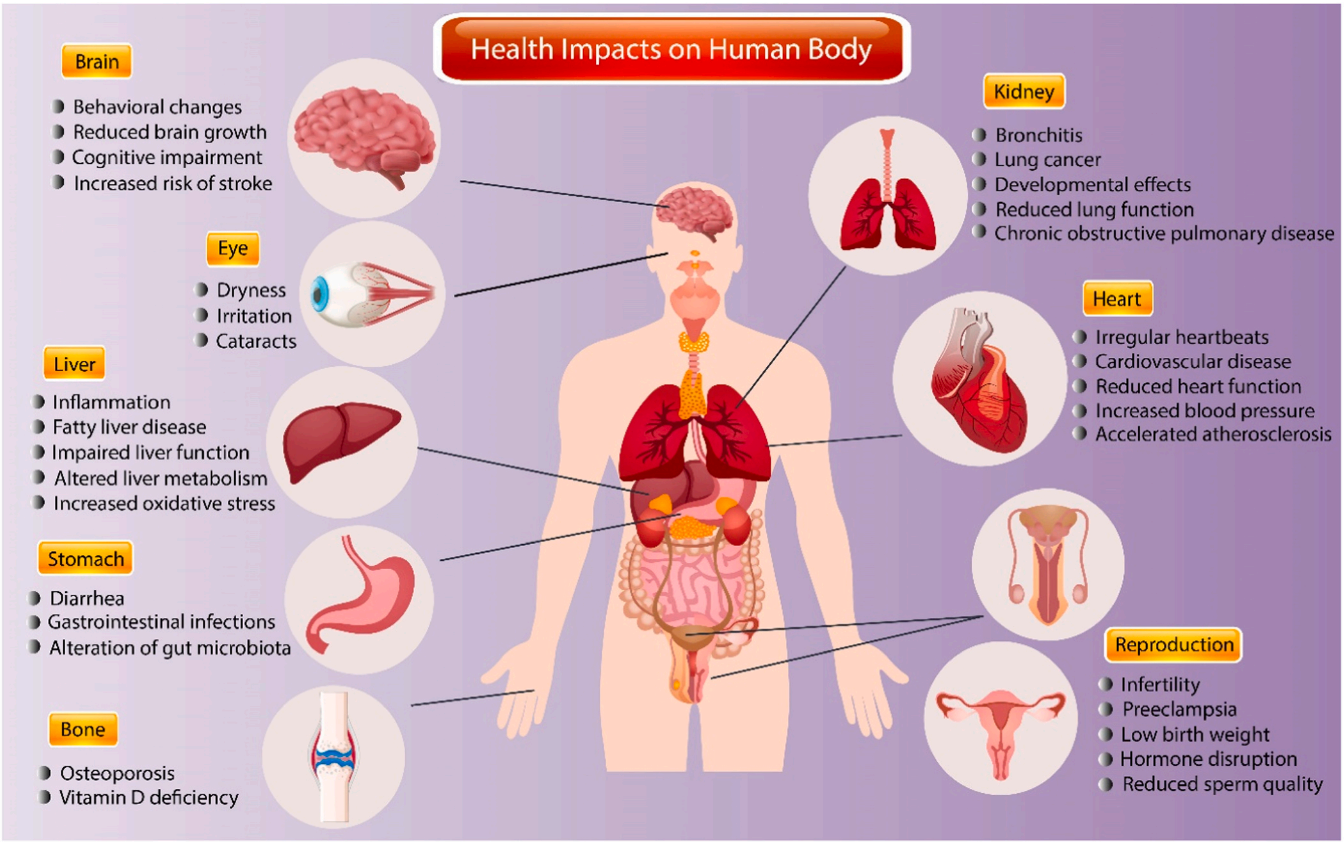

Fig. 4. Depicts the various health impacts of air pollution on the human body, detailing specific ailments associated with different organs. The brain is shown to be affected by behavioral changes, reduced growth, cognitive impairment, and an increased risk of stroke. The eye can suffer from dryness, irritation, and cataracts. The liver's afflictions due to pollution include inflammation, fatty liver disease, impaired function, altered metabolism, and increased oxidative stress. For the stomach, air pollution is linked to diarrhea, gastrointestinal infections, and alterations in gut microbiota. The bone is susceptible to osteoporosis and vitamin D deficiency as a result of air pollution. In the respiratory system, the kidney (though possibly an error in the image, as the kidneys are part of the excretory system, not respiratory) is associated with diseases such as bronchitis, lung cancer, developmental effects, reduced lung function, and chronic obstructive pulmonary disease (COPD). The heart may experience irregular heartbeats, cardiovascular disease, reduced function, increased blood pressure, and accelerated atherosclerosis. Lastly, the reproductive system is not spared; it faces challenges such as infertility, preeclampsia, low birth weight, hormone disruption, and reduced sperm quality. The figure serves as a comprehensive overview of the extensive nature of air pollution's impact on health, highlighting the need for urgent action in air quality management and health prevention measures.

and economic resilience, supporting long-term sustainable development goals (Xu et al., 2022c).

8.2. Policy implications

The quantification of health and economic losses from air pollution has significant implications for policy. First and foremost, it provides a strong rationale for investing in air quality improvements (Xu et al., 2022c). When the health and economic benefits of cleaner air are made clear, the costs of implementing pollution control measures can be seen in the context of the substantial savings they can bring in terms of reduced healthcare costs and increased productivity (Shang et al., 2022). This economic argument can be a powerful tool in advocating for stricter air quality regulations and more sustainable urban and industrial practices (Zhang et al., 2022d).

Policymaking in this realm must also consider equity and justice, as the impacts of air pollution are not distributed evenly across populations (Liu et al., 2022c). Vulnerable groups, such as low-income communities, children, and the elderly, are often disproportionately affected by air pollution, and policies need to address these disparities (Bank., 2022). This might involve targeted interventions in the most affected areas, such as improving public transportation to reduce vehicle emissions in low-income urban neighborhoods, or providing subsidies for cleaner cooking fuels in rural areas (Xu et al., 2022b). Moreover, the transboundary nature of air pollution requires international cooperation in policy formulation (Amini et al., 2020). Pollutants can travel long distances, meaning that effective air quality management often requires coordination across regional and national borders (Leroutier and Quirion, 2022). International agreements and collaborations, such as the United Nations Framework Convention on Climate Change, can play a crucial role in addressing the global challenge of air pollution (Cifuentes-Faura, 2022). In conclusion, the health and economic losses from air pollution are substantial, necessitating urgent action from policymakers. The development of effective policies should be informed by comprehensive assessments of these impacts, taking into account the needs of the most vulnerable populations and the necessity for international cooperation (Ren et al., 2023). By addressing the issue of air pollution, not only can we improve public health and reduce economic losses, but we can also move towards a more sustainable and equitable future (Meisner et al., 2023).

9. Research on air pollution intervention measures

9.1. Strategies and effectiveness

Research on intervention measures for air pollution is pivotal in combating its detrimental effects on health and the environment (Rawat and Kumar, 2023). Various strategies have been proposed and implemented globally, ranging from regulatory policies to technological innovations and public awareness initiatives. Regulatory interventions are among the most direct and effective strategies (Mahardhani, 2023). These include setting stringent emission standards for industries and vehicles, enforcing air quality standards, and promoting cleaner energy sources (Khan et al., 2022). Such regulations, when effectively enforced, have proven to reduce pollutant levels significantly. For instance, emission standards for vehicles, such as the Euro standards in Europe, have led to a notable decrease in nitrogen oxides and particulate matter emissions (Schripp et al., 2022).

Technological interventions also play a crucial role. Advancements in fuel and engine technologies have led to cleaner transportation options (Khan and Lawrence, 2022). The adoption of renewable energy sources, such as wind and solar, and the transition from coal to natural gas in power generation have significantly reduced emissions of key pollutants (Kartal et al., 2023). Moreover, the implementation of air purification technologies in industrial processes and urban settings has helped in mitigating pollution levels (Mata et al., 2022). Public awareness and behavioral change campaigns are equally important. Educating the public about the sources and impacts of air pollution, and promoting behavior that reduces personal exposure and emissions, can have a substantial collective impact (McCarron et al., 2023). Encouraging the use of public transportation, carpooling, and energy-efficient appliances are examples of such behavior changes (Paramati et al., 2022). The proliferation of smart technologies, like IoT devices for monitoring air quality, provides individuals and communities with real-time data, empowering them to make informed decisions about their daily activities. Green urban planning, which integrates vegetation and open spaces into city designs, can improve air quality by acting as natural filters for pollutants (Kartal et al., 2023). Governments and organizations are also leveraging these technologies to track pollution sources and deploy resources more effectively for air quality improvements (Khan et al., 2022). Furthermore, policies that incentivize the adoption of electric vehicles and retrofitting buildings with energy-efficient systems not only reduce emissions but also set a precedent for responsible environmental stewardship at a community level (Khan and Lawrence, 2022).

9.2. Case studies

Numerous case studies highlight the effectiveness of these intervention strategies. One notable example is the implementation of the Low Emission Zone (LEZ) in London. This policy restricts access to the city center for high-emitting vehicles, encouraging the use of cleaner transportation options. The LEZ has led to a significant reduction in emissions of particulate matter and nitrogen oxides in the city (Hajmohammadi and Heydecker, 2022). Another case study is the transformation of energy infrastructure in Denmark. Denmark has invested heavily in wind energy, significantly reducing its reliance on fossil fuels for power generation (Kirikkaleli et al., 2023). This shift has not only contributed to a decrease in greenhouse gas emissions but also in air pollutants like sulfur dioxide and particulate matter (Chen et al., 2023b).

In Beijing, a city once notorious for its air pollution, a combination of regulatory and technological interventions has been employed to improve air quality (Liu et al., 2022a). These include the closure of polluting factories, the upgrading of vehicle emission standards, and the expansion of green spaces. These efforts have led to a noticeable improvement in air quality in recent years (Marks and Miller, 2022). Additionally, Beijing has invested heavily in public transportation infrastructure, including the metro and electric bus fleets, to reduce reliance on personal vehicles. Public campaigns to raise awareness about air pollution and encourage the use of masks on high-pollution days have also contributed to protecting public health (Wang and Wang, 2022). The city's air quality monitoring network has been expanded, providing residents with timely information on pollution levels and health advisories. As a result of these comprehensive measures, Beijing is transforming into a model city for air quality improvement, demonstrating the effectiveness of concerted action in tackling environmental challenges (Abhijith et al., 2022). In summary, research on air pollution intervention measures reveals a diverse array of strategies that can be effective in different contexts. The success of these interventions depends on a combination of regulatory enforcement, technological advancement, and public participation. The case studies discussed demonstrate the potential for significant improvements in air quality and public health, underscoring the importance of continued commitment and innovation in the fight against air pollution. Fig. 5 depicting the benefits of green infrastructure, this figure shows how urban planning can mitigate air pollution and improve public health.

10. New findings and insights

10.1. Recent discoveries in the field

The field of air pollution research is continuously evolving, with recent discoveries shedding new light on the sources, impacts, and mitigation strategies of air pollution (Arregocés et al., 2023a). One significant advancement is in the understanding of secondary pollutants like ground-level ozone and fine particulate matter. Researchers have found that these pollutants, formed through complex chemical reactions in the atmosphere, can have a more significant impact on health and the environment than primary pollutants. This has led to a reevaluation of air quality management strategies to address these secondary pollutants more effectively (Kalashnikov et al., 2022). Furthermore, the use of advanced satellite imaging and air quality sensors has improved the precision of detecting and monitoring these secondary pollutants over broad geographic areas. This enhanced detection capability allows for more timely and localized responses to air quality issues, potentially reducing exposure risks (Wang and Wang, 2022). Research into the socioeconomic factors influencing exposure to air pollution has also gained traction, emphasizing the need for policies that address disparities in air quality. Lastly, there is a growing emphasis on the role of climate change in exacerbating air pollution, leading to a push for integrated strategies that tackle both environmental challenges concurrently (Abhijith et al., 2022).

Another critical area of discovery is the identification and characterization of new types of air pollutants. For instance, researchers have recently identified microplastics in the atmosphere, which can travel long distances and pose health risks when inhaled. Additionally, the role of airborne nanoparticles, which can penetrate deep into the lungs and even enter the bloodstream, is becoming clearer. These findings have significant implications for public health, particularly regarding the development of standards and regulations for these emerging contaminants (Aghapour et al., 2022). Advancements in sensor technology and data analysis are also leading to new insights in air pollution research. The use of low-cost sensors and citizen science initiatives has increased the spatial and temporal resolution of air pollution data, providing a more detailed understanding of pollution patterns and hotspots (Rhouati et al., 2022). Big data analytics and machine learning are being used to analyze these large datasets, leading to more accurate predictions of air pollution levels and more effective intervention strategies (Liu et al., 2022b).

10.2. Implications for future research

The recent discoveries in air pollution research have significant implications for future studies. One of the key areas for future research is the health impacts of emerging pollutants like microplastics and nanoparticles. There is a need for more comprehensive studies to understand the exposure pathways, dose-response relationships, and long-term health effects of these contaminants. This research is crucial for developing effective regulatory standards and public health guidelines (Bala et al., 2022). In addition to health impacts, future research must also

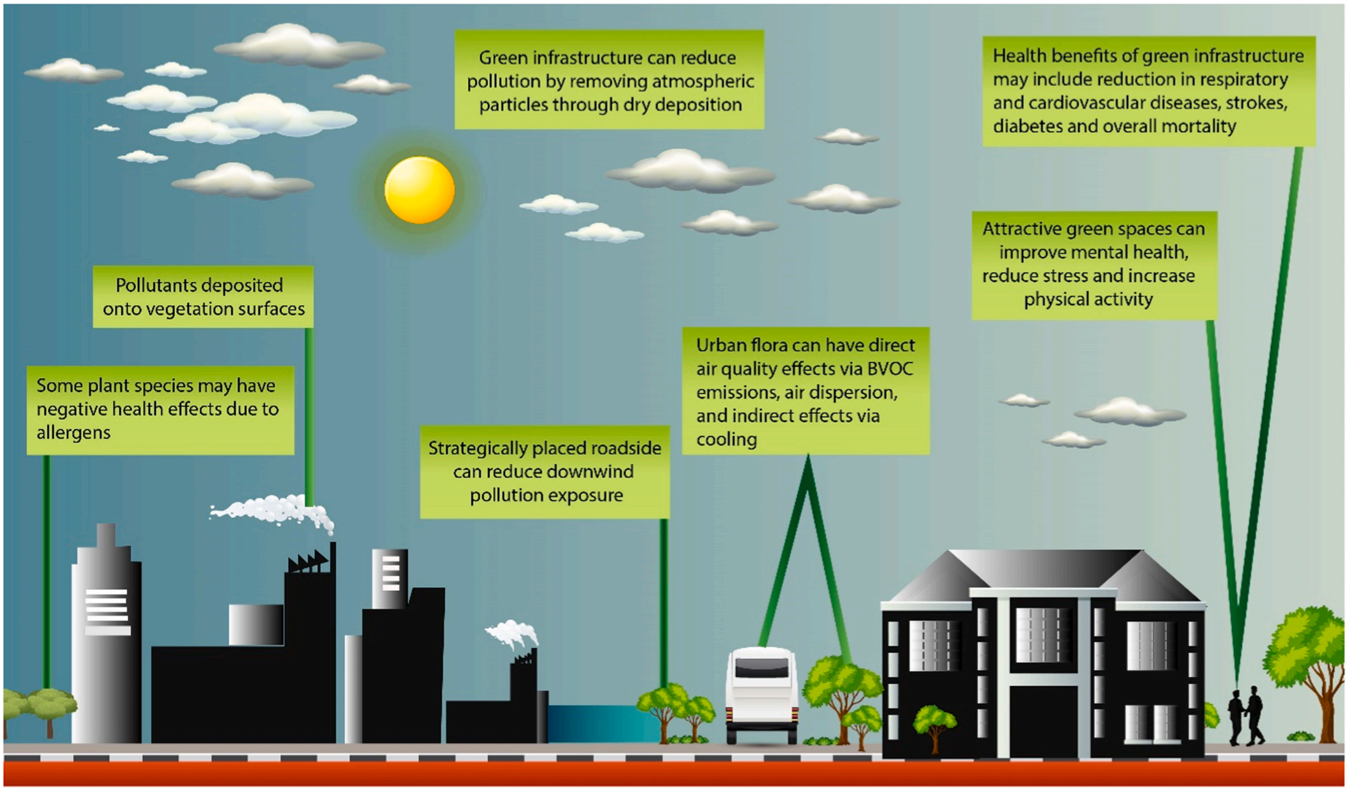

Fig. 5. Visualizes the role of green infrastructure in urban environments as a mitigative measure against air pollution and its related health impacts. On the left side of the illustration, pollutants are shown being deposited onto vegetation surfaces, indicating the role of plants in capturing airborne particles. A caution is noted that some plant species may have negative health effects due to allergens, which suggests a need for careful selection of plant types for urban greening. The center of the figure emphasizes the strategic placement of roadside greenery to reduce downwind pollution exposure for pedestrians and residents, illustrating how urban planning can incorporate natural elements to shield public spaces from vehicular emissions. To the right, the figure outlines the health benefits of such green infrastructure. It mentions reductions in respiratory and cardiovascular diseases, strokes, diabetes, and overall mortality rates, linking green spaces to substantial public health improvements. Additionally, it is noted that attractive green spaces can enhance mental health, reduce stress, and increase physical activity among urban dwellers. The figure also highlights the direct air quality effects that urban flora can have through the emission of biogenic volatile organic compounds (BVOCs), aiding in air dispersion and providing cooling effects, which indirectly affect air quality. Overall, the figure encapsulates the multi-dimensional benefits of green infrastructure in urban air quality management, from reducing pollutant levels to enhancing the physical and mental well-being of the population.

consider the environmental consequences of these emerging pollutants, such as their persistence in ecosystems and potential to disrupt biological processes. Interdisciplinary approaches combining toxicology, environmental science, and public health are essential to address these complex issues (Wang and Wang, 2022). With the advent of big data and machine learning, there are opportunities to analyze large datasets to identify trends and correlations that were previously unattainable. Moreover, public engagement and citizen science initiatives can play a pivotal role in monitoring air quality, thus democratizing the process and raising awareness on a global scale (Liang et al., 2023).

Another important area for future research is the interaction between air pollution and climate change. As the climate continues to change, it is expected to impact air quality through changes in weather patterns, temperature, and precipitation. Understanding these interactions is vital for developing integrated strategies to address both air pollution and climate change (Perera and Nadeau, 2022). Moreover, there is a growing need for research on effective intervention strategies, particularly in urban areas where air pollution is a significant concern. This includes not only technological solutions like cleaner transportation and energy sources but also policy and planning interventions like urban green spaces and sustainable urban design (Song et al., 2022). In summary, recent discoveries in air pollution research are providing new insights into the sources, impacts, and mitigation of air pollution. These findings are shaping the future direction of research in the field, with a focus on understanding emerging pollutants, the interaction between air pollution and climate change, and effective intervention strategies. This research is crucial for informing policy and public health interventions, and for ensuring a cleaner, healthier environment for future generations. Fig. 6 The world map provides a comparative visualization of the impact of various health risks, including air pollution, on life expectancy across the globe.

11. Air pollution and health: a global perspective

11.1. Differences in impacts and responses worldwide

Air pollution and its health effects present a complex global challenge, with varying impacts and responses observed across different regions of the world. The disparities are primarily influenced by factors such as the level of industrialization, urbanization, environmental policies, and socio-economic conditions (Lynch, 2022). In developing countries, particularly in parts of Asia and Africa, the health impacts of air pollution are often more severe due to higher levels of pollutants from industrial emissions, vehicular traffic, and the widespread use of biomass for cooking and heating. These regions typically experience a higher incidence of respiratory and cardiovascular diseases linked to air pollution (Isaifan, 2023). In contrast, many developed countries, such as those in Western Europe and North America, have witnessed significant improvements in air quality over the past decades due to stringent environmental regulations and advanced pollution control technologies. However, despite these improvements, air pollution remains a concern in many urban areas, and disparities exist within countries, often linked

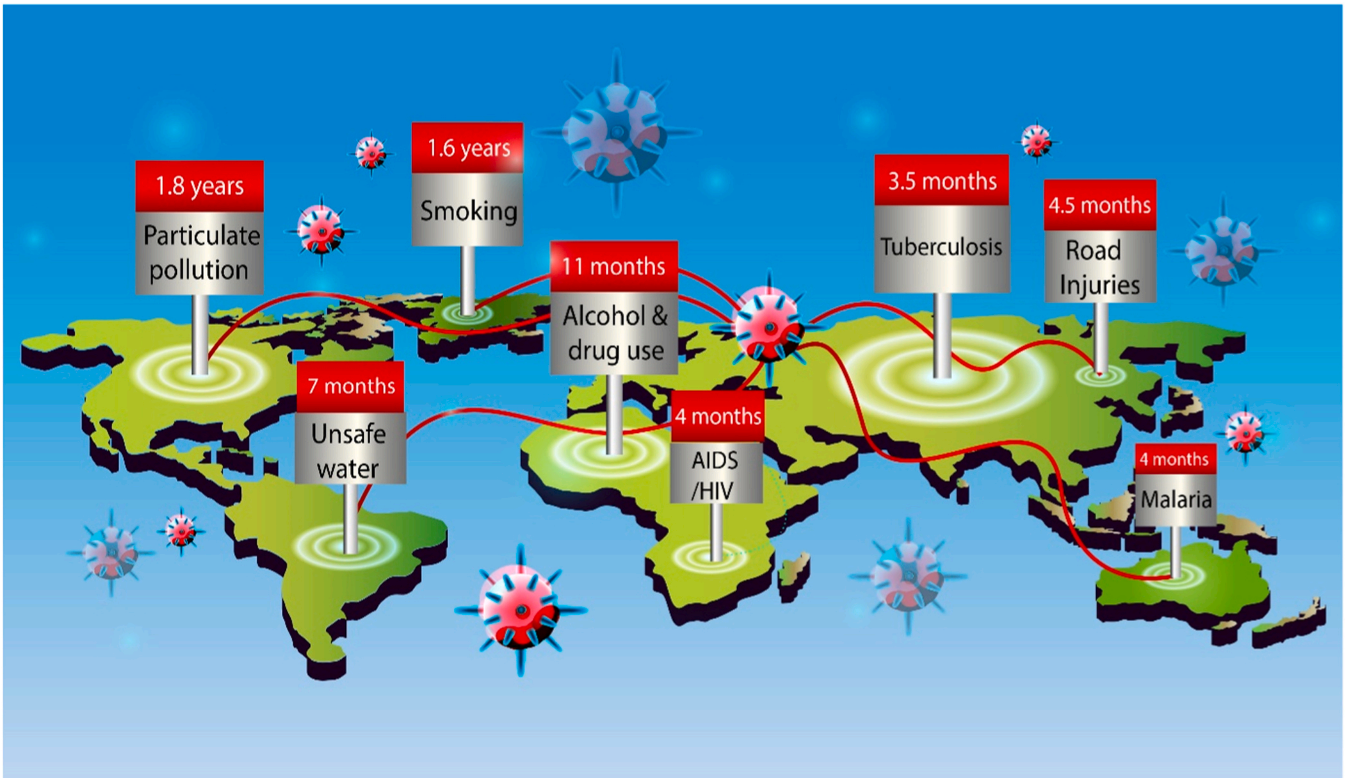

Fig. 6. Presents a world map that graphically represents the average reduction in life expectancy attributed to various global health risks, with a focus on air pollution. The map uses stylized virus and bacteria icons to symbolize different health risks. Each icon is connected by red lines to different regions of the world, suggesting the widespread nature of these risks. Highlighted prominently is particulate pollution, which is shown to reduce life expectancy by 1.8 years, indicating that it has one of the most significant impacts on global health. Other health risks include smoking, with a reduction in life expectancy of 1.6 years, alcohol and drug use at 11 months, unsafe water at 7 months, AIDS/HIV at 4 months, tuberculosis at 3.5 months, road injuries at 4.5 months, and malaria at 4 months. These figures provide a stark visual comparison of the health impacts of air pollution relative to other serious health risks (Dominski et al., 2021).

to socio-economic status and access to resources (Jin et al., 2022).

The global response to air pollution also varies widely. In some regions, proactive measures such as the implementation of strict emission standards, promotion of renewable energy, and public awareness campaigns have been effective in reducing pollution levels (Chen et al., 2023b). In contrast, other regions struggle with the enforcement of environmental policies, lack of infrastructure for pollution control, and limited public awareness, leading to continued high levels of air pollution. These differences in response are often a reflection of varying economic priorities, political will, and public awareness levels (Marks and Miller, 2022).

11.2. International cooperation and policy

The transboundary nature of air pollution necessitates international cooperation and coordinated policy responses. Air pollutants do not respect national borders, and their dispersion can cause environmental and health problems in neighboring countries and regions (Singh and Chauhan, 2022). This realization has led to the establishment of various international agreements and frameworks aimed at reducing air pollution and its impacts. For example, the United Nations Framework Convention on Climate Change (UNFCCC) and its Paris Agreement play a critical role in addressing emissions that contribute to both air pollution and climate change. Regional initiatives, such as the Convention on Long-range Transboundary Air Pollution (CLRTAP) in Europe, have also been successful in reducing certain types of air pollution across national borders (Mar et al., 2022).

International cooperation in research and technology transfer is another crucial aspect of the global response to air pollution. Sharing knowledge, experiences, and best practices can help countries, especially those with limited resources, to implement effective air pollution control strategies. Financial and technical support from international organizations and developed countries can also aid in building the necessary infrastructure and capacity for monitoring and managing air pollution in less developed regions (Ren et al., 2023).

In summary, air pollution and its health impacts represent a global challenge that varies significantly across regions. While developed countries have made notable progress in addressing this issue, many developing regions continue to face severe air quality problems. International cooperation and coordinated policy responses are essential to effectively tackle this global health threat. By working together, sharing knowledge and resources, and implementing effective policies and strategies, it is possible to reduce the impacts of air pollution and protect public health worldwide (Mishra, 2023).

12. Public awareness and education

Public awareness and education play a crucial role in addressing the issue of air pollution. The media and educational institutions are key players in this regard, as they have the power to influence public perception and behavior. Campaigns that effectively disseminate information about the sources of air pollution, its health effects, and ways to reduce personal exposure can motivate individuals to adopt healthier lifestyles. Schools can integrate air quality topics into their curricula, fostering a new generation that is more conscious of environmental issues. Social media platforms can also be leveraged to spread awareness quickly and engage a wider audience in conversations about air quality and sustainability. Furthermore, community-based programs that encourage local action, such as tree planting and clean-up drives, can help translate knowledge into tangible improvements in air quality

(Calderón-Garcidueñas and Ayala, 2022).

12.1. Role of media and education

The media, encompassing a wide range of platforms from traditional newspapers and television to social media and digital news outlets, has a significant impact on raising public awareness about air pollution. Through reporting on air quality issues, health risks associated with pollution, and mitigation strategies, the media can educate the public and influence policymakers (Nazar and Niedoszytko, 2022). The visual representation of pollution levels, stories of affected communities, and coverage of research findings all contribute to a more informed public. Moreover, social media platforms have become a powerful tool in spreading awareness rapidly and engaging a broader audience. They allow for the sharing of real-time air quality information, personal stories, and community-led initiatives, fostering a more participatory approach to addressing air pollution (Kenis and Barratt, 2022).

Education systems also play a pivotal role in shaping public understanding and attitudes towards air pollution. Incorporating environmental education into school curriculums can instill awareness from a young age. Teaching children about the causes and effects of air pollution, as well as ways to reduce personal exposure and contribute to cleaner air, can lead to a generation more conscious of and committed to environmental issues. Additionally, educational institutions can engage in research and community outreach programs, further spreading knowledge and awareness. Beyond formal education, engaging youth in citizen science projects that monitor local air quality can provide hands-on learning experiences and foster a sense of stewardship for the environment. Universities can contribute by developing innovative solutions to air pollution and training students in cutting-edge research methods. Collaborative partnerships between educational institutions, government bodies, and non-governmental organizations can amplify the impact of educational initiatives on air quality improvement. Finally, by incorporating sustainability and environmental health into various academic disciplines, educational institutions can create a multidisciplinary approach to solving the complex problem of air pollution (Bashir, 2022).

12.2. Impact on public behavior

The heightened awareness and understanding gained through media and education can lead to significant changes in public behavior. Informed individuals are more likely to take steps to reduce their own contribution to air pollution, such as using public transportation, carpooling, or using energy-efficient appliances and vehicles. They may also be more inclined to support policies and initiatives aimed at

Fig. 7. Is a vibrant illustration that depicts a variety of actions the public can take to reduce air pollution and promote environmental sustainability. On the left side of the image, a person is seen turning off the car engine to prevent unnecessary emissions, highlighting the practice of reducing vehicle idling. Below this, another individual is planting a tree, an activity that not only beautifies the urban landscape but also contributes to carbon sequestration and improved air quality. The image includes icons indicating alternative energy sources like solar panels, emphasizing the transition to cleaner energy options. In the center, the illustration features a bus stop where people are using public transport instead of personal vehicles, showcasing the community's effort to lower traffic emissions. This section underscores the significance of utilizing mass transit systems to reduce individual carbon footprints. On the right, inside a home, a person responsibly turns off lights and electronics when not in use, which conserves energy and decreases demand on power plants that may produce air pollutants. Further to the right, the concept of better waste management is introduced with an image of a recycling truck and people sorting waste into categorized bins, suggesting that recycling can reduce the amount of waste that might otherwise be burned or landfilled, leading to air pollution. Lastly, the bottom right corner of the figure presents community members engaged in raising awareness about air pollution, with two individuals holding a banner. This action calls for community involvement and education regarding the effects of air pollution and ways to counteract it.

reducing air pollution (Hopkins et al., 2022).

Public awareness also plays a role in holding corporations and governments accountable for their actions related to air quality. An informed public is more likely to advocate for stronger environmental regulations, support sustainable practices, and demand transparency and action from policymakers and industry leaders (Tan and Zhu, 2022). Moreover, increased awareness can lead to community engagement and grassroots movements, where local communities take initiative in monitoring air quality, organizing awareness campaigns, and implementing local solutions to combat air pollution. Such community-led efforts can be particularly effective in bringing about change at the local level (Loopmans et al., 2022). In summary, public awareness and education are essential components in the fight against air pollution. The media and educational institutions are instrumental in disseminating information and shaping public perception and behavior. An informed and engaged public can drive significant change in both personal behavior and broader policy and corporate practices, contributing to a concerted effort to tackle air pollution (Tran et al., 2023). Fig. 7 showcases practical steps individuals and communities can take to mitigate air pollution, including the adoption of sustainable practices such as using public transportation, conserving energy, and proactive recycling.

13. Future directions in air pollution research

13.1. Emerging trends

The landscape of air pollution research is continuously evolving, driven by emerging trends that reflect the dynamic nature of environmental challenges and technological advancements (Li et al., 2023c). One prominent trend is the increasing focus on the interaction between air pollution and climate change. Researchers are delving into how air pollutants, particularly greenhouse gases and aerosols, influence climate systems and vice versa. This area of study is crucial for developing integrated strategies that address both air quality and climate resilience (Campbell-Lendrum et al., 2023).

Another emerging trend is the utilization of advanced technologies in air pollution monitoring and analysis. The advent of low-cost sensors and IoT (Internet of Things) technology has revolutionized data collection, allowing for real-time, hyper-local air quality monitoring. This technological leap enhances the precision of air quality assessments and facilitates more targeted intervention strategies (Chen et al., 2022b). The exploration of the health impacts of air pollution is also expanding to include a broader range of effects. Beyond respiratory and cardiovascular diseases, there is growing research into the neurological effects of air pollution, examining links to cognitive decline, mental health issues, and developmental disorders. This holistic approach to understanding the health impacts of air pollution underscores the pervasive nature of these environmental hazards (Jbaily et al., 2022).

13.2. Potential areas of exploration

In terms of future research, several potential areas hold promise for advancing our understanding and management of air pollution (Honscha et al., 2021). One such area is the in-depth analysis of the sources and composition of emerging pollutants, such as microplastics and pharmaceuticals in the atmosphere. Understanding the behavior, distribution, and health impacts of these novel pollutants is crucial for developing effective control and mitigation strategies (Zhang et al., 2022a).

Another promising area of research is the development and implementation of sustainable urban planning practices that reduce air pollution. This includes the integration of green infrastructure, such as urban forests and green walls, which can play a significant role in filtering air pollutants, and the promotion of smart city concepts that incorporate environmental considerations into all aspects of urban development (Huang et al., 2022).

The exploration of innovative air purification technologies is also an exciting area of research. Advancements in materials science could lead to the development of more efficient and cost-effective air filtration systems for industrial, commercial, and residential use (Hendryx and Zullig., 2009). Additionally, the potential of biotechnology, including the use of plants and microorganisms for biofiltration, presents a novel approach to reducing indoor and outdoor air pollution (Roser, 2023). Finally, the application of big data analytics and artificial intelligence in air pollution research holds significant potential. These technologies can be used to analyze complex environmental datasets, improve air quality forecasting models, and develop more effective pollution control policies. The integration of AI in environmental monitoring can also enhance the predictive capabilities of air quality models, enabling proactive rather than reactive responses to air pollution episodes (Subramaniam et al., 2022). In summary, the future of air pollution research is marked by a confluence of emerging trends and potential areas of exploration. From advanced monitoring technologies to comprehensive health impact studies, and from sustainable urban planning to cutting-edge purification technologies, the field is poised for significant advancements. These efforts are critical for addressing the multifaceted challenges posed by air pollution and for safeguarding public health and the environment (Al-Mandhari et al., 2022).

14. Conclusion

The exploration of air pollution and its impacts on health and the environment underscores the complexity and urgency of this global challenge. Key points from the research highlight that air pollution is a multifaceted problem with significant health implications, ranging from respiratory and cardiovascular diseases to emerging concerns about neurological and mental health impacts. The sources of air pollution are diverse, with both traditional pollutants and new contaminants like microplastics and nanoparticles contributing to the problem.

Regionally, the impacts and responses to air pollution vary significantly, with developing countries often facing greater challenges due to industrialization and limited resources for pollution control. Technological advancements, particularly in monitoring and data analysis, have revolutionized our understanding of air pollution patterns and are crucial in developing effective mitigation strategies. Public awareness and education have emerged as vital tools in combating air pollution, emphasizing the role of media and educational institutions in shaping public perception and behavior. Future directions in air pollution research point towards a more integrated approach that considers the intersection of air pollution with broader environmental issues like climate change, the development of sustainable urban infrastructures, and the exploration of innovative technologies for air purification.

This comprehensive overview calls for a concerted global effort to address the issue of air pollution. Policymakers, researchers, industry leaders, and the public must collaborate to develop and implement effective strategies to reduce air pollution and mitigate its impacts. This includes enforcing stricter emissions standards, investing in sustainable technologies, raising public awareness, and supporting research initiatives. In summarize, tackling air pollution is not only an environmental imperative but also a public health necessity. The path forward requires a collective commitment to creating cleaner, healthier environments for current and future generations. This call to action is a reminder that the fight against air pollution is a shared responsibility, demanding engagement and action at all levels of society.

Future recommendations for combating air pollution should focus on embracing a circular economy to minimize waste and encourage recycling, thus reducing the release of pollutants from disposal processes. Urban planning must prioritize green spaces and support infrastructure for non-motorized transport, such as walking and cycling, to reduce vehicular emissions. There should be an acceleration in the transition to renewable energy, with incentives for businesses and homeowners to install solar panels or wind turbines. Global health organizations can work on integrating air quality indicators into public health surveillance systems to better understand the impact of air pollution on health outcomes. Investment in education and citizen science projects should be increased to engage communities in air quality measurement and improvement efforts, fostering a sense of ownership and action. Regulatory bodies must also consider the global nature of air pollution and work towards international agreements that set binding targets for emissions reductions. Innovation in clean technologies should be encouraged through grants and subsidies, facilitating the development and deployment of pollution control technologies. Lastly, there is a need to establish a global air quality monitoring network that provides real-time data accessible to all, enhancing transparency and accountability in pollution management.

CRediT authorship contribution statement

Fu Chen: Writing – review & editing, Writing – original draft, Visualization, Funding acquisition. **Wanyue Zhang:** Visualization, Software, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Manar Fawzi Bani Mfarrej:** Validation, Resources, Project administration, Data curation, Conceptualization. **Muhammad Hamzah Saleem:** Writing – review & editing, Writing – original draft, Visualization, Software. **Khalid Ali Khan:** Writing – original draft, Supervision, Software, Conceptualization. **Jing Ma:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software. **António Raposo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software. **Heesup Han:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision.

Declaration of Competing Interest

We, the authors of this review, hereby declare that there are no financial or non-financial conflicts of interest related to the content of this manuscript. Our work has been conducted and presented with full academic integrity, free from any undisclosed influences or conflicts that could affect the objectivity or credibility of our research and findings.

Data availability

No data was used for the research described in the article.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (No. 41907405, No. 52374170). The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University Saudi Arabia for funding this work through Large Groups Project under grant number RGP2/328/45.

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