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REVIEW PAPER

Unveiling the hidden hazards of smog: health implications and antibiotic resistance in perspective

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Abstract Smog is a form of pollution composed of smoke and fog. It is one of the major environmental and public health problems in many urban areas around the world. Intriguingly, recent evidences have unveiled the potential link between smog and antimicrobial resistance (AMR). Smog can contribute to AMR through a complex and multifaceted set of mechanisms, including particulate matter (PM) which is found in smog, mediated transport of AMR microorganisms and genes, disruption of the respiratory microbiome, and modulation of host immune responses. Since the PM can lodge deeper in the lungs and harbors antibiotic resistance genes (ARGs), it should be considered that PM contributes to AMR toward the respiratory tract infections and other infections. PM can create conditions conducive to bacterial survival and growth in the respiratory system due to inflammation and immune suppression. PM2. 5 and PM10 have been associated with several respiratory system ailments due to their capability to penetrate inner areas. Moreover, PM can serve as a carrier for ARGs and other microbial components, aiding in their spread. This interaction may accelerate the development and spread of AMR. It is imperative to further unleash the mechanisms adopted by microbial extracellular DNA associated with the PM to envisage the potential health and environmental hazards. eDNA, for example, has been shown to contribute to the diversity and composition of microbiota associated with PM, such as bacteria, fungi, and viruses. This review focuses on PM, ARGs, and microbial eDNA as emerging environmental contaminants. A comprehensive analysis is conducted of the mechanisms and circumstances that contribute to its spread in diverse settings. Considering the current explosive increase in microbial resistance to the antibiotics, this also necessitates uncovering the underpinnings of the smog's effect on AMR and developing effective strategies for mitigating these deleterious smog effects on health and environment.

Keywords Smog · Air pollution · Antibiotic resistance · Particulate matter 2.5 · Airborne bacteria · Lung diseases

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1 Introduction

In the present era, air contamination is a foremost source of sickness and death. Solids, gases, and liquids are the main pollutant forms in the air. The negative effects of these air pollutants are hazardous to public health. Exposure to particulate matter (PM) has been linked with respiratory symptoms such as asthma, COPD, and decreased lung function. It is also associated with an increased frequency of hospitalizations due to respiratory illnesses and increased mortality (Abdul Jabbar et al., 2022; Mannucci et al., 2017; Srinamphon et al., 2022).

Looking back at the "Great London Smog" of 1952, which occurred between December 5–9, the reason for that smog was a predominance of stagnant air conditions. The number of deaths attributed to this pollution outbreak is estimated to be between 4000 and 20,000. Since then, industrialization and frequent transportations are considered as the main cause of air pollution. Similar patterns of airborne pollutants emission and concentration in air during last few decades all over the world raise questions about global health (Sokhi et al., 2021).

Only a few earlier studies have investigated the historical background and demographic shifts, offering novel insights into the relationship between smog and mortality. For instance, despite a decrease in household pollution, there has been a global increase observed in mortality related to ambient particulate matter found in smog and ozone (Zhang et al., 2020). In many countries, particulate matter pollution increases the risk of dying from illnesses like ischemic heart disease and a substantial spike in diabetes cases as shown in Fig. 1 (Guo et al., 2017). In China, fine particulate matter in the air has been related to an increase in lung cancer mortality (Velasco & Jarosińska, 2022).

Particulate matter (PM) found in smog and the air is a major risk factor for disorders related to lipid metabolism. The cross-sectional study by Zhang et al. in 2023 first estimated the relationships between metabolism of lipids, innate immune cells, and air particulate matter. According to this study, long-term exposure to the particulate matter may change the distribution of innate immune cells in the peripheral circulation, which may disrupt the metabolism of lipids and increase the risk of cardiovascular disease (Zhang et al., 2023).

Besides the conventional considerations, pollutants in the air concentrate environmental toxins in the kidney and filter blood, which makes it a substantial risk factor for impaired kidney function in addition to the usual causes. According to a study by Wang et al., in 2019 renal function in Chinese adult women is inversely impacted by the combined toxicity of air pollutants, which may increase the risk of chronic kidney disease (Wang et al., 2020).

Long-term exposure to particulate matter has adverse effects on the cardiovascular and respiratory systems (Eze et al., 2014; Manisalidis et al., 2020) with former being more common in industrialized and highly air-polluted countries (Kaun et al., 2018). In India, New Delhi is the most polluted city, with air quality reaching deadly levels. Pollution is increasing due to industrialization, urbanization, and transportation (Thomas et al., 2022; Yu et al., 2022). The accumulation of sulfur dioxide and smoke in the air is related to increased deaths (Stansfeld, 2015). Consequently, the reduction or removal of pollutants from the air improves health by preventing these life-threatening diseases and the ecology of the environment (Mira-Salama et al., 2008).

Air quality is assessed according to the quality standards developed by WHO and Environmental Protection Agency (EPA) for air pollutants (Mira-Salama et al., 2008; Zhou et al., 2015). Large-scale operations of industrial power plants, combustion engines, and vehicle operations are recognized as the primary source of environmental toxins. Automobiles account for over 80% of the pollution (Altowayti et al., 2022). Besides these, petrochemical plants, fertilizer industries, and other industrial plants and human activities have an influence on the environment and health of the population (D'amato et al., 2016).

In recent years, one of the most significant social challenges has been the deterioration of air quality. Most pollutant emissions are known to be related to the level of industrial production. Aerosol chemicals and gaseous compounds are both hazardous to the respiratory system. Aerosols are microscopic chemicals that have a tremendous impact on the environment (Manisalidis et al., 2020) and are more hazardous than gaseous compounds due to their microscopic size. Additionally, they have a larger penetration capacity in the respiratory system. Our respiratory system can more easily eliminate gaseous pollutants,

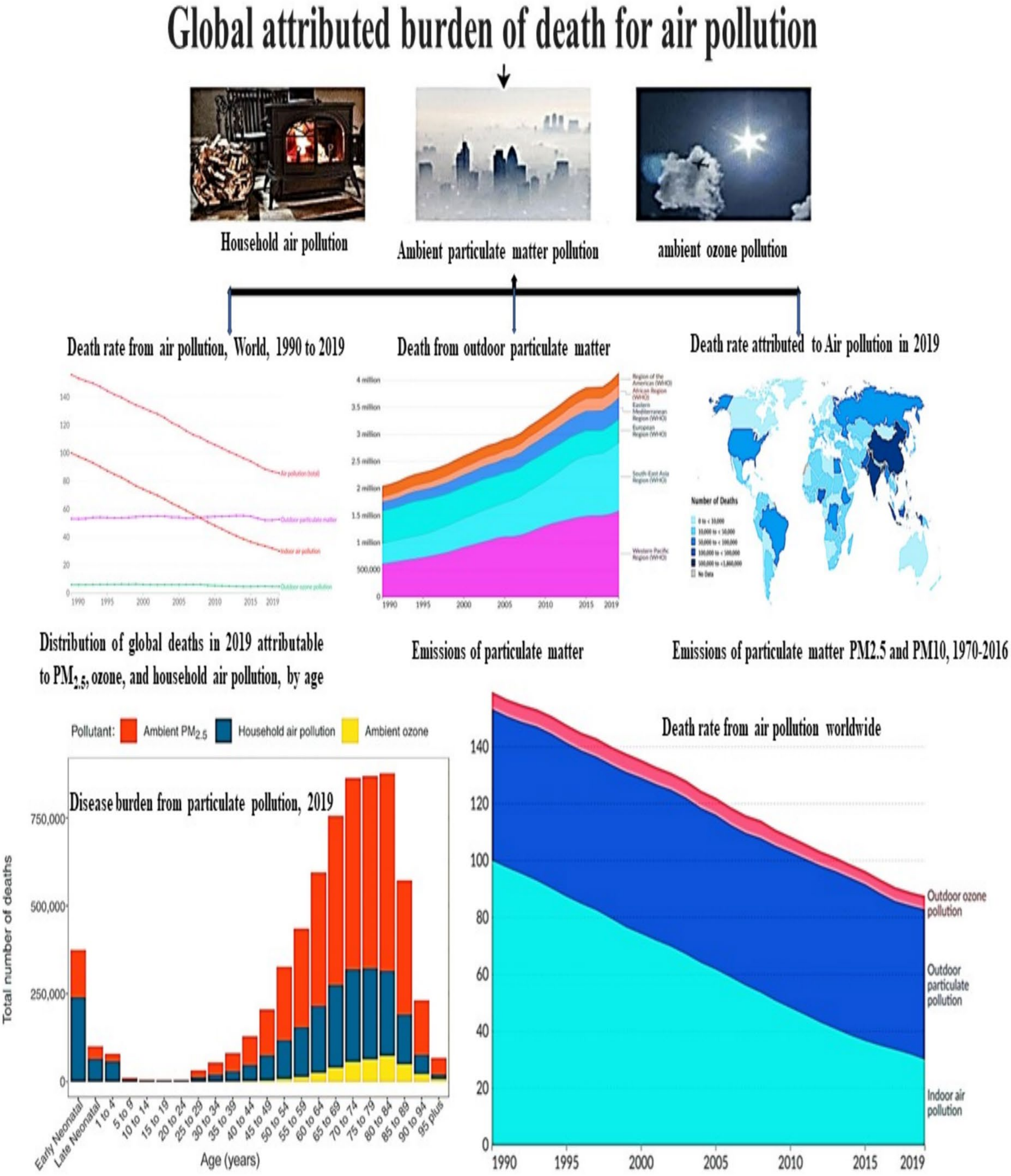

Fig. 1 Global attributed burden of death for air pollution: demographics, decomposition, and birth cohort

whereas aerosol particles can cause damage to the lungs, leading to the early death of millions of people each year. Moreover, it seems that aerosol acidity ([H+]) stimulates the development of secondary organic aerosols (SOA), while other studies disagree (Hahad et al., 2020).

Inhaled particulate matter enters the host through the lungs. Deep inhalation of fine particulate matter overwhelms the body's defense by causing oxidative stress from an overabundance of free radicals. The inflammation that PM causes within the body throws off the normal harmony of the respiratory microbiota, resulting in a change in the microbial makeup that can encourage the spread of AMR strains. While PM10 particles are initially blocked by the nasal mucous layer and cilia, continuous exposure can cause localized irritation and harm the nasal protective barrier. This may worsen diseases like allergic rhinitis. The key variables in assessing the effects of PM exposure on health are shown in Fig. 2 (Rahoma et al., 2010; Sokhi et al., 2021).

Pollution is caused by changes in the physical, chemical, or biological elements of the environment. For example, high levels of toxins, present for a long period of time, define air pollution (Bezirtzoglou et al., 2011). Pollutants influence our atmosphere by raising normal levels or adding hazardous compounds that endanger human health. There are numerous and diverse sources of air pollution, including natural, local, stationary, and mobile (Castelli et al., 2017; Watson et al., 2007) as shown in Fig. 3.

Large combustion plants (including power plants and combined heat and power plants) are the main sources of sulfur oxide emissions. The second and third places are occupied by industrial combustion processes and housing (local boiler houses). The main sources of nitrogen dioxide are road transport, metallurgy, and cement mills. Primary pollutants are released directly from sources such as vehicles, industrial processes, and natural sources like wildfires and dust storms, whereas secondary pollutants are released due to primary pollutants.

The change in the climate is another major issue that is damaging the condition of our globe's condition (Chen et al., 2017). As a result of pollutants such as aerosols, black carbon, tropospheric, and methane, greenhouse gas concentrations increased significantly. The atmospheric buildup of greenhouse gases, which trap solar heat and result in a warming effect known as the greenhouse effect, is the primary cause of the Earth's temperature rise (Wielgosiński & Czerwińska, 2020; Yang & Wang, 2017). Natural calamities such as storms, which appear to be occurring more frequently recently, are linked to epidemics.

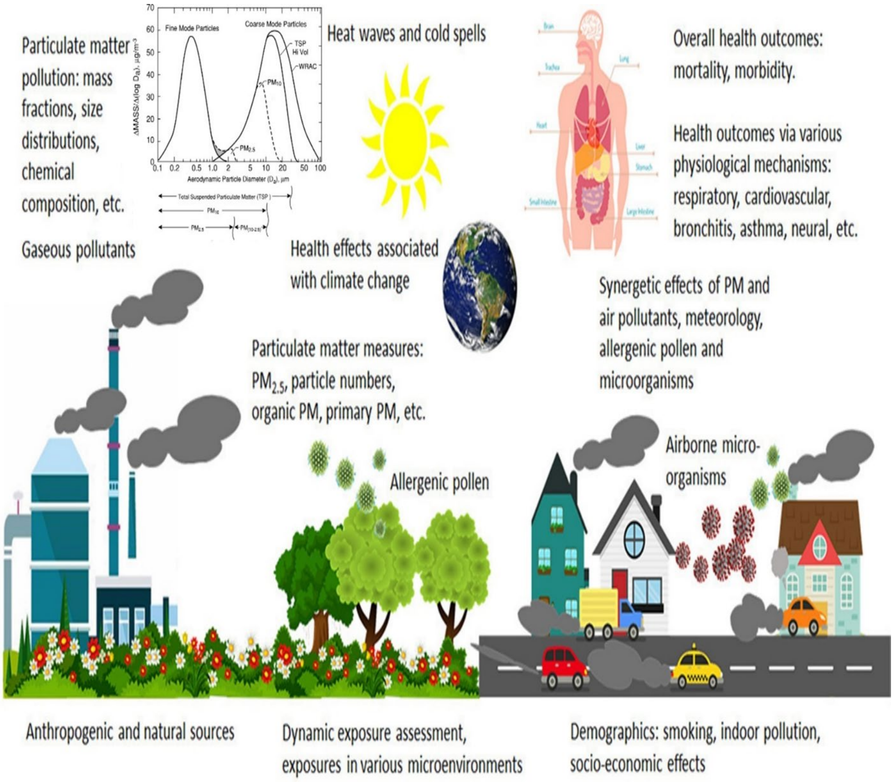

Fig. 2 Schematic representation of the important parameters in determining the health impacts of PM exposure (Rahoma et al., 2010; Sokhi et al., 2021)

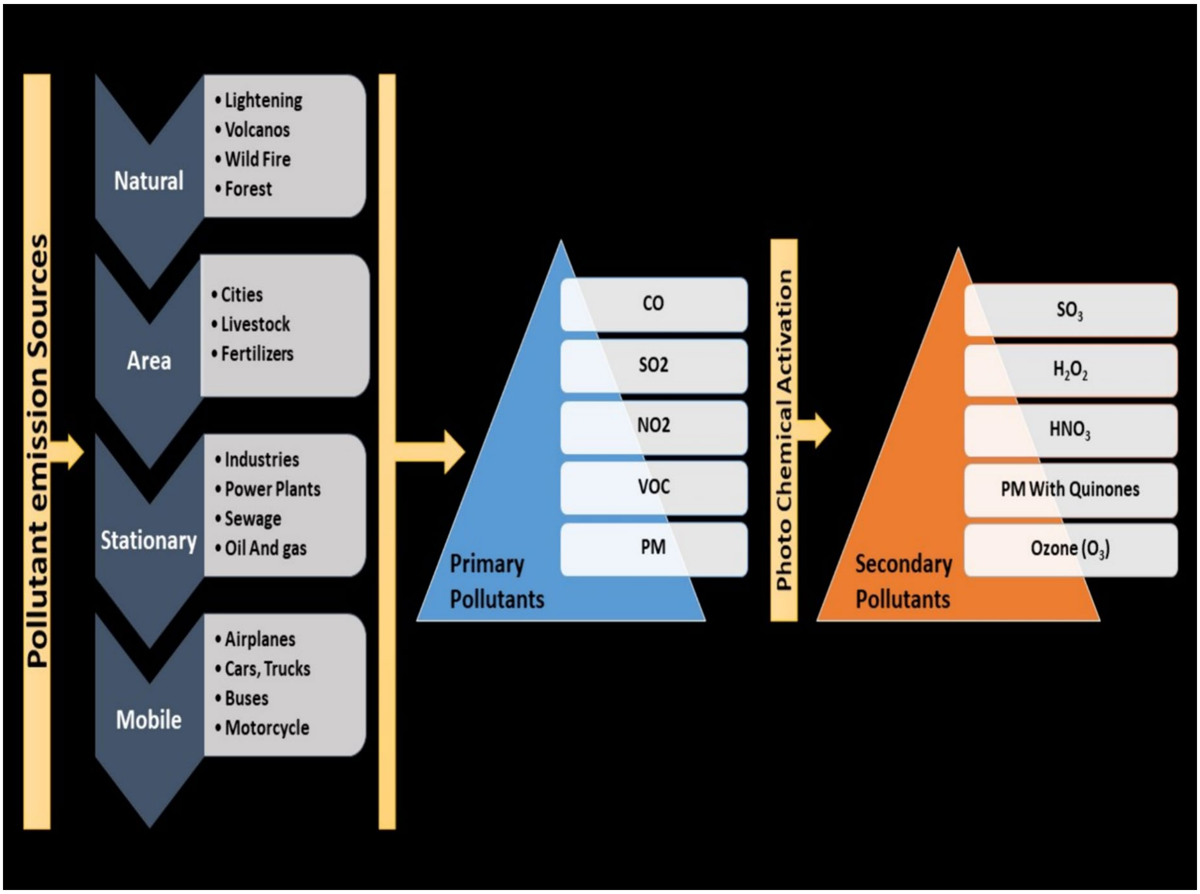

Fig. 3 Four basic categories of air pollutants: local, natural, stationary, mobile, and reactive gases including volatile organic compounds (Ying et al., 2007)

These occurrences can affect sanitation and health care, increasing the risk of disease transmission through contaminated water, compromised healthcare access, and population mobility, highlighting the complex relationship between environmental changes and epidemic vulnerability (Wang et al., 2017).

With an emphasis on their microscopic size and penetrating power, this study intends to emphasize the impact of aerosol components and fine particulate matter (PM) on respiratory health. Nanoscale particles (NPs), which are a type of particulate matter (PM) pollution, are thought to pose substantial risks to public health. The adverse effects of ultrafine particles (PM0.2) and their nano-sized sub-fraction on human brain functioning during the lifespan have received a large amount of attention recently. Despite having different chemical compositions, both nPM (nano-PM) and sPM (sub-PM) cause neurotoxic reactions in cerebral cortex tissue. This could be because these two substances contain toxicants such organics and transition metals. But due to the sPM's high concentration of water-insoluble PAHs, gestational exposure to sPM has a special effect on glutamatergic gene expression. Research has linked exposure to PM with detrimental effects on cognitive growth, including abnormalities and DNA damage. An increased incidence of dementia and rapid cognitive decline have also been connected to later-life exposure to PM 0.2. These particles, which may translocate to the brain, deposit on the olfactory bulb upon inhalation. The latest literature has highlighted the potential role of these particles in neurodegenerative diseases.

In addition, there will be a better understanding of the intricate connection between pandemic vulnerability, air pollution, and climate change. Moreover, this study will look at the presence of extracellular DNA (eDNA) and antibiotic resistance genes (ARGs) in airborne PM. It will pinpoint the origins and sources of ARGs, assess any potential negative effects on health, and analyze the persistence of eDNA. Furthermore, the study will evaluate the effect of air quality on ARG presence and compare ARG profiles in PM to those in other contexts. Overall, this study offers vital information for efforts to manage the environment and public health.

2 Composition and health effects of smog

Smog is an air pollution caused by chemical reactions that occur in the atmosphere due to the presence of chemicals such as nitrogen oxides or volatile organic compounds. Photochemical smog is the most common type of smog and accounts for most urban pollution. Smog has the most well-known detrimental effect on the atmosphere's ground layer (Mousavi et al., 1999; Wielgosiński et al., 2018). It is an atmospheric phenomenon that comes from the co-occurrence of human-caused air pollution and is consequential in temperature inversion and, in some cases, fog (Table 1).

Originally, the term smog was coined by combining the phrases smoke and fog to describe a phenomenon that occurred in London in the early 1950s. Today, we commonly refer to smog as excessive air pollution in cities caused by emissions from residential burning and automobiles, under climatic conditions. The vertical movement of the atmosphere is severely hampered as a result, and there is a concentration of contaminants at the Earth's surface in light wind or windless conditions (Czerwińska & Wielgosiński, 2020; Kryzia & Pepłowska, 2019).

An acid aerosol is created around the ground level, which is hazardous to humans and the environment, as well as allergenic to some people (Pastuszka et al., 2010; Wilson et al., 1997). Nitrogen oxides, carbon monoxide, and hydrocarbons are the primary constituents of photochemical smog, with ozone being the most prevalent due to photochemical processes. Smog is a major issue in many countries and towns. This is a problem that exists in Poland, as well. Pollutants with the largest above average concentrations include benzo (a) pyrene, particulate matter, and nitrogen dioxide (NO_2). Furnaces, coal, and wood-fired boilers are the main sources of particulate matter and benzopyrene, while automobiles are the leading sources of NO_2 (Cheung et al., 2011; Zhang et al., 2019).

In Poland, household boilers are the primary cause of smog as they generate significant quantities of PM10 and PM2. 5 as well as other carcinogenic compounds (Kloog et al., 2013). This type of pollution is not unique to Poland; identical metrological circumstances and pollutant emission patterns exist in other European countries (Kappos et al., 2004).

The principal pollutants in the air have been identified by WHO as particle matter, ozone at ground level, carbon monoxide, nitrogen oxide, sulfur dioxide, and lead (Pb). Air pollution can wreak havoc on different areas of the ecosystem and the atmosphere. It poses a significant danger to all forms of life. Acid rain and changes in weather conditions are significant environmental consequences of air pollution (Sivakumar & Ramya, 2021). Particulate matter pollution is defined by the US Environmental Protection Agency "as particles with sizes of 10 μm (μm) or less, known as PM10, as well as extremely small particles with dimensions of 2.5 μm (μm) or fewer" called PM2. 5 (Manisalidis et al., 2020) (Boschi, 2012) and nanoscale particles (NPs, with a diameter of less than 1 μm).

Long-term exposure to PM is linked to cardiovascular (CV) disease and neonatal mortality (Lorenzini & Saitanis, 2003). Due to the lack of data, studies are restricted to study regions or city areas and do not represent the total population. Researchers have

Table 1 The table below shows the difference between industrial and photochemical smog

Industrial Smog	Photochemical smog
Known as "London Smog"	Known as "Los Angeles Smog"
Grayish color	Brownish color
Formed by burning of coal or oil in power plants	Formed by the automobile waste and solar radiation reaction
Sulfur oxide combined with particulate matter	Nitrogen oxide reacts with organic compounds

recently developed a PM2. 5 model using remote sensing. This allows for regional resolution of short-term impacts and evaluation of side effects over the long term. Moreover, long-term chronic effects such as respiratory diseases and immune system problems have been observed (Fares et al., 2013).

PM has a negative impact on people who have respiratory or cardiovascular difficulties. PM2. 5 and PM10 have been associated with several respiratory system ailments (Arias-Pérez et al., 2020; Loaiza-Ceballos et al., 2022) due to their capability to penetrate inner areas as shown in Fig. 4 and Table 2 (Amann, 2008; Caples et al., 2010; Fares et al., 2013; Lorenzini & Saitanis, 2003). Lung problems are also documented as chronic effects. As a result of their capacity to permeate, PM2. 5 and PM10 are intimately associated with respiratory disorders

Table 2 The table below shows the degree of penetration of different particulate matters in the human respiratory system

PM size	Degree of penetration in respiratory system
≥ 11 μm	Upper respiratory tract
7–11 μm	Nasal cavity
4.7–7 μm	Larynx
3.3–4.7 μm	Trachea
2.1–3.3 μm	Bronchial area
1.1–2.1 μm	Terminal bronchial
0.65–1.1 μm	Bronchioles
0.43–0.65 μm	Alveolar

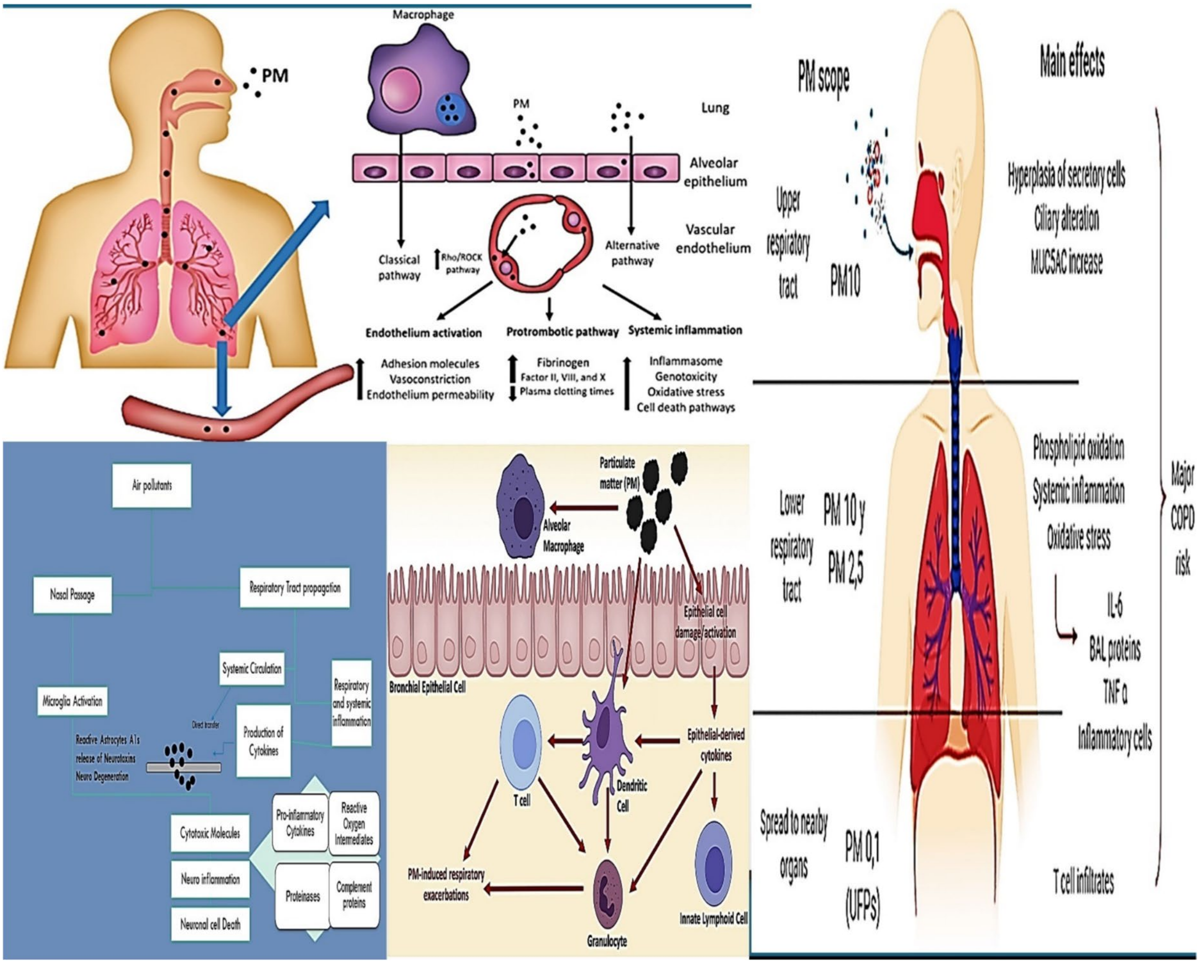

Fig. 4 Effect of particulate matter on the immune system (Arias-Pérez et al., 2020; Loaiza-Ceballos et al., 2022)

(Reizer et al., 2016; Wang, 2019; Zhu et al., 2020). These elements can be organic or inorganic (Boschi, 2012).

Tropospheric ozone is initiated by the reaction of NO and organic compounds, which is distributed by anthropogenic activities. Given the rising levels in urban areas, it is remarkable that ozone levels in urban areas are quite low, which could impact cultures, forests, and vegetation by restricting carbon uptake (Cacciottolo et al., 2017; Geddes & Murphy, 2012). The most prevalent route of absorbing ozone is through inhalation, and it damages the stratified layers of the skin (Ilyas et al., 2008). The inhaled ozone can penetrate deeply into the lungs (Sun et al., 2016). Ozone is harmful in cities, producing biochemical, morphologic, functional, and immunological issues (Matus et al., 2012).

Carbon monoxide is formed when fossil fuel combustion is incomplete. CO poisoning causes headaches, weakness, nausea, vomiting, and ultimately death. Carbon monoxide binds to hemoglobin significantly more strongly than oxygen. Exposure to high levels of CO for an extended period may lead to serious health problems, like hypoxia and ischemic heart disease (IHD).

NO is a contaminant that is emitted by automobile engines (Cacciottolo et al., 2017; Geddes & Murphy, 2012; Ilyas et al., 2008; Jia et al., 2017; Matus et al., 2012; Reizer et al., 2016; Sun et al., 2016; Wang, 2019; Zhu et al., 2020). Concentrations of more than 0.2 ppm influence T-lymphocytes, specifically natural killer cells that yield an immune response, whereas concentrations of more than 2.0 ppm affect T-lymphocytes, particularly CD8 + cells and natural killer cells that produce an immunological reaction (Yadav & Rawal, 2016). Long NO_2 exposure has been associated with the development of chronic lung disease. NO_2 exposure can impair one's sense of smell (Yadav & Rawal, 2016).

Sulfur dioxide (SO_2) is a gas that can be dangerous. It is emitted from the burning of fossil fuels and industrial processes. It affects humans, animals, and plants. Since SO_2 is an irritant, it transforms into bisulfite when it penetrates the lung and interacts with sensory receptors, causing bronchoconstriction. Moreover, it causes respiratory irritation and bronchitis (Yadav & Rawal, 2016).

PM10, PM2. 5, CO, NO, SO_2, and ozone are the pollutants in the ambient air that cause serious public health problems, according to the WHO (Li et al., 2021). These pollutants are mostly emitted by anthropogenic activities such as gasoline used in cars and heating operations (Raza et al., 2021). People who are exposed to high levels of pollution develop a variety of diseases, specifically people over the age of sixty-five, children, and diabetics who have a predisposing CV or lung disease, particularly asthma. Short-term side effects include eye, skin, and throat irritation, coughing, and breathing difficulties, as well as asthma, pneumonia, bronchitis, and heart complications. People exposed to air pollution for a short time may experience headaches and dizziness.

Air quality extents are vital for enhancing the quality of air suitable for human health since pollutants cause a variety of ailments, including heart, skin, and eye problems. Smog exposure is linked to several inflammatory responses (Mostafaei et al., 2021). They can also induce a variety of ear, nose, and throat (ENT) related disorders (Clarke et al., 2021). Pollutants such as those listed above produce oxidative interactions with tear film components, altering their makeup. As a result, these structures are in direct touch with smog-caused air pollution, making people vulnerable to ocular disorders such as dry eye, infections, and other disorders of the eye. There are historical examples that date back to 1952 where dense pollution generated by massive coal combustion killed thousands of Londoners.

Photochemical haze covered Los Angeles in the 1940s and 1950s, causing thousands of early deaths and traffic fatalities (Jedrychowski et al., 2005; Li et al., 2021; Rice et al., 2015). Smog is thought to have killed almost 2 million people in China and India (Rice et al., 2015). PM10 and PM2.5 were reported as haze in November 2016 and used to estimate air quality in India's capital, New Delhi (Kennedy et al., 2018). In early November 2016, the same dense haze settled on Lahore, blocking out the sun. Certain direct effects, such as health concerns, and indirect effects, such as road accidents, were documented during this smog event (Soh et al., 2018). PM2. 5 has been related to several health concerns because it penetrates deeply in the respiratory system. In China, a continuous decrease in PM2. 5 in recent years is observed, which is due to an improved understanding of physicochemical components. Bioaerosols make up 5–10% of the particulate matter in the atmosphere. Inhalable biological particles, particularly those with a finer particle size than PM2. 5, have the potential to affect human health.

Several studies have found that bioaerosols act as a carrier for a variety of opportunistic bacterial pathogens linked with respiratory infections (Claude et al., 2012). Microorganisms associated with human and animal feces were also discovered in Hurricane Earl after it passed through densely populated areas. Bioaerosols contain antibiotic resistance microorganisms and ARGs (Shao et al., 2020). According to several epidemiological evidence, inhaling pollutants from the environment tends to lead to upper respiratory infections (URIs) (Troeger et al., 2018) and lower respiratory infections (LRIs).

In most cases of pneumonia, for example, the etiologic agent is unknown. The identification of the microbiological etiology of pneumonia is still difficult due to technological restrictions in obtaining samples, distinguishing infection from colonization, and growing organisms on artificial media. As a result, only a few studies identify a link between air pollution and lung infections. While there is a lack of published studies on URIs primarily caused by viruses, a limited number of researchers have directed their attention toward cases of pneumonia with positive outcomes. Nonetheless, an accumulating body of evidence suggests an association of air pollution with bacterial infections in the lungs of people with cystic fibrosis (CF) and tuberculosis (TB) (Cairns & Baigent, 2014).

Exposure to pollutants in pregnancy or during the first year of life has been linked to childhood LRIs in epidemiological research (Ashraf et al., 2019; Grabiec & Hussell, 2016; Leary et al., 2014; Yegambaram et al., 2015). Despite the lack of research on the impact of prenatal exposure to air pollution on bacterial infections of the air passages, new investigations provide indirect evidence (Abelsohn & Stieb, 2011; Ashraf et al., 2019; Zhan et al., 2018). A study of infants aged 1000 days or less (Abelsohn & Stieb, 2011) looked at the link between exposure to PM2. 5 from coal mine fire emissions and physician visits or the use of antibiotics to treat infections. Antibiotic use was found to be higher in the year following the fire, indicating an increase in childhood bacterial illnesses.

Another study found strong scientific evidence for children's increased vulnerability to subsequent lung illness caused by opportunistic bacterial infections after prenatal exposure to air pollution (Zhan et al., 2018). Pregnant BALB/c mice were exposed to ambient air tobacco smoke for one week before birth (Yegambaram et al., 2015). The puppies were given an influenza A virus inoculation at 7 weeks of age, followed by a *Staphylococcus aureus* challenge a week later. Perinatal environmental tobacco smoke (ETS) exposure increased subsequent lung infection by *Staphylococcus aureus* in BALB/c mice, resulting in increased pulmonary inflammation. Exposure to ambient pollution has been associated with a cumulative set of cardiovascular effects [69]. Long-term exposure may cause changes in blood cells, which may influence CV function. Traffic pollution exposure has been associated with coronary arteriosclerosis (Xiong et al., 2021), and exposure over a short period of time is associated with heart failure, stroke, and myocardial ischemia. Long-term exposure to NO_2 has been linked with ventricular hypertrophy (Parsajou & Nasrabadi, 2021).

Neurodegenerative disease is caused by oxidative stress, protein aggregation, inflammation, and mitochondrial failure in neurons. It is critical to find that air pollutants affect the immune system, causing neuroinflammation (Sun et al., 2021). Levels of immunoglobulins are elevated (Wang, 2019). Another source of worry is that air pollution influences antigen presentation by increasing the expression of co-stimulatory molecules on macrophages such as CD-80 and CD-86 (Qin et al., 2019).

In Pakistan, the high amount of nitrogen is about 17 times greater, according to a study of smog data. Other air pollutants including sulfur dioxide and ozone are four times higher than the baseline levels of CO and volatile organic compounds (VOC), and PM2. 5 levels are two times higher. In Pakistan, smog data show elevated NO production when comparing satellite photos from the year of the smog event to the same period of the previous year. This pollution can be avoided by reducing NOx emissions through reducing personal vehicle loads, increasing public transportation use, reducing industrial emissions, increasing tree planting, and developing collaborative policies among stakeholders to address the transboundary issue. According to the report, there was a 60% increase in the number of patients with ocular surface illnesses during the Lahore haze (Cao et al., 2014).

3 Air quality index (AQI)

The air quality index, also known as AQI, is an indicator for describing an area's air quality. The AQ index is calculated by the Environment Protection Agency of the USA (US-EPA). It is based on the concentration of five major air pollutants: tropospheric ozone, particulate matter, CO, SO_2, and nitric oxide concentration. Air, Earth, and particle pollution is an air quality monitoring system that uses sensors to monitor particulate matter in the air. The system can be used to improve air quality in real time or to collect data for later analysis. The system can be used for air quality in homes, office buildings, factories, and other environments. The greater the air quality index, the more serious the threat to health.

The AQI can have values ranging from 0 to 500. Suppose that the AQI falls within a range from 0 to 50. In that case, it falls in the good (green) area of air quality. But if the AQI value is between 51 and 100, it has moderate (yellow) air quality, which is also acceptable; however, some pollutants may cause health concerns for some people. For example, people with respiratory diseases such as asthma may have trouble breathing. All others should limit their outdoor activity. The 101–150 AQI is unhealthy for sensitive populations (orange). Members of sensitive populations may experience adverse health effects. This range of AQI will not affect the rest of the public. Sensitive groups include the elderly, children, and people suffering from lung disease, heart disease, or other chronic respiratory diseases. People with asthma should follow their asthma action plans and call their healthcare providers to see if their lungs are acting up or if they have other breathing problems. People with heart or circulatory conditions should remain alert for symptoms such as palpitations, shortness of breath, or unusual fatigue and report these symptoms to a healthcare provider (Qin et al., 2020).

4 Composition and diversity of air microbiome

The atmosphere also contains microbiological bioaerosols, which account for 30–80% of PM, and mostly consist of bacteria and fungi, as well as viruses, cell debris, and pollens (Yoo et al., 2017). Although airborne bacteria were originally comprehensively reported by Louis Pasteur in 1860, they have only piqued the interest of scientists due to the development of DNA-based molecular technologies (Zhang et al., 2021). Bacteria enter the troposphere via the aerosolization of many surfaces, including soils and plants (Wang et al., 2022).

Bacterium (60–100%) can live in unfavorable conditions for some time by sticking to these particles or forming cell agglomerations, whereas free-living microorganisms have a shorter lifespan. As a result, the size range of culturable bioaerosols varies greatly (0.0001–100 mm) and is closely connected to the period they may persist in the atmosphere. This affects whether bacterial short-range or long-range movement is possible. Bacteria can be carried over lengthy distances, especially if particles from desert dust or hurricanes accompany them. The study reported a significant terrestrial microbe (5102–8104 cells/m3) with seventeenth-day residence duration in airborne bacteria. They concluded that with the help of islands, fifty percent of prokaryotes might remain adjourned after traveling for almost 22,000 km (Figueras et al., 2011).

Microorganisms like bacteria, viruses, fungi, archaea, and along with their metabolites and genomes make up the pulmonary microbiota. The upper and lower airways contain a variety of bacteria. The microbial population of the airways begins to grow as soon as the person is born. However, this process can be very dynamic as it is affected by environmental factors and genetic predisposition. The respiratory tract microbiota may be negatively impacted by exposure to indoor and outdoor air pollution, which may increase the risk of infectious diseases like pneumonia (He et al., 2021).

Agriculture and wastewater treatment both contribute significantly to bioaerosol generation (Do et al., 2017). It has been observed that such aerosol types may pose a risk of infection to workers at wastewater treatment plants (WWTP), individuals with impaired immune systems, and the surrounding populations (Singh et al., 2021). Studies on epidemiology have revealed that workers at WWTP are susceptible to allergies, hypersensitivity reactions, gastrointestinal disorders, and respiratory tract infections brought on by exposure to airborne microbes (Han et al., 2020). It is concerning that bioaerosols from intensive livestock farming have also been shown to cause illnesses and/or symptoms in industrial settings, raising concerns about potential health effects on nearby residents (Douglas et al., 2018).

Particulate matter in them smog and air can carry microbiota and pathogens into the body. The airborne transmission of contaminants (especially inhalable particulate matter) is one way that the microbiome in the gastrointestinal tract and respiratory tract can undergo compositional changes (Zhang et al., 2021). The metagenomic analysis of Beijing's PM pollution revealed that bacteria were the most prevalent microorganisms during severe smog, and some of these were pathogenic. Qin et al. found that 142 novel microbiota taxa were present in the post-smog pharyngeal microbial community. These taxa came from various sources including soil, sewage sludge, and water resources (Figueras et al., 2017). These unanticipated differences in microbiota from pre- to post-smog episodes suggest that PM could act as a central core of adsorption and transport for microorganisms coming from a variety of foreign sources in the human respiratory tract.

The most abundant prokaryotic microorganisms found in PM2. 5 and PM10 pollution are bacteria. The most common phyla of PM are *Actinobacteria* (including *Proteobacteria*), *Chloroflexi* (including *Firmicutes*), *Bacteroidetes,* and *Euryarchaeota*. The bacteria in PM2. 5 and PM10 samples come from fecal or terrestrial sources. The classified bacterial species G. obscurus discovered on PM2. 5 is the most prevalent. During the highly polluted days, the overall abundance of adenovirus in PM2. 5 and PM10 appeared to have increased (Navarro & Martínez-Murcia, 2018). Particulate matter, Propionibacterium acnes, Escherichia coli, Acinetobacter lwoffii, Lactobacillus amylovorus, and Lactobacillus reuteri predominated among the airborne microbes. Ustilago maydis, Porcine type C oncovirus, Lactobacillus amylovorus, and Lactobacillus reuteri were the top four species, and their proportions in PM10 were much higher than those in PM2. 5. Since the makeup of the air microbiome is likely derived from a range of sources, its phylogenetic and functional diversity are comparable to those of the soil and water environments (Pessoa et al., 2019).

5 Role of particulate matter in antibiotic resistance

Microbiological dangers encompass the threat of antimicrobial resistance, where microorganisms evolve to resist the effects of antibiotics, rendering infections more difficult to treat effectively. PM2. 5 is a significant vector, which is mainly responsible for the spread of possible microbiological dangers. Antibiotic resistance is one of them, and it is a twenty-first century health challenge. Modern studies have shown the rise of extensively drug-resistant (XDR) and multidrug-resistant (MDR) bacterial infections from several sources, including humans, fish, poultry, animals, and other food products (Haghani et al., 2020). Antibiotic abuse and misuse have resulted in the rise of antibiotic resistance bacteria (ARB) and "superbugs" in recent years, rendering the treatments used to treat diseases useless (Tang et al., 2024).

The research by Algammal et al., (2023a, 2023b) (Wang et al., 2023) reveals the significant public health threat posed by the spread of highly drug-resistant *Pseudomonas aeruginosa* in grilled chickens. The cohabitation of virulence, Quorum sensing, and resistance genes is emphasized, highlighting the complex interplay between antimicrobial resistance and pathogenicity in poultry.

According to another study by Lin et al. (2022) and Mustață et al., (2023), multidrug-resistant Escherichia coli bacteria recovered from companion animals in a Shanghai veterinary hospital have mobile colistin resistance genes, suggesting a possible danger of transfer to human populations (Haghani et al., 2020).

As a result of the potential that resistance may spread to humans and its impact on the effectiveness of existing antibiotic therapy, antibiotic resistance is increasingly recognized as an emerging issue of significant public health concern. Antibiotic resistance has increased in incidence among numerous infectious diseases caused by bacteria (Mustață et al., 2023). Massive healthcare-associated MRSA (HA-MRSA) infections are mostly brought on by methicillin-resistant S. aureus (MRSA), which was initially discovered in 1962 and, together with specific Enterococcus species, are to blame for the global antibiotic resistance epidemic (Manigrasso et al., 2019).

The discovery of ARGs in bioaerosols has recently brought to light a more serious problem. The occurrence of ARGs may be associated with a rise in human respiratory illnesses, as highly aerosolized bacteria are believed to possess antibiotic resistance. The primary way that ARGs reach the human body is through inhalation through the respiratory tract (Lee et al., 2022). Human health may be at danger from inhaled or consumed ARGs, which is usually carried by atmospherically influenced bioaerosols (Chen et al., 2022). ARGs are emerging pollutants that could be dangerous to the health of individuals globally (Yoo et al., 2020). Medical interventions have been severely hampered by the development and rapid dissemination of ARGs, which have raised the cost of treating bacterial infections (Yang et al., 2018).

Antibiotic environmental factors promote the dispersion of antibiotic resistance genes by enhancing the survival of resistant microorganisms and facilitating gene transfer. Pollution, diverse microbial interactions, and ecological exposures contribute to this gene dispersion, amplifying antibiotic resistance concerns (Kumar & Thakur, 2022). In addition, the ARGs can be transferred from the air to humans via exposure paths such as inhalation. In the realm of biogeochemistry, Earth surface bacteria are introduced into the atmosphere through the process of soil resuspension, and they traverse significant distances carried by wind currents. The size of particulate matter linked with bacteria in locations is roughly 4 µm, larger than the normal size of such microorganisms, 1 µm (Tang et al., 2024).

As a result of their widespread dispersal, airborne bacterial populations may be subjected to physicochemical stressors that terrestrial counterparts are not. Therefore, PM2.5 is an important factor for propagating environmental ARGs. To measure their contributions, inhaling must be integrated as an inherent component of human exposure ARG routes. A better understanding of these elements would aid in developing intelligent mitigation measures for ARG sources and human exposure concerns, as well as addressing public health issues related to antibiotic resistance and the influence of bioaerosols.

A study has discovered that host bacterial communities, environmental factors, and anthropogenic factors all impact environmental resistome, resulting in distinct ARG profiles (Lowry et al., 2014). The resistome is an extensive, sophisticated, and adaptable network of genes which directly or indirectly inhibit antibiotic activity. *Aeromonas* bacteria are microorganisms that cause illness in animals and humans. *Aeromonas* resistance (AR) has been observed in clinical and environmental contexts (Gillings, 2013; Hu et al., 2017; Martínez et al., 2017). *Aeromonas* is a Gram-negative bacterium, rod-shaped, from 1 to 3 µm in length and from 0.3 to 1 um in width (LA ACADÉMICA et al.; Perry & Wright, 2013). The genus is a member of the *Aeromonadaceae* family and the *Gammaproteobacteria* class in the order *Aeromonadales* (Wright, 2010). These bacteria produce catalase and oxidase, and they can ferment glucose and liquid gelatin, but not inositol. They are classified as halophiles due to their ability to resist high salt chloride concentrations (0.3–5%) (Galán et al., 2013). Among other extracellular hydrolytic enzymes, they can produce amylases, deoxyribonucleases, peptidases, and lipase enzymes (Leclercq et al., 2013).

Antibiotic concentrations in the environment are increasing, particularly in human waste materials, whereby the process of gene coupling, in which the resistance genes evolved are coupled with antibiotics and other compounds, potentially contributes to the spread of antimicrobial resistance (Lekunberri et al., 2018). Horizontal gene transfer (HGT) events are produced when ambient bacteria are exposed to this mixture and its penetrability in new environments and hosts (Shintani & Biochemistry, 2017). As a result of the lack of a distinct biochemical classification system, identifying Aeromonas species using conventional methods is challenging (Zhang et al., 2020). Aeromonas bacterial infections are notoriously difficult to tackle due to their intrinsic resistance to beta-lactam antibiotics (Dubey & Ben-Yehuda, 2011; García-Aljaro et al., 2017).

Total environmental bacterial resistance genes, many of which are present in the soil, make up the resistome (Thomas & Nielsen, 2005). As a result of the ability for genes to be activated via the bacterial genome, the implications of evolution of resistance are important (Skippington & Ragan, 2011). There are two types: intrinsic (innate) and extrinsic. The intrinsic resistome can be defined as a group of genes on chromosomal chromosomes that are involved in innate resistance. Their presence in strains is not related to HGT or previous antibiotic exposure (Gandolfi et al., 2015; Hu et al., 2018).

Extrinsic genes are also a group of genes that have been acquired by numerous genome alterations and can be passed on from one generation to another in a stable way. All these genes can be passed on to bacteria, both pathogenic and non-pathogenic. This occurs in both humans and animals. The resistome is made up of naturally occurring genes (Thomas & Nielsen, 2005). The word “mobilome” refers to mobile elements that mobilize resistance genes in a range of genetic conditions (Shen et al., 2015). Enzymes involved in these occurrences are recombinases, which allow for homologous recombination as the host's encoded machinery that ensures genome integrity; transposases are enzymes that catalyze the movement and insertion of transposons, allowing for elements such as resistance cassettes to be inserted into integrins via site-specific recombination (Amann, 2008). Mobile elements that promote gene excision are responsible for expressing many enzymes. The importance of understanding these mechanisms of genetic material transmission in natural environments is increasing due to their implications for businesses such as the food industry, hospital and clinic settings, and aquaculture.

The transfer of DNA, particularly through horizontal gene transfer (HGT), plays a vital role in the evolution of bacteria. This transfer often involves genes that provide resistance to antibiotics and metals, allowing bacteria to adapt and survive in changing environments. The latter can improve a bacterium's fitness not just by allowing it to use novel substrates, but also by allowing it to flourish in otherwise harmful settings (Chen et al., 2013). Transformation, transduction, and conjugation are the three basic processes of DNA transfer described in prokaryotic species. Other techniques, including the presence of outer membrane vehicles, nanotubes (Qin et al., 2022), and virus-like gene transfer agents (Blanco et al., 2016), have recently been discovered, but have yet to be well understood and investigated. It is worth noting that there are various barriers to horizontal genetic transmission. For example, the restriction modification system detects foreign DNA and destroys it with restriction endonucleases, cleaving ds-DNA into short fragments that are further destroyed by other enzymes. Another barrier system is CRISPR, composed of DNA sequences found in prokaryotic genomes. It acts as a prokaryotic immune system, preventing the spread of plasmids and phage infections via the action of Cas proteins (CRISPR associated) (Pietramellara et al., 2013; Soler et al., 2016).

The number and variety of airborne ARGs were investigated using a metagenomics approach. ARGs were found in lower abundance in airborne PMs than in feces, but at similar amounts in soil and activated sludge. The resistome of various environments like particulate matter and soils has the same antibiotic resistance gene profiles; this demonstrates how an environment's attributes may affect an airborne ARG profile. Since bacteria mostly transmit ARGs, Hu, et al. (2018) hypothesized that bacteria originating from terrene could be a major source of airborne ARGs in smog, which is corroborated by earlier research (Nagler et al., 2018; Zoran et al., 2020). On smog days, the total number of detectable ARGs and a variety of airborne ARGs were higher than on non-smog sessions. This could be because, in hazy weather, industrial waste, soot, and automotive exhaust can offer bacterial adhesion sites, but PMs are easily suspended and difficult to deposit (Algammal et al., 2020). Inactivation of antibiotics is the most common resistance mechanism for common antibiotics such as aminoglycosides, lactams, and macrolides (Abolghait et al., 2020).

Previous studies show that in response to the increased selective pressure provided by several pollutants in human affected environments, airborne bacteria can evolve new resistance genes and mechanisms (Abdelazeem M Algammal et al., 2022a, 2022b). Membrane efflux proteins have been found to excrete a wide range of intracellular pollutants, including drugs and heavy metals (Abelazeem M Algammal et al., 2022a, 2022b). Interestingly, a study concluded that the increase in airborne ARGs during smog days is largely due to the accumulation in smog of lactam and aminoglycoside resistant genes. Tetracycline resistance may be prevalent due to its widespread use in treating human and animal ailments, and as a growth enhancer for cattle feed (A. Algammal et al., 2023a, 2023b).

The bacterial community, physicochemical variables, and climatic parameters can all impact profiles of airborne ARGs. *Lactobacillus and sul1* (sulfonamide resistance gene 1) are the cornerstones of the microbial taxonomy and ARG co-occurrence network in smog air. Since opportunistic diseases and some ARGs co-occur in PMs, severe smog can enhance the quantity and variety of airborne ARGs, potentially posing a health concern to local inhabitants. As has been repeatedly argued, to effectively lower PM levels, a variety of sectors having a stake in air quality management—including the health, environment, energy, transportation, and housing—must work together on a regional, national, and international level. More efforts should be made to prevent and control potential hazards caused by airborne AR bacteria and AR genes. To achieve an environment that is healthier and cleaner, public behavior must also be changed. This calls for effective communication and ongoing education.

6 Role of extracellular DNA in antibiotic resistance

Extracellular DNA, known as eDNA, is the nucleic acid content outside the living cells. Extracellular DNA (eDNA) is the DNA outside cell membranes, as opposed to intracellular DNA (iDNA), which is the DNA inside cell membranes. It is possible to find extracellular DNA (eDNA) in various environmental samples. eDNA is defined as "originating from intracellular DNA via active or passive extrusion mechanisms or by cell lysis" (Lin et al., 2022). Early in the 1950s, when it was discovered to be widespread in the environment, eDNA was investigated concerning horizontal gene transmission (HGT) and the capacity of bacteria to acquire antibiotic resistance by genetic modification with non-native (extracellular plasmid) DNA. eDNA was investigated concerning its ability to withstand nuclease degradation in the soil during the 1980s and 1990s by attaching to diverse soil components (A. M. Algammal et al., 2023a, 2023b).

Several studies have shown the importance of eDNA regarding PM and air pollution. eDNA, for example, has been shown to contribute to the diversity and composition of microbiota associated with PM, such as bacteria, fungi, and viruses. PM-associated DNA has been shown to have implications for the survival, colonization, and spread of microorganisms. eDNA from PM can also transfer genetic information to other organisms. This includes antibiotic resistance genes (ARGs), a concern for antimicrobial resistance (AMR) (Navarro & Martínez-Murcia, 2018). Antimicrobial resistance (AMR) is one of the top 10 hazards to global health. One issue that is acknowledged as a significant etiologic factor in the emergence of AMR is the abuse or misuse of antibiotics on a global scale. Statistics show that compared to high-income countries, low- and middle-income countries are leading the way in promoting AMR rates (Haghani et al., 2020).

The presence of ARGs within PM-associated eDNA raises concern about the possibility of horizontal gene transfer and the spread of antibiotic resistance. The airborne PM can travel a long distance and be inhaled by humans and pets, increasing the risk of ARG exposure. This has important implications for public safety and highlights the need to understand better the role of eDNA within PM in ARGs and the spread of AMR (Navarro & Martínez-Murcia, 2018; Wang et al., 2023).

Recent research has used advanced molecular methods, such as metagenomics, to study eDNA in the air. These techniques have given insights into the composition and abundance of eDNA within PM as well as its dynamics. They also provided information on the sources, transportation, and fates of eDNA. Nevertheless, there are still challenges in quantifying eDNA accurately, understanding its function, and assessing the potential risks associated with PM-associated eDNA. Considering the current explosive increase in microbial resistance to the antibiotics, this also necessitates uncovering the underpinnings of the smog's effect on AMR and developing effective strategies for mitigating these deleterious smog effects on health and environment.

7 Conclusions

Particulate matter is a principal pollutant present in smog and is a solid surface for various airborne microorganisms and a substrate for antibiotic resistance genes. ARGs on PM are involved in disseminating antibiotic resistance. Long-term PM exposure is associated with chronic effects such as respiratory diseases, cardiovascular, and immune system problems. Short-term side effects of PM include eye, skin, throat irritation, coughing, and breathing difficulties, as well as asthma, pneumonia, bronchitis, and neurological complications. eDNA in PM is a new area of research that has the potential to shed more light on complex interactions between microorganisms in the air and PM. eDNA within PM can impact the composition, diversity, and possible dissemination of microorganisms. Since opportunistic diseases and some ARGs co-occur with PM, severe smog can enhance the quantity and variety of airborne ARGs, potentially posing a health concern to the local inhabitants. New research on ARGs' occupancy on particulate matter during smog may aid in a better understanding of the general dispersion characteristics of airborne ARGs and serve as a guide for assessing the health concerns of smog.

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Declarations

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References

Abdul Jabbar, S., Tul Qadar, L., Ghafoor, S., Rasheed, L., Sarfraz, Z., Sarfraz, A., & Health, P. (2022). Air quality pollution and sustainability trends in South Asia: A population-based study. *International Journal of Environmental Research and Public Health, 19*(12), 7534.

Abelsohn, A., & Stieb, D. M. J. C. F. P. (2011). Health effects of outdoor air pollution: Approach to counseling patients using the air quality health index. *Canadian Family Physician, 57*(8), 881–887.

Abolghait, S. K., Fathi, A. G., Youssef, F. M., & Algammal, A. M. (2020). Methicillin-resistant staphylococcus aureus (MRSA) isolated from chicken meat and giblets often produces staphylococcal enterotoxin B (SEB) in non-refrigerated raw chicken livers. *International Journal of Food Microbiology, 328*, 108669.

Algammal, A. M., Enany, M. E., El-Tarabili, R. M., Ghobashy, M. O., & Helmy, Y. A. J. P. (2020). Prevalence, antimicrobial resistance profiles, virulence and enterotoxins-determinant genes of MRSA isolated from subclinical bovine mastitis in Egypt. *Pathogens, 9*(5), 362.

Algammal, A. M., Abo Hashem, M. E., Alfifi, K. J., Al-Otaibi, A. S., Alatawy, M., ElTarabili, R. M., & Resistance, D. (2022a). Sequence analysis, antibiogram profile, virulence and antibiotic resistance genes of XDR and MDR Gallibacterium anatis isolated from layer chickens in Egypt. *Infection and Drug Resistance, 15*, 4321–4334.

Algammal, A. M., Ibrahim, R. A., Alfifi, K. J., Ghabban, H., Alghamdi, S., Kabrah, A., & Donadu, M. G. J. P. (2022b). A first report of molecular typing, virulence traits, and phenotypic and genotypic resistance patterns of newly emerging XDR and MDR Aeromonas veronii in Mugil seheli. *Pathogens, 11*(11), 1262.

Algammal, A., Hetta, H. F., Mabrok, M., & Behzadi, P. J. (2023a). Emerging multidrug-resistant bacterial pathogens “superbugs”: A rising public health threat. *Frontiers in Microbiology, 14*, 1135614.

Algammal, A. M., Eidaroos, N. H., Alfifi, K. J., Alatawy, M., Al-Harbi, A. I., Alanazi, Y. F., Resistance, D. (2023). opr L gene sequencing, resistance patterns, virulence genes, quorum sensing and antibiotic resistance genes of XDR Pseudomonas aeruginosa isolated from broiler chickens. 853–867.

Altowayti, W. A. H., Shahir, S., Othman, N., Eisa, T. A. E., Yafooz, W. M., Al-Dhaqm, A., & Abaker, M. J. P. (2022). The role of conventional methods and artificial intelligence in the wastewater treatment: A comprehensive review. *Processes, 10*(9), 1832.

Amann, M. (2008). Health risks of ozone from long-range transboundary air pollution. WHO Regional Office Europe.

Arias-Pérez, R. D., Taborda, N. A., Gómez, D. M., Narvaez, J. F., Porras, J., & Hernandez, J. C. (2020). Inflammatory effects of particulate matter air pollution. *Environmental Science and Pollution Research, 27*(34), 42390–42404.

Ashraf, A., Butt, A., Khalid, I., Alam, R. U., Ahmad, S. R. J. A., & e. (2019). Smog analysis and its effect on reported ocular surface diseases: A case study of 2016 smog event of Lahore. *Atmospheric Environment, 198*, 257–264.

Bezirtzoglou, C., Dekas, K., & Charvalos, E. J. A. (2011). Climate changes, environment and infection: Facts, scenarios and growing awareness from the public health community within Europe. *Anaerobe, 17*(6), 337–340.

Blanco, P., Hernando-Amado, S., Reales-Calderon, J. A., Corona, F., Lira, F., Alcalde-Rico, M., & Martinez, J. L. J. M. (2016). Bacterial multidrug efflux pumps: Much more than antibiotic resistance determinants. *Microorganisms, 4*(1), 14.

Boschi, N. (2012). Defining an educational framework for indoor air sciences education. In *Education and Training in Indoor Air Sciences* (pp. 3–6). Springer.

Cacciottolo, M., Wang, X., Driscoll, I., Woodward, N., Saffari, A., Reyes, J., & Morgan, T. E. J. T. P. (2017). Particulate air pollutants, APOE alleles and their contributions to cognitive impairment in older women and to amyloidogenesis in experimental models. *Translational Psychiatry, 7*(1), e1022–e1022.

Cairns, B. J., & Baigent, C. (2014). Air pollution and traffic noise: Do they cause atherosclerosis? *European Heart Journal, 35*(13), 826–828.

Cao, C., Jiang, W., Wang, B., Fang, J., Lang, J., & Tian, G. (2014). Inhalable microorganisms in Beijing’s PM2. 5 and PM10 pollutants during a severe smog event. *Environmental Science & Technology, 48*(3), 1499–1507.

Caples, S. M., Rowley, J. A., Prinsell, J. R., Pallanch, J. F., Elamin, M. B., Katz, S. G., & Harwick, J. D. J. S. (2010). Surgical modifications of the upper airway for obstructive sleep apnea in adults: A systematic review and meta-analysis. *Sleep, 33*(10), 1396–1407.

Castelli, F., & Sulis, G. J. C. M. (2017). Migration and infectious diseases. *Clinical Microbiology and Infection, 23*(5), 283–289.

Chen, B., Yang, Y., Liang, X., Yu, K., Zhang, T., & Li, X. (2013). Metagenomic profiles of antibiotic resistance genes (ARGs) between human impacted estuary and deep ocean sediments. *Environmental Science & Technology, 47*(22), 12753–12760.

Chen, J., Chen, H., Wu, Z., Hu, D., & Pan, J. Z. J. I. S. (2017). Forecasting smog-related health hazard based on social media and physical sensor. *Information Systems, 64*, 281–291.

Chen, P., Guo, X., & Li, F. (2022). Antibiotic resistance genes in bioaerosols: Emerging, non-ignorable and pernicious pollutants. *Journal of Cleaner Production, 348*, 131094.

Cheung, K., Daher, N., Kam, W., Shafer, M. M., Ning, Z., Schauer, J. J., & Sioutas, C. J. A. (2011). Spatial and temporal variation of chemical composition and mass closure of ambient coarse particulate matter (PM10–2. 5) in the Los Angeles area. *Atmospheric Environment, 45*(16), 2651–2662.

Clarke, K., Manrique, A., Sabo-Attwood, T., & Coker, E. S. (2021). A narrative review of occupational air pollution and respiratory health in farmworkers. *IJERPH, 18*(8), 4097.

Claude, J. A., Grimm, A., Savage, H. P., & Pinkerton, K. E. J. I. (2012). Perinatal exposure to environmental tobacco smoke (ETS) enhances susceptibility to viral and secondary bacterial infections. *International Journal of Environmental Research and Public Health, 9*(11), 3954–3964.

Czerwińska, J., Wielgosiński, G. J. J., & o. E. E. (2020). The effect of selected meteorological factors on the process of "Polish smog" formation. *Journal of Ecological Engineering, 21*(1), 180.

D'amato, G., Pawankar, R., Vitale, C., Lanza, M., Molino, A., & Stanziola, A. (2016). Climate change and air pollution: effects on respiratory allergy. *Allergy, Asthma & Immunology Research, 8*(5), 391–395.

Do, T. T., Murphy, S., & Walsh, F. (2017). Antibiotic resistance and wastewater treatment process. *Antimicrobial Resistance in Wastewater Treatment Processes*. https://doi.org/10.1002/9781119192428.ch15

Douglas, P., Robertson, S., Gay, R., Hansell, A. L., & Gant, T. W. (2018). A Systematic review of the public health risks of bioaerosols from intensive farming. *International Journal of Hygiene and Environmental Health, 221*(2), 134–173.

Dubey, G. P., & Ben-Yehuda, S. J. C. (2011). Intercellular nanotubes mediate bacterial communication. *Cell, 144*(4), 590–600.

Eze, I. C., Schaffner, E., Fischer, E., Schikowski, T., Adam, M., Imboden, M., & Probst-Hensch, N. (2014). Long-term air pollution exposure and diabetes in a population-based Swiss cohort. *Environment International, 70*, 95–105.

Fares, S., Vargas, R., Detto, M., Goldstein, A. H., Karlik, J., Paoletti, E., & Vitale, M. J. G. C. B. (2013). Tropospheric ozone reduces carbon assimilation in trees: Estimates from analysis of continuous flux measurements. *Global Change Biology, 19*(8), 2427–2443.

Figueras, M., Alperi, A., Beaz-Hidalgo, R., Stackebrandt, E., Brambilla, E., & Monera, A. (2011). Aeromonas rivuli sp. nov., isolated from the upstream region of a karst water rivulet. *International Journal of Systematic and EvolutionaryMicrobiology, 61*(2), 242–248.

Figueras, M., Latif-Eugenín, F., Ballester, F., Pujol, I., Tena, D., & Berg, K. (2017). 'Aeromonas intestinalis' and 'Aeromonas enterica'isolated from human faeces, 'Aeromonas crassostreae'from oyster and 'Aeromonas aquatilis' isolated from lake water represent novel species. *New Microbes and New Infections, 15*, 74–76.

Galán, J.-C., González-Candelas, F., Rolain, J.-M., & Cantón, R. (2013). Antibiotics as selectors and accelerators of diversity in the mechanisms of resistance: From the resistome to genetic plasticity in the β-lactamases world. *Frontiers in Microbiology*. https://doi.org/10.3389/fmicb.2013.00009

Gandolfi, I., Bertolini, V., Bestetti, G., Ambrosini, R., Innocente, E., & Rampazzo, G. (2015). Spatio-temporal variability of airborne bacterial communities and their correlation with particulate matter chemical composition across two urban areas. *Applied Microbiology and Biotechnology, 99*, 4867–4877.

García-Aljaro, C., Ballesté, E., & Muniesa, M. J. C. O. (2017). Beyond the canonical strategies of horizontal gene transfer in prokaryotes. *Current Opinion in Microbiology, 38*, 95–105.

Geddes, J. A., & Murphy, J. G. (2012). The science of smog: A chemical understanding of ground level ozone and fine particulate matter. *Metropolitan sustainability*. Elsevier. https://doi.org/10.1533/9780857096463.3.205

Gillings, M. R. J. F. (2013). Evolutionary consequences of antibiotic use for the resistome, mobilome and microbial pangenome. *Frontiers in Microbiology*. https://doi.org/10.3389/fmicb.2013.00004

Grabiec, A. M., & Hussell, T. (2016). The role of airway macrophages in apoptotic cell clearance following acute and chronic lung inflammation. *Seminars in Immunopathology*. https://doi.org/10.1007/s00281-016-0555-3

Guo, Y., Zeng, H., Zheng, R., Li, S., Pereira, G., Liu, Q., & Huxley, R. (2017). The burden of lung cancer mortality attributable to fine particles in China. *Science of the Total Environment, 579*, 1460–1466.

Haghani, A., Johnson, R., Safi, N., Zhang, H., Thorwald, M., Mousavi, A., & Finch, C. E. (2020). Toxicity of urban air pollution particulate matter in developing and adult mouse brain: Comparison of total and filter-eluted nanoparticles. *Environment International, 136*, 105510.

Hahad, O., Lelieveld, J., Birklein, F., Lieb, K., Daiber, A., & Münzel, T. J. I. (2020). Ambient air pollution increases the risk of cerebrovascular and neuropsychiatric disorders through induction of inflammation and oxidative stress. *International Journal of Molecular Sciences, 21*(12), 4306.

Han, Y., Yang, T., Xu, G., Li, L., & Liu, J. (2020). Characteristics and interactions of bioaerosol microorganisms from wastewater treatment plants. *Journal of Hazardous Materials, 391*, 122256.

He, T., Jin, L., Xie, J., Yue, S., Fu, P., Li, X. J. E. S., & Letters, T. (2021). Intracellular and extracellular antibiotic resistance genes in airborne PM2. 5 for respiratory exposure in urban areas. *Environmental Science & Technology Letters, 8*(2), 128–134.

Hu, J., Zhao, F., Zhang, X.-X., Li, K., Li, C., Ye, L., & Li, M. (2018). Metagenomic profiling of ARGs in airborne particulate matters during a severe smog event. *Science of the Total Environment, 615*, 1332–1340.

Hu, Y., Gao, G. F., & Zhu, B. J. F. (2017). The antibiotic resistome: Gene flow in environments, animals and human beings. *Frontiers of Medicine, 11*, 161–168.

Ilyas, S. Z., Nasir, S., Raza, S. J. J. o. A. S., & Management, E. (2008). Air pollution problems and diseases caused by hazardous gases in Quetta, Pakistan. *12*(1).

Jedrychowski, W., Galas, A., Pac, A., Flak, E., Camman, D., Rauh, V., & Perera, F. J. E. (2005). Prenatal ambient air exposure to polycyclic aromatic hydrocarbons and the occurrence of respiratory symptoms over the first year of life. *European Journal of Epidemiology, 20*, 775–782.

Jia, H., & Wang, L. (2017). Peering into China's thick smog. *C&EN Global Enterprise, 95*(4), 19–22.

Kappos, A. D., Bruckmann, P., Eikmann, T., Englert, N., Heinrich, U., & Höppe, P. (2004). Health effects of particles in ambient air. *International Journal of Hygiene and Environmental Health, 207*(4), 399–407.

Kaun, A., & Uldam, J. (2018). Digital activism: After the hype. *New Media & Society, 20*(6), 2099–2106.

Kennedy, C. M., Pennington, A. F., Darrow, L. A., Klein, M., Zhai, X., Bates, J. T., & Strickland, M. J. J. E. E. (2018). Associations of mobile source air pollution during the first year of life with childhood pneumonia, bronchiolitis, and otitis media. *Environmental Epidemiology, 2*(1), e007.

Kloog, I., Ridgway, B., Koutrakis, P., Coull, B. A., & Schwartz, J. D. (2013). Long-and short-term exposure to PM2. 5 and ortality: Using novel exposure models. *Epidemiology, 24*(4), 555–561.

Kryzia, D., & Pepłowska, M.J.P.E.-E.P.J. (2019). The impact of measures aimed at reducing low-stack emission in Poland and on energy efficiency and the household emission of pollutants. *Polityka Energetyczna Energy Policy Journal, 22*, 121–132.

Kumar, R., & Thakur, A. J. M. M. (2022). Younis Ahmad Hajam, Rahul Datta, Sonika, Ajay Sharma. 93.

LA ACADÉMICA, D. N. E., DE, D. L. E. E. A., EL, S. R. A., & DE NÚMERO, Y. P. LA RESISTENCIA BACTERIANA A LOS ANTIBIÓTICOS, SIETE DÉCADAS DESPUÉS DE FLEMING.

Leary, P. J., Kaufman, J. D., Barr, R. G., Bluemke, D. A., Curl, C. L., & Hough, C. L. (2014). Traffic-related air pollution and the right ventricle The multi-ethnic study of atherosclerosis. *American Journal of Respiratory and Critical Care Medicine, 189*(9), 1093–1100.

Leclercq, R., Cantón, R., Brown, D. F., Giske, C. G., Heisig, P., & MacGowan, A. P. (2013). EUCAST expert rules in antimicrobial susceptibility testing. *Clinical Microbiology and Infection, 19*(2), 141–160.

Lee, G. K., & Yoo. (2022). A Review of the emergence of antibiotic resistance in bioaerosols and its monitoring methods. *Reviews in Environmental Science and Bio/technology, 21*(3), 799–827.

Lekunberri, I., Balcázar, J. L., & Borrego, C. M. J. E. (2018). Metagenomic exploration reveals a marked change in the river resistome and mobilome after treated wastewater discharges. *Environmental Pollution, 234*, 538–542.

Li, B., Zhou, Y., Zhang, T., & Liu, Y. J. A. (2021). The impact of smog pollution on audit quality: Evidence from China. *Atmosphere, m, 12*(8), 1015.

Lin, H., Chen, W., Zhou, R., Yang, J., Wu, Y., Zheng, J., & Li, J. J. F. (2022). Characteristics of the plasmid-mediated colistin-resistance gene mcr-1 in Escherichia coli isolated from a veterinary hospital in Shanghai. *Frontiers in Microbiology, 13*, 1002827.

Loaiza-Ceballos, M. C., Marin-Palma, D., Zapata, W., & Hernandez, J. C. (2022). Viral respiratory infections and air pollutants. *Air Quality Atmosphere Health, 15*(1), 105–114.

Lorenzini, G., & Saitanis, C. (2003). Ozone: a novel plant "pathogen." In L. Sanità, B. di Toppi, & Pawlik-Skowrońska (Eds.), *Abiotic stresses in plants* (pp. 205–229). Dordrecht: Springer. https://doi.org/10.1007/978-94-017-0255-3_8

Lowry, R., Balboa, S., Parker, J. L., & Shaw, J. G. (2014). Aeromonas flagella and colonisation mechanisms. *Advances in Bacterial Pathogen Biology* (pp. 203–256). Elsevier. https://doi.org/10.1016/bs.ampbs.2014.08.007

Manigrasso, M., Protano, C., Vitali, M., & Avino, P. (2019). Where do ultrafine particles and nano-sized particles come from? *Journal of Alzheimer's Disease, 68*(4), 1371–1390. https://doi.org/10.3233/JAD-181266

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and health impacts of air pollution: A review. *Frontiers in Public Health*. https://doi.org/10.3389/fpubh.2020.00014

Mannucci, P., & Franchini, M. (2017). Health effects of ambient air pollution in developing countries. *International Journal of Environmental Research and Public Health, 14*(9), 1048. https://doi.org/10.3390/ijerph14091048

Martínez, J. L., Coque, T. M., Lanza, V. F., de la Cruz, F., & Baquero, F. (2017). Genomic and metagenomic technologies to explore the antibiotic resistance mobilome. *Annals of the New York Academy of Sciences, 1388*(1), 26–41. https://doi.org/10.1111/nyas.13282

Matus, K., Nam, K. M., Selin, N. E., Lamsal, L. N., Reilly, J. M., & Paltsev, S. (2012). Health damages from air pollution in China. *Global Environmental Change, 22*(1), 55–66. https://doi.org/10.1016/j.gloenvcha.2011.08.006

Mira-Salama, D., Grüning, C., Jensen, N. R., Cavalli, P., Putaud, J.-P., Larsen, B. R., Raes, F., & Coe, H. (2008). Source attribution of urban smog episodes caused by coal combustion. *Atmospheric Research, 88*(3–4), 294–304. https://doi.org/10.1016/j.atmosres.2007.11.025

Mostafaei, S., Sayad, B., Azar, M. E. F., Doroudian, M., Hadifar, S., Behrouzi, A., Riahi, P., Hussen, B. M., Bayat, B., Nahand, J. S., & Moghoofei, M. (2021). The role of viral and bacterial infections in the pathogenesis of IPF: A systematic review and meta-analysis. *Respiratory Research*. https://doi.org/10.1186/s12931-021-01650-x

Mousavi, M., Soltanieh, M., & Badakhshan, A. J. E. (1999). Influence of turbulence and atmospheric chemistry on grid size with respect to location in modeling and simulation of photochemical smog formation and transport. *Environmental Modelling & Software, 14*(6), 657–663.

Mustață, D.-M., Ionel, I., Popa, R.-M., Dughir, C., & Bisorca, D. J. A. S. (2023). A Study on particulate matter from an area with high traffic intensity. *Applied Sciences, 13*(15), 8824.

Nagler, M., Insam, H., Pietramellara, G., & Ascher-Jenull, J. (2018). Extracellular DNA in natural environments: Features, relevance and applications. *Applied Microbiology and Biotechnology, 102*(15), 6343–6356. https://doi.org/10.1007/s00253-018-9120-4

Navarro, A., Martínez-Murcia, A. J. J., & o. a. m. (2018). Phylogenetic analyses of the genus Aeromonas based on housekeeping gene sequencing and its influence on systematics. *Journal of Applied Microbiology, 125*(3), 622–631.

Parsajou, H., & Nasrabadi, T. (2021). Evaluation of greenhouse gases emission and human health risk levels due to operation and maintenance of sareyn city wastewater treatment plant. *Journal of Environmental Studies., 47*(1), 45–64.

Pastuszka, J. S., Rogula-Kozłowska, W., & Zajusz-Zubek, E. (2010). Characterization of PM10 and PM2. 5 and associated heavy metals at the crossroads and urban background site in Zabrze, Upper Silesia, Poland, during the smog episodes. *Environmental Monitoring and Assessment., 168*, 613–627.

Perry, J. A., & Wright, G. D. (2013). The antibiotic resistance "mobilome": Searching for the link between environment and clinic. *Frontiers in Microbiology., 30*(4), 138.

Pessoa, R. B., de Oliveira, W. F., Marques, D. S., dos Santos Correia, M. T., de Carvalho, E. V., & Coelho, L. C. (2019). The genus aeromonas: A general approach. *Microbial Pathogenesis., 1*(130), 81–94.

Pietramellara, G., Ascher, J., Baraniya, D., Arfaioli, P., Ceccherini, M. T., & Hawes, M. (2013). Relevance of extracellular DNA in rhizosphere. In: EGU General Assembly Conference Abstracts

Qin, N., Liang, P., Wu, C., Wang, G., Xu, Q., Xiong, X., Wang, T., Zolfo, M., Segata, N., Qin, H., & Knight, R. (2020). Longitudinal survey of microbiome associated with particulate matter in a megacity. *Genome Biology., 21*, 1–1.

Qin, S., Xiao, W., Zhou, C., Pu, Q., Deng, X., Lan, L., Liang, H., Song, X., & Wu, M. (2022). Pseudomonas aeruginosa: Pathogenesis, virulence factors, antibiotic resistance, interaction with host, technology advances and emerging therapeutics. *Signal Transduction and Targeted Therapy., 7*(1), 199.

Qin, T., Zhang, F., Zhou, H., Ren, H., Du, Y., Liang, S., Wang, F., Cheng, L., Xie, X., Jin, A., & Wu, Y. (2019). High-level PM2. 5/PM10 exposure is associated with alterations in the human pharyngeal microbiota composition. *Frontiers in Microbiology., 28*(10), 54.

Rahoma, U. A., & Emara, E. (2010). Health impacts estimation of mineralogical and chemical characterization of suspended atmospheric particles over the east desert. *American Journal of Infectious Diseases, 6*(4), 75.

Raza, W., Saeed, S., Saulat, H., Gul, H., Sarfraz, M., Sonne, C., Sohn, Z. H., Brown, R. J., & Kim, K. H. (2021). A review on the deteriorating situation of smog and its preventive measures in Pakistan. *Journal of Cleaner Production., 10*(279), 123676.

Reizer, M., & Juda-Rezler, K. (2016). Explaining the high PM 10 concentrations observed in polish urban areas. *Air Quality, Atmosphere & Health., 9*, 517–531.

Rice, M. B., Rifas-Shiman, S. L., Oken, E., Gillman, M. W., Ljungman, P. L., Litonjua, A. A., Schwartz, J., Coull, B. A., Zanobetti, A., Koutrakis, P., & Melly, S. J. (2015). Exposure to traffic and early life respiratory infection: a cohort study. *Pediatric Pulmonology., 50*(3), 252–259.

Shao, J., Zosky, G. R., Wheeler, A. J., Dharmage, S., Dalton, M., Williamson, G. J., O'Sullivan, T., Chappell, K., Knibbs, L. D., & Johnston, F. H. (2020). Exposure to air pollution during the first 1000 days of life and subsequent health service and medication usage in children. *Environmental Pollution., 1*(256), 113340.

Shen, X. J., Sun, J. Y., Zhang, X. Y., Zhang, Y. M., Zhang, L., Che, H. C., Ma, Q. L., Yu, X. M., Yue, Y., & Zhang, Y. W. (2015). Characterization of submicron aerosols and effect on visibility during a severe haze-fog episode in Yangtze River Delta. *China. Atmospheric Environment., 1*(120), 307–316.

Shintani, M. (2017). The behavior of mobile genetic elements (MGEs) in different environments. *Bioscience, Biotechnology, and Biochemistry., 81*(5), 854–862.

Singh, N. K., Sanghvi, G., Yadav, M., Padhiyar, H., & Thanki, A. (2021). A state-of-the-art review on wwtp associated bioaerosols: Microbial diversity, potential emission stages, dispersion factors, and control strategies. *Journal of Hazardous Materials, 410*, 124686.

Sivakumar, S., & Ramya, V. (2021). A review on air quality parameters for ambient pollution management framework. *REVISTA GEINTEC-GESTAO INOVACAO E TECNOLOGIAS., 11*(4), 149–181.

Skippington, E., & Ragan, M. A. (2011). Lateral genetic transfer and the construction of genetic exchange communities. *FEMS Microbiology Reviews., 35*(5), 707–735.

Soh, S. E., Goh, A., Teoh, O. H., Godfrey, K. M., Gluckman, P. D., Shek, L. P., & Chong, Y. S. (2018). Pregnancy trimester-specific exposure to ambient air pollution and child respiratory health outcomes in the first 2 years of life: effect modification by maternal pre-pregnancy BMI. *International Journal of Environmental Research and Public Health., 15*(5), 996.

Sokhi, R. S., Moussiopoulos, N., Baklanov, A., Bartzis, J., Coll, I., Finardi, S., Friedrich, R., Geels, C., Grönholm, T., & Halenka, T. (2021). Advances in air quality research-current and emerging challenges. *Atmospheric Chemistry and Physics Discussions, 2021*, 1–133.

Soler, L., Miller, I., Hummel, K., Razzazi-Fazeli, E., Jessen, F., Escribano, D., & Niewold, T. (2016). Growth promotion in pigs by oxytetracycline coincides with down regulation of serum inflammatory parameters and of hibernation-associated protein HP-27. *Electrophoresis, 37*(10), 1277–1286.

Srinamphon, P., Chernbumroong, S., & Tippayawong, K. Y. J. S. (2022). The effect of small particulate matter on tourism and related SMEs in Chiang mai Thailand. *Sustainability, 14*(13), 8147.

Stansfeld, S. A. (2015). Noise effects on health in the context of air pollution exposure. *International Journal of Environmental Research and Public Health, 12*(10), 12735–12760.

Sun, C., Yuan, X., & Yao, X. (2016). Social acceptance towards the air pollution in China: evidence from public's willingness to pay for smog mitigation. *Energy Policy, 1*(92), 313–324.

Sun, X., Li, D., Li, B., Sun, S., Geng, J., Ma, L., & Qi, H. (2021). Exploring the effects of haze pollution on airborne fungal composition in a cold megacity in Northeast China. *Journal of Cleaner Production., 20*(280), 124205.

Tang, Y.-W., Hindiyeh, M. Y., Liu, D., Sails, A., Spearman, P., & Zhang, J.-R. J. M. M. M. (2024). Molecular medical microbiology—from bench to bedside. 1–6.

Thomas, C. M., & Nielsen, K. M. (2005). Mechanisms of, and barriers to, horizontal gene transfer between bacteria. *Nature Reviews Microbiology, 3*(9), 711–721.

Thomas, W., & Daud, A. M. (2023). Impact of meteorological conditions on airborne particulates (PM2. 5 & PM10) Concentration on Universiti Tun Hussein Onn Malaysia (UTHM) Ambient. *Recent Trends in Civil Engineering and Built Environment, 4*(3), 31–38.

Troeger, C., Blacker, B., Khalil, I. A., Rao, P. C., Cao, J., Zimsen, S. R., Albertson, S. B., Deshpande, A., Farag, T., Abebe, Z., & Adetifa, I. M. (2018). Estimates of the global, regional, and national morbidity, mortality, and aetiologies of lower respiratory infections in 195 countries, 1990–2016: A systematic analysis for the Global Burden of Disease Study 2016. *The Lancet Infectious Diseases, 18*(11), 1191–1210.

Velasco, R. P., & Jarosińska, D. (2022). Update of the WHO global air quality guidelines: Systematic reviews–an introduction. *Environment International, 1*(170), 107556.

Wang, L. (2019). Discussion about the Health Effects, Causes, and Probable Solutions to the Air Pollutions Caused by Vehicle Exhaust Emissions. IOP Conference Series: Earth and Environmental Science,

Wang, H.-H., Zhang, S.-C., Wang, J., Chen, X., Yin, H., & Huang, D.-Y. (2020). Combined toxicity of outdoor air pollution on kidney function among adult women in Mianyang City Southwest China. *Chemosphere, 238*, 124603.

Wang, J., Hipel, K. W., & Dang, Y. (2017). An improved grey dynamic trend incidence model with application to factors causing smog weather. *Expert Systems with Applications, 30*(87), 240–251.

Wang, Q., Hou, Z., Li, L., Guo, S., Liang, H., Li, M., Luo, H., Wang, L., Luo, Y., & Ren, H. (2022). Seasonal disparities and source tracking of airborne antibiotic resistance genes in Handan, China. *Journal of Hazardous Materials, 15*(422), 126844.

Wang, R., Liu, J., Qin, Y., Chen, Z., Li, J., Guo, P., Shan, L., Li, Y., Hao, Y., Jiao, M., & Qi, X. (2023). Global attributed burden of death for air pollution: Demographic decomposition and birth cohort effect. *Science of the Total Environment, 20*(860), 160444.

Watson, J. T., Gayer, M., & Connolly, M. A. (2007). Epidemics after natural disasters. *Emerging Infectious Diseases, 13*(1), 1.

Wielgosiński, G., Czerwińska, J., Namiecińska, O., & Cichowicz, R. (2018). Smog episodes in the Lodz agglomeration in the years 2014–17. E3S web of conferences,

Wielgosiński, G., & Czerwińska, J. J. A. (2020). Smog episodes in Poland. *11*(3), 277.

Wilson, W. E., & Suh, H. H. (1997). Fine particles and coarse particles: Concentration relationships relevant to epidemiologic studies. *Journal of the Air & Waste Management Association, 47*(12), 1238–1249.

Wright, G. D. J. E. o. o. d. d. (2010). The antibiotic resistome. *5*(8), 779–788.

Xiong, G., & Luo, Y. (2021). Smog, media attention, and corporate social responsibility—empirical evidence from Chinese polluting listed companies. *Environmental Science and Pollution Research., 28*, 46116–46129.

Yadav, S., & Rawal, G. J. I. J. I. R. M. (2016). The great Delhi smog. *1*, 78-79.

Yang, Y., Zhou, R., Chen, B., Zhang, T., Hu, L., & Zou, S. (2018). Characterization of airborne antibiotic resistance genes from typical bioaerosol emission sources in the urban environment using metagenomic approach. *Chemosphere, 213*, 463–471.

Yang, Z., & Wang, J. (2017). A new air quality monitoring and early warning system: Air quality assessment and air pollutant concentration prediction. *Environmental Research., 1*(158), 105–117.

Yegambaram, M., Manivannan, B., Beach, T. G., & Halden, U. (2015). Role of environmental contaminants in the etiology of Alzheimer's disease: A review. *Current Alzheimer Research, 12*(2), 116–146.

Ying, Q., Fraser, M. P., Griffin, R. J., Chen, J., & Kleeman, M. J. (2007). Verification of a source-oriented externally mixed air quality model during a severe photochemical smog episode. *Atmospheric Environment, 41*(7), 1521–1538.

Yoo, K., Lee, T. K., Choi, E. J., Yang, J., Shukla, S. K., Hwang, S.-I., & Park, J. (2017). Molecular approaches for the detection and monitoring of microbial communities in bioaerosols: A review. *Journal of Environmental Sciences, 51*, 234–247.

Yoo, K., Yoo, H., Lee, J., Choi, E. J., & Park, J. (2020). Exploring the antibiotic resistome in activated sludge and anaerobic digestion sludge in an urban wastewater treatment plant via metagenomic analysis. *Journal of Microbiology, 58*, 123–130.

Yu, Y., Dai, C., Wei, Y., Ren, H., & Zhou, J. (2022). Air pollution prevention and control action plan substantially reduced PM2. 5 concentration in China. *Energy Economics, 1*(113), 106206.

Zhan, D., Kwan, M. P., Zhang, W., Yu, X., Meng, B., & Liu, Q. (2018). The driving factors of air quality index in China. *Journal of Cleaner Production, 1*(197), 1342–1351.

Zhang, G.-H., Zhu, Q.-H., Zhang, L., Yong, F., Zhang, Z., Wang, S.-L., & Tao, G.-H.J.N.C. (2020). High-performance particulate matter including nanoscale particle removal by a self-powered air filter. *Nature Communications, 11*(1), 1653.

Zhang, L., Yang, Y., Li, Y., Qian, Z. M., Xiao, W., Wang, X., Rolling, C. A., Liu, E., Xiao, J., Zeng, W., & Liu, T. (2019). Short-term and long-term effects of PM2. 5 on acute nasopharyngitis in 10 communities of Guangdong China. *Science of the Total Environment., 688*, 136–142.

Zhang, S., Hu, J., Xiao, G., Chen, S., & Wang, H. (2023). Urban particulate air pollution linked to dyslipidemia by modification innate immune cells. *Chemosphere, 319*, 138040.

Zhang, X., Li, Z., Jiamin, H., Yan, L., He, Y., Li, X., Wang, M., Sun, X., & Hai, X. (2021). The biological and chemical contents of atmospheric particulate matter and implication of its role in the transmission of bacterial pathogenesis. *Environmental Microbiology, 23*(9), 5481–5486.

Zhou, M., He, G., Fan, M., Wang, Z., Liu, Y., Ma, J., Ma, Z., Liu, J., Liu, Y., Wang, L., & Liu, Y. (2015). Smog episodes, fine particulate pollution and mortality in China. *Environmental Research, 136*, 396–404. https://doi.org/10.1016/j.envres.2014.09.038

Zhu, Y., Xie, J., Huang, F., & Cao, L. (2020). Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China. *Science of the Total Environment, 727*, 138704.

Zoran, M. A., Savastru, R. S., Savastru, D. M., & Tautan, M. N. (2020). Assessing the relationship between surface levels of PM2. 5 and PM10 particulate matter impact on COVID-19 in Milan Italy. *Science of the Total Environment, 738*, 139825.