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Review of the Sources, Impacts, and Control of Fine Particulate Matter

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Abstract:

$PM_{2.5}$ pollution presents a severe threat to air quality and public health in China. The harmful components of PM2.5 are diverse, including black carbon, organic carbon, metal elements, polycyclic aromatic hydrocarbons, and others. Prolonged exposure to high concentrations of PM2.5 can lead to serious diseases such as lung cancer, heart disease, and stroke, as well as contribute to many lung and heart problems. Additionally, PM2.5 alters urban landscapes on multiple levels, affecting visibility, the appearance of buildings, plant health, residents' quality of life, and landscape perception. Therefore, taking good steps to control PM2.5 pollution is not only crucial for improving air quality, but also an urgent task for protecting public health and reducing health risks to the population. The main sources of PM2.5 in China include industrial emissions, vehicle exhaust, construction dust, and agricultural activities. PM2.5 source composition varies regionally and seasonally. In winter, because of higher heating needs and the widespread use of coal, coal-related emissions are an important source, especially in the north. In summer and autumn, however, motor vehicle and industrial emissions are more prominent. PM2.5 concentrations are affected by multiple factors, which mainly include meteorological conditions, topography, environmental factors, and the burning of fossil fuels. The key measures for PM2.5 pollution control include strengthening source control, promoting clean energy, improving traffic and industrial emission standards, expanding green areas, and improving urban planning.

Keywords: PM2.5; source apportionment methods; PM2.5 hazards; pollution control

1 Introduction

The issue of urban smog and its impact has become one of the key environmental concerns globally, particularly in regions experiencing rapid industrialization and urbanization [1]. Global burden of disease

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studies indicates that among the risk factors detrimental to human health, air pollution ranks as the fourth leading cause, with fine particulate matter (PM2.5) being the primary air pollutant, responsible for 4.14 million deaths globally, of which 1.42 million deaths occur in China [2]. $PM_{2.5}$ refers to fine particulate matter with an aerodynamic diameter of 2.5 μm or less and greater than 0.1 μm, consisting of a blend of various chemical components or substances [3]. Black carbon and organic carbon are the major harmful constituents of PM2.5, and the numerous metal elements and polycyclic aromatic hydrocarbons contained within PM2.5 have also been proven to be health-related. Apart from natural factors, such as meteorological conditions, humidity, and temperature changes, the formation of urban smog is closely linked to anthropogenic factors, including extensive industrial emissions during the industrialization process, traffic pollution, construction activities, and dust. These fine particles can penetrate deep into the human respiratory tract and even lungs, and long-term exposure to high-concentration smog environments can lead to an increased incidence of various respiratory diseases, such as chronic obstructive pulmonary disease (COPD) and asthma. Several cities in China frequently suffer from smog, resulting in significantly worse air quality, which is now a key factor harming people's lives, the environment, and the long-term development of society and the economy [4]. In response, the central government has prioritized the Beijing-Tianjin-Hebei region and surrounding areas in the national air pollution control efforts, introducing a series of specific pollution control measures. The air pollution control programs include the "Air Pollution Prevention and Control Action Plan" (The "Ten Measures") [5]. As a result of these measures, the annual average PM2.5 concentration in Beijing has decreased from 89.5 $\mu g/m^3$ to 33.0 $\mu g/m^3$. The number of deaths avoided due to the reduction in PM2.5 concentration has reached a total of 44,195, resulting in big financial benefits [2]. Given the massive population and rapid economic development in these cities, the improvement in air quality has direct health and quality-of-life implications for tens of millions of citizens, and the success of these control measures is instrumental to the overall air quality improvement of the country. [5].

2 Characteristics and Impacts of PM2.5

2.1 Physical and Chemical Properties of PM2.5

PM2.5 is a complex chemical mixture [3], and its components are in the air as solid or liquid suspensions. Due to their high surface-area-to-mass ratio, these particles can adsorb a variety of toxic chemicals and penetrate deep into the lungs, imposing a heavy load on the lungs, heart, and other organs, and may trigger inflammatory reactions. The chemical composition of PM2.5 can be classified into three types: the first type is soluble particles, including F^-, Cr^-, SO_4^{2-}, NH_4^+, Na^+, K^+, etc.; the second type is inorganic elements, including natural dust and metallic elements; the third type is carbon-containing compounds, including organic carbon (OC), elemental carbon (EC), and polycyclic aromatic hydrocarbons. The composition of particulate matter from different sources exhibits tremendous differences. For instance, primary pollutants, including atmospheric dust and sea salt particles, often include elements like Al, Fe, Ni, Zn, Cu, As, Cd, and Pb, while aerosols from secondary pollutants are full of ammonium salts, sulfate, and organic compounds [6]. In mass distribution, the main components of PM2.5 are SO_4^{2-}, NO_3^-, NH_4^+, sea salt, mineral dust, organic compounds, and black carbon or elemental carbon, each accounting for 10%–30% of the total mass. Due to the diversity and complexity of PM2.5's composition, its chemical and biological toxicity can be very different, and even at the same mass, its potential to harm health and the environment can be different.

2.2 Health Impacts of PM2.5 on the Human Body

Both short- and long-term exposures to many constituents of PM2.5 have been closely associated with disease incidence and mortality [7]. Black carbon and organic carbon are considered the significant deleterious components of PM2.5, particularly their negative impacts on health, even more so in cardiovascular diseases. The evidence for the harmful effects of black carbon is strongest. Exposure to black carbon increases the incidence and mortality risk for cardiovascular diseases.

The association of the health effects with various metal components in PM2.5 has also been an area of extensive study. Potassium, silicon, zinc, vanadium, and nickel are the elements for which most epidemiological data are available [8]. For example, potassium, derived from biomass combustion, is closely related to cardiovascular and respiratory health [9]; vanadium and nickel are significantly associated with cardiovascular disease mortality[10]. Toxicological studies and epidemiological findings complement each other, reinforcing the harmful effects of heavy metals and metalloid elements in PM2.5 on human health, particularly in terms of biological pathogenic mechanisms. For instance, related toxicological studies have revealed that nickel exposure in the environment may lead to health problems such as altered heart rate variability, delayed arrhythmia, bradycardia, and hypothermia [11]. Zinc shows a significant negative correlation with vasodilation and vasoconstriction, further supporting zinc's role as a potentially harmful component of PM2.5 [12].

Polycyclic aromatic hydrocarbons (PAHs), as one of the key components in PM2.5, have acute effects on human health primarily influenced by exposure concentration, duration, toxicity, and exposure route [13]. Short-term exposure to PAHs may impair lung function in asthma patients and promote thrombosis in coronary artery disease patients. Long-term exposure, however, is associated with various health problems, including carcinogenicity, teratogenicity, and genotoxicity. Individuals with long-term occupational exposure to PAHs, especially in industrial settings, face a significantly increased risk of skin cancer, lung cancer, bladder cancer, and gastrointestinal cancers [14]. Benzo[a]anthracene, benzo[a]pyrene, and dibenzo[a,h]anthracene are major carcinogens in $PM_{2.5}$ and high concentrations of these substances may pose serious health threats [14].

Research by Yang et al. further confirmed the negative impact of secondary inorganic aerosols (such as SO_4^{2-} and NO_3^-) on disease incidence and mortality. After adjusting for the confounding effects of PM2.5 concentration, exposure to SO_4^{2-} and NO_3^- was significantly associated with cardiovascular disease mortality, while exposure to NO_3^- was highly correlated with respiratory disease incidence. Guo et al. [15] pointed out that NO_3^- is a major risk factor for respiratory disease emergencies, and both NO_3^- and Cl^- contribute to the increase in the number of cardiovascular disease-related emergencies. The impact of Cl^- from secondary inorganic aerosols on cardiovascular disease hospital admissions is particularly significant in coastal areas, a phenomenon that has been effectively validated in studies conducted in Hong Kong [16].

Overall, the harmful components of PM2.5 are numerous, and their impact on human health spans multiple aspects. Components such as black carbon, organic carbon, metal elements, and polycyclic aromatic hydrocarbons, particularly the long-term health effects of exposure to these substances, highlight the complexity and hazard of PM2.5 pollution.

3 Main Sources of PM2.5

3.1 Source Apportionment

Source apportionment of particulate matter is an important field in air pollution research, and it typically employs three main methods: receptor models, emission inventory methods, and dispersion modeling [17].

Among them, receptor models examine chemical tracers in environmental samples and emission source samples to recognize pollution sources and their contributions to the environment, and are commonly applied in PM2.5 source apportionment research [18]. In comparison with emission inventory methods and dispersion modeling, the advantage of receptor models is that they do not require tracking the particle transport process or depending on specific emission data, terrain, and meteorological data. Therefore, receptor models are more suitable for source analysis of particulate matter in the ambient atmosphere. Common receptor models are Chemical Mass Balance (CMB), Positive Matrix Factorization (PMF), Principal Component Analysis (PCA), Factor Analysis (FA), and Multivariate Linear Model (UNMIX). These models can be selected flexibly based on various needs and conditions. The CMB model estimates the contribution of pollution sources by examining the chemical concentrations in the ambient air and matching them with known source profiles [19]; while PMF employs statistical methods to extract potential source categories via matrix factorization, which can better handle missing and outlier data and is superior when handling complex datasets [20]. Types of source profiles and species selection can significantly affect the source apportionment results, so the selection of appropriate source profiles is very critical when applying the CMB model. Since domestic source profiles are relatively scarce in China, most research adopts foreign source profiles [21], which will lead to deviations in the source apportionment results. Therefore, the development of local source profiles and direct testing of the primary pollution sources of local PM2.5 are crucial to improving the accuracy of source apportionment. Unlike the CMB model, the PMF model does not require source profile data and instead estimates the contribution of pollution sources through statistical analysis of the chemical composition of ambient particulate matter. The main advantage of PMF is its ability to handle complex data structures and provide reliable results even in the presence of missing data and outliers. The PMF method typically requires a large sample size, with studies involving larger sample sizes being more likely to yield accurate source apportionment results. Although the PMF method does not require source profile input, understanding the tracers of different pollution sources remains necessary. In addition to PMF, other receptor models that do not require source profile input include PCA, FA, and the UNMIX model (collectively referred to as the PPUF method). The PPUF method reveals the potential sources of particulate matter through statistical analysis of environmental samples. Many sample data are needed to ensure the reliability of the results. Depend-

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ing on the type of input species, the PPUF method can be classified into inorganic (including elements, ions, OC, EC), organic (including OC, EC, and organics), and integrated (including elements, ions, OC, EC, and organics) categories. The advantage of the PPUF method lies in its efficiency and flexibility; however, it also faces challenges in clearly separating source categories and determining the validity of the source apportionment results, particularly in identifying the number and types of sources.

The source inventory method is a method used to analyze and quantify the contribution of different pollution sources to atmospheric pollutant concentrations. The core idea of the source inventory method is to collect air quality data, along with information such as emission inventories, monitoring data, and meteorological conditions, to identify and quantify the contribution of different pollution sources to the concentration of atmospheric pollutants in a specific region or location, thereby helping to understand the distribution characteristics of pollution sources and the origins of pollutants [22].

Dispersion modeling is the prediction of the pollutant diffusion process in the atmosphere through the use of mathematical models. It can simulate the spatial distribution of pollutant concentrations from the source to the environment, and it can be utilized to learn the way pollutants diffuse under different meteorological and terrain conditions [23]. Dispersion modeling has the benefit of being capable of providing precise spatial distribution prediction, dynamic spatiotemporal analysis, and the assessment of pollution control effectiveness compared to the emission inventory method and receptor models. Dispersion modeling is more suitable for coping with complex environmental conditions, dynamic pollution sources, and fine simulation of the diffusion paths of localized pollution sources [24]. Dispersion models can be classified into different types based on the complexity of the simulation and application environments, and common models include the Gaussian model, Lagrangian diffusion model, and Eulerian diffusion model. The Gaussian model is the simplest and most popular model, which presumes that pollutant dispersion in the horizontal and vertical directions follows a Gaussian distribution. It is suitable for simple environmental conditions, e.g., flat terrain and homogeneous atmospheric conditions. This model has simple calculations but is poorly adaptive to complex meteorological conditions [25]. The Lagrangian diffusion model postulates that pollutants exist in the form of particles and calculates the concentration distribution by tracing the movement of pollutant particles. It is suitable for irregular emission sources and complex terrains. This method is more precise and can describe more complex diffusion paths [25]. The Eulerian diffusion model simulates the variation of pollutant concentrations in different space areas by adopting fixed grids, considering more meteorological factors and terrain features. It is suitable for large-scale regional air quality prediction [25]. Dispersion modeling faces several challenges and limitations. The diffusion of pollutants is governed by several factors, including wind speed, wind direction, atmospheric stability, terrain features, and emission rates. Thus, precise meteorological data is required for model predictions; however, in regions with limited meteorological monitoring, the lack of precise meteorological data can affect model performance.

Overall, the choice of a source apportionment method has to be based on the specific goals of the study, sample size, data conditions, and requirements for source profiles.

3.2 Sources of PM2.5 in China

China is one of the countries with the most serious air pollution in the world, particularly in large cities and industrialized regions where PM2.5 levels often exceed safety standards. Li et al. [26] conducted a source apportionment of PM2.5 in certain Chinese cities, and the results revealed that the major sources of PM2.5 include several factors, among which coal combustion, motor vehicle emissions, and industrial emissions are the main contributors. Coal combustion is a major contributor to PM2.5, especially in the north. In some heavily polluted areas, the contribution of coal combustion to PM2.5 can be as high as 30%-40%. With the growth in the number of vehicles, motor vehicle emissions have also become a significant source of PM2.5, particularly in the downtown areas of cities. The particulate matter from vehicles is rich in nitrogen oxides and particulates and accounts for 20%-30% of PM2.5. In industrialized areas, industrial emissions also serve as an important contributor to PM2.5, with the pollutants often containing toxic gases and heavy metals and accounting for approximately 15%-25% of PM2.5. Other sources, such as construction site dust, road dust, biomass burning, and natural sources, account for 5%-15% of PM2.5 levels. The reasons for winter and summer PM2.5 are very different. In winter, due to the need for heating and the widespread use of coal, the ratio of coal combustion is greater, particularly in northern China. At the same time, in winter, due to low temperatures, atmospheric stability, low wind speed, and poor vertical air diffusion, it is easy for pollutants to accumulate near the ground, leading to high concentrations of PM2.5. In contrast, in summer and autumn, motor vehicle emissions and industrial emissions are more significant, particularly in metropolises and industrialized centers. In summer, due to more precipitation and greater winds, pollutants are dispersed and diluted, leading to low concentrations of PM2.5.

Generally speaking, PM2.5 source structure in China varies in different areas and seasons. PM2.5 source structure in China will change in the future, and the proportion of motor vehicle and industrial emission contributions in big cities and industrialized areas will increase, whereas the impact of coal burning and biomass burning will gradually decrease.

3.3 Sources of PM2.5 in Different Regions of China

The sources of PM2.5 in China show significant spatial characteristics. In northern regions, coal combustion and heating are the main sources of PM2.5 in winter, whereas in southern regions, particularly in large cities, motor vehicle emissions and industrial pollution sources contribute more significantly [26].

Beijing, located in northern China, has long been facing severe air pollution problems as the capital of China. Zhang et al. [27] collected PM2.5 samples from Beijing during the winter of 2013 and analyzed them using the PMF model. The results indicated that coal combustion and motor vehicle emissions are the main sources of PM2.5 in Beijing, especially during the winter heating season and periods of high pollution, with the contribution from coal combustion being particularly prominent, around 20%-30%. Although motor vehicle emissions contribute slightly less than coal combustion, their pollution impact is still substantial due to the large number of vehicles, particularly in the high-density urban centers, contributing about 15%-25%. Industrial emissions and construction dust are the major sources of coal combustion and vehicle emissions. Industrial emissions account for a smaller proportion of PM2.5 sources in Beijing, partly due to the relocation of industrial parks. In recent years, Beijing has implemented industrial restructuring and the relocation of industrial parks, moving energy-intensive and heavily polluting industries out of the city, particularly to surrounding areas such as Hebei province. This policy has effectively reduced industrial emissions within the city. As a result, industrial emissions and construction dust make up a smaller proportion of Beijing's total PM2.5 sources, but a larger proportion of PM2.5 sources in Hebei, ranging from 30% to 40% [28]. In summer, traffic emissions, dust, and secondary pollutant formation are the main sources of PM2.5 in Beijing, occupying a significant proportion. In particular, traffic emissions contribute approximately 25%-40% [29].

In coastal areas, the Pearl River Delta in southern China is one of the most economically developed areas in China. The area has a humid climate, and monsoons cause strong airflow that helps disperse and dilute pollutants. Moreover, stricter air pollution control policies have been adopted, so PM2.5 concentrations in the Pearl River Delta are relatively low. Sun et al. [30] applied the Chemical Mass Balance (CMB) model and Positive Matrix Factorization (PMF) to perform source apportionment of PM2.5 in the area. The research showed the complexity of PM2.5 pollution in the Pearl River Delta. Motor vehicle emissions and industrial emissions are the dominant sources of PM2.5, especially in urban center areas. The contribution of motor vehicle emissions is about 20%-30% of the total concentration of PM2.5, and industrial emissions contribute about 15%-20%. The contribution of coal combustion and biomass burning sources is high in winter and spring, especially in rural areas.

For inland regions, Xi'an, in northwest China, has faced deteriorating air pollution issues with increasing urbanization, particularly with the increasing concentration of PM2.5, which seriously affects public health and sustainable urban development. Chen et al. [31] developed a multi-model analysis and concluded that coal burning, motor vehicle emissions, and industrial emissions are the primary sources of PM2.5 in Xi'an, and construction dust and biomass burning play more important roles in certain seasons. Xi'an has traditionally depended on coal as the primary energy source, particularly for winter heating, and thus coal burning is a key source of PM2.5. The analysis concluded that coal burning accounts for approximately 20%-30% of the PM2.5 concentration. Additionally, motor vehicle emissions and industrial emissions account for 15%-25% each. Winter and spring are the peak seasons for PM2.5 concentrations in Xi'an, particularly in winter, due to the combined influences of heating, coal burning, traffic, and biomass burning, which result in higher PM2.5 concentrations. Conversely, PM2.5 concentrations are relatively lower in summer and autumn, with motor vehicle emissions and industrial emissions contributing relatively more.

4 Factors Affecting PM2.5 Concentration and Its Control

PM2.5 concentration is affected by many factors, mainly weather, terrain, and the burning of fossil fuels [32]. Weather conditions, like wind speed, temperature, and humidity, influence how PM2.5 spreads and builds up in the air [33]. High temperatures can increase secondary pollutants, like ozone, and cause PM2.5 levels to rise. Temperature inversions can trap pollutants near the ground. Humidity has a mixed effect—it can either increase PM2.5 by helping particles stick together or lower it by making particles settle faster. Low wind speeds and stable air also

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cause PM2.5 to build up near the surface [34].

Terrain plays a role too. In areas with mountains and valleys, poor air circulation keeps pollutants trapped. Better airflow through improved urban planning, such as better building layouts and more green spaces, can help reduce pollution [35]. Avoiding industrial areas in low-lying regions and planting forests can also improve air circulation.

The burning of fossil fuels is a major source of PM2.5. Traffic, industries, and coal heating are key contributors. During winter, coal use for heating increases PM2.5 levels. To lower emissions, cleaner heating options like natural gas should be promoted. Reducing traffic pollution involves better road planning, using electric vehicles, and limiting high-emission vehicles. Cleaner industrial practices and better exhaust treatment systems can also help. Governments can enforce strict emission standards and regulations to further control pollution [36].

Urban greening reduces PM2.5 by using plants to trap particles. Leaves, trunks, and branches capture PM2.5, with large plants being more effective. Plants also increase humidity, helping particles settle. Green belts can reduce heat, improve airflow, and prevent pollutant build-up, improving air quality [37].

In summary, reducing PM2.5 requires monitoring weather, controlling pollution, improving urban design, and managing traffic. These steps can improve air quality, protect public health, and support sustainable development.

5 Conclusion

Three commonly used methods for particulate matter source analysis include receptor models, source inventory methods, and diffusion modeling. The receptor model does not rely on the transmission process or special data and is therefore applicable to large-scale regions; the source inventory method provides an accurate estimate of the contribution of pollution sources through emission data and is therefore suitable for complex source conditions; and the diffusion modeling method can better predict the spatial distribution and temporal-spatial variation of pollutants and is, therefore, most applicable to complex environments and dynamic sources. Based on these source apportionment methods, studies have found that PM2.5 pollution sources in China vary by region. In northern China, the major contributors during winter are coal combustion and heating, with coal contributing 20%-30% and motor vehicle emissions contributing 15%-25%. In the southern regions, where the climate is humid and pollution control is strengthened, motor vehicles and industrial emissions are the primary sources, contributing 20%-30% and 15%-20%, respectively. In inland cities, coal combustion, motor vehicle emissions, and industrial emissions are the major sources of pollution, with coal combustion making a larger contribution (20%-30%) during the winter heating period. In general, northern regions are primarily dominated by coal combustion, southern regions by motor vehicle and industrial emissions, and inland cities show more diverse pollution sources.

PM2.5 poses a serious threat not only to human health but also to urban environments and landscapes. In terms of human health, the harmful components of PM2.5 are closely related to disease incidence and mortality. Black carbon and organic carbon primarily affect cardiovascular diseases, with black carbon exposure increasing the risk of cardiovascular morbidity and mortality. Metals in PM2.5, such as potassium, zinc, vanadium, and nickel, are also associated with health risks, particularly cardiovascular diseases. Polycyclic aromatic hydrocarbons, especially carcinogens like benzo[a]pyrene, can affect asthma and coronary heart disease with short-term exposure, and with long-term exposure, they are associated with cancers and other health issues. Secondary inorganic aerosols are significantly related to the incidence and mortality of cardiovascular and respiratory diseases. PM2.5 pollution is complex and harmful, with long-term exposure having significant negative impacts on health. Regarding landscapes, PM2.5 not only reduces urban visibility, and blurs landscapes but also impacts buildings, plants, and residents' health. High concentrations of PM2.5 particles deposit on building surfaces, leading to pollution and aging, especially harming historical buildings. It also inhibits plant photosynthesis, affecting urban vegetation and potentially leading to ecological decline. PM2.5 presents several challenges to urban ecology, environment, and human health.

PM2.5 concentrations are influenced by multiple factors such as meteorological conditions, topography, and combustion of fossil fuels. Meteorological conditions such as wind speed, temperature, and humidity directly influence the diffusion and accumulation of pollutants. Pollutants will accumulate under low wind speed and a stable atmosphere, and temperature inversions and high humidity will further worsen the pollution. Furthermore, terrain conditions such as mountains and basins will lead to the retention of pollutants. Pollution sources such as transportation, industrial emissions, and coal heating are the major sources of PM2.5, and pollution will be more severe during the winter heating period and traffic rush hour. Clean heating and enhanced emission control can effectively reduce pollution. To improve air quality, meteorological monitoring, urban layout optimization, and intensified greening should be strengthened. Urban greening can effectively filter PM2.5, enhance air humidity, and enhance pollutant deposition, relieving the urban heat island effect and optimizing air circulation. The optimization of the urban plan and greening layout can address this issue. In summary, to manage PM2.5 concentrations, measures should be taken in meteorological monitoring, fossil fuel management, urban planning, and traffic management to improve air quality and public health.

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