Analysis of the Pollution Characteristics and Influencing Factors of Urban Atmospheric Particulate Matter

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Abstract: Urban atmospheric particulate matter is a complex pollutant resulting from the combined effects of primary emissions and secondary formation. Drawing on nationwide simulations, observations from representative cities, and quasi-experimental studies, this paper analyzes the size distribution, spatiotemporal variation, formation mechanisms, and impacts of urban atmospheric particulate matter. The results indicate that emission intensity determines the baseline pollution level, while secondary transformation, regional transport, and boundary-layer meteorology jointly shape individual pollution episodes. Emission-control measures have been the primary driver of the decline in particulate matter concentrations in recent years; nevertheless, stagnant and humid conditions continue to amplify pollution. Future efforts should prioritize the coordinated reduction of multiple pollutants, joint regional prevention and control, and exposure-oriented management.

Keywords: atmospheric particulate matter; $PM_{2.5}$; secondary aerosol; meteorological factors; urban pollution

Introduction

Urban atmospheric particulate matter is commonly classified as PM_{10} or $PM_{2.5}$ according to its aerodynamic equivalent diameter. PM_{10} contains a relatively high proportion of coarse particles, such as fugitive dust and soil dust, whereas $PM_{2.5}$ is enriched in sulfate, nitrate, ammonium, organic matter, black carbon, and trace metals. $PM_{2.5}$ remains in the atmosphere for relatively long periods, can penetrate deep into the pulmonary alveoli, and can be transported by regional atmospheric circulation. It therefore exhibits the combined characteristics of local emissions, regional complex pollution, and health risks.

Following sustained pollution-control efforts in China, particulate matter concentrations have declined considerably. However, pollution has gradually shifted from being dominated by intensive primary emissions to being driven by the interaction among primary emissions, secondary formation, and adverse meteorological conditions, thereby increasing the marginal difficulty of further control. Based on peer-reviewed research, this paper summarizes the pollution characteristics and causal pathways of urban particulate matter and proposes corresponding approaches to refined pollution management. Because the indicators, study periods, and methodologies adopted in the cited studies differ, their quantitative findings are interpreted only within their respective analytical frameworks and are not used for simplistic cross-study rankings.

1 Pollution Characteristics of Urban Atmospheric Particulate Matter

1.1 Particle Size and Chemical Composition

The environmental behavior of particulate matter is primarily governed by particle size. Coarse particles in PM_{10}, which are generally produced through mechanical fragmentation, settle relatively rapidly and are strongly affected by construction activities, accumulated road dust, and wind speed. $PM_{2.5}$ is predominantly emitted through combustion or formed through the transformation of gaseous precursors. It has a larger specific surface area and a stronger adsorption capacity.

The chemical composition of $PM_{2.5}$ generally includes inorganic ions, organic matter, elemental carbon, crustal elements, and water, although the relative proportions of these components vary with the energy structure, industrial profile, and season. During winter, combustion emissions, the partitioning of ammonium nitrate at low temperatures, and heating activities frequently increase the concentrations of carbonaceous components and nitrate. During warmer seasons, enhanced photochemical reactions can promote the formation of secondary organic aerosol. A single mass-concentration indicator therefore cannot fully characterize the toxicity or sources of particulate matter. Chemical composition, particle-size distribution, and oxidative potential should also be considered.

1.2 Spatiotemporal Variation

Urban particulate matter exhibits multiscale differences characterized by "regional background–urban increment–neighborhood hotspot" patterns. Urban agglomerations with concentrated high-emission industries, dense populations, and unfavorable dispersion conditions generally form continuous areas of elevated pollution. Within individual cities, particulate matter concentrations are affected by roads, industrial point sources, construction activities, and ventilation corridors. Consequently, traffic arteries and enclosed street canyons may become short-term exposure hotspots.

Diurnal variations are controlled by morning and evening traffic, changes in boundary-layer height, and nighttime chemical reactions. Seasonally, the combination of stagnant weather and heating emissions in northern China makes persistent pollution episodes more likely during winter, while coarse particulate matter can also be influenced by dust storms in spring. The effectiveness of pollution control in different cities should not be compared solely on the basis of annual mean concentrations. The frequency of severe pollution, duration of concentration peaks, and population-weighted exposure should also be evaluated.

1.3 Evolution of Pollution Episodes

Severe pollution does not result from the linear accumulation of emissions. Instead, it evolves through a sequence of initiation, growth, persistence, and removal. Based on observations in Beijing, Guo et al. found that nucleation during clean periods initially produced large numbers of nanoparticles, which subsequently underwent continuous growth for approximately 2–4 days or longer. During this process, particulate matter mass concentrations could rise to several hundred micrograms per cubic meter. Weak winds and stagnant conditions controlled the pollution cycle, whereas precipitation provided an effective removal mechanism [1].

This process indicates that particle number concentrations, precursor concentrations, and atmospheric oxidative capacity during the initial stage of pollution have considerable value for early warning. If emergency controls are activated only after $PM_{2.5}$ mass concentrations have increased substantially, the opportunity for relatively low-cost early intervention may already have been missed.

2 Sources and Formation Mechanisms

2.1 Combined Contributions of Primary Emissions

Primary particulate matter is mainly generated by coal and other fuel combustion, industrial processes, motor-vehicle exhaust and non-exhaust wear, construction and road dust, cooking activities, and biomass burning. Different source categories produce particles with different size distributions and chemical compositions. Combustion-derived particles are generally finer and enriched in carbonaceous components, whereas fugitive dust is coarser and contains higher concentrations of crustal elements. Motor vehicles emit both black carbon and nitrogen oxides.

Urban emission inventories that account only for stack and exhaust emissions may underestimate tire and brake wear, road-dust resuspension, solvent use, and residential sources. Pollution management should therefore use dynamic emission inventories to integrate source monitoring, enterprise operating conditions, traffic flows, and construction-site activities. Uniform proportional reductions should not be used as a substitute for identifying specific emission sources.

2.2 Secondary Transformation and Regional Transport

Sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds undergo gas-phase oxidation, aqueous-phase reactions, and heterogeneous reactions, producing sulfate, nitrate, ammonium, and secondary organic aerosol, respectively. A study of severe haze samples collected in Beijing, Shanghai, Guangzhou, and Xi’an in January 2013 showed that secondary aerosols accounted for 30%–77% of $PM_{2.5}$, while secondary components represented 44%–71% of organic aerosols. The contributions of secondary organic and secondary inorganic aerosols were also of comparable magnitude [2]. Controlling primary particulate matter alone is therefore insufficient to eliminate severe haze. Coordinated reductions in SO_2, NO_x, VOCs, and NH_3 are also required.

Regional transport and local formation are not mutually exclusive. Gaseous precursors emitted upwind can undergo atmospheric aging during transport and then be rapidly transformed under humid urban conditions. Conversely, locally emitted pollutants can enter the regional background atmosphere. The respective contributions of different sources vary with wind direction, boundary-layer height, and the stage of a pollution episode. A fixed ratio of “local” to “transported” pollution should therefore not be applied indiscriminately to all polluted days. Scientific decision-making should combine chemical-composition monitoring, backward-trajectory analysis, source apportionment, and chemical transport modeling to attribute individual pollution episodes using consistent emission inventories and meteorological fields.

3 Factors Influencing Urban Particulate Matter Concentrations

3.1 Meteorological and Boundary-Layer Conditions

Meteorological conditions do not generate anthropogenic pollutants, but they affect the efficiency of dilution, transport, transformation, and removal. Low wind speeds, temperature inversions, and a shallow boundary layer compress the atmospheric mixing space, causing near-surface pollutant concentrations to accumulate rapidly. High relative humidity promotes hygroscopic particle growth as well as aqueous-phase and heterogeneous reactions. Precipitation removes particulate matter through wet deposition. Strong winds facilitate atmospheric dispersion but may also resuspend surface dust.

Air temperature exerts opposing effects on ammonium nitrate volatilization and photochemical reactions; it is therefore inappropriate to assume that increasing temperatures necessarily aggravate pollution. Short-term forecasts should jointly consider emission intensity, the ventilation coefficient, boundary-layer height, humidity, and precipitation.

3.2 Urban Form and Underlying Surfaces

High-density buildings alter surface roughness and street-canyon circulation. Where buildings are continuously arranged at similar heights and roads are poorly aligned with the prevailing wind direction, pollutants can accumulate within the pedestrian breathing zone. Conversely, extensive low-density urban expansion may increase commuting distances and motor-vehicle emissions.

The effects of urban vegetation on particulate matter are also context-dependent. Appropriately designed green spaces can suppress fugitive dust and improve the urban thermal environment, whereas overly dense tree canopies in narrow street canyons may restrict ventilation. Urban planning should therefore account for regional ventilation potential and near-surface exposure, preserve ventilation corridors, optimize the spatial relationship between workplaces and residential areas, and establish low-emission buffer zones around sensitive locations such as schools and hospitals.

3.3 Emission Structure and Control Measures

Emissions constitute the fundamental and controllable driver of particulate pollution. Using emission inventories and the WRF–CMAQ modeling system, Zhang et al. estimated that China's population-weighted annual mean $PM_{2.5}$ concentration declined from 61.8 μg/m³ in 2013 to 42.0 μg/m³ in 2017, primarily because of reductions in anthropogenic emissions. Over the same period, emissions of SO_2, NO_x, and primary $PM_{2.5}$ declined by 59%, 21%, and 33%, respectively [3].

The strengthening of emission standards for the power sector and other high-emission industries, the regulation of industrial boilers, the phaseout of outdated production capacity, and the replacement of residential solid fuels with cleaner alternatives contributed reductions of 6.6, 4.4, 2.8, and 2.2 μg/m³, respectively [3]. These findings demonstrate that structural measures deliver more sustained benefits than end-of-pipe emergency controls. Nevertheless, the nonlinear atmospheric chemistry involving NO_x, VOCs, and NH_3 requires policy to move beyond the reduction of individual pollutants toward the coordinated optimization of multiple precursors.

Table 1. Quantitative evidence from representative studies and its interpretive boundaries

Evidence theme	Study object and method	Principal findings
Evolution of severe haze	Integrated observations at an urban site in Beijing	Particles grew continuously for approximately 2–4 days or longer following nucleation, and mass concentrations could exceed several hundred μg/m³ [1].
Secondary components	Samples and source apportionment from four cities in January 2013	Secondary aerosols accounted for 30%–77% of $PM_{2.5}$, while secondary components accounted for 44%–71% of organic aerosols [2].
Nationwide improvement	Emission inventory–chemical transport modeling	The population-weighted $PM_{2.5}$ concentration declined from 61.8 to 42.0 μg/m³, representing a reduction of approximately 32.0% [3].
Long-term health effects	Quasi-experimental analysis of the Huai River heating policy and PM_{10} exposure	Each 10 μg/m³ increase in PM_{10} was associated with a 0.64-year reduction in life expectancy (95% CI: 0.21–1.07) [4].

4 Environmental and Health Impacts

4.1 Visibility, Radiation, and Ecological Effects

Fine particulate matter reduces visibility by scattering and absorbing solar radiation. Under humid conditions, sulfate, nitrate, and hygroscopic organic matter increase in particle size, thereby intensifying light extinction. Black carbon absorbs radiation and heats the atmosphere, whereas light-scattering particles produce a cooling effect. Together, these processes alter the surface radiation budget, boundary-layer structure, and cloud processes.

Particle deposition also transports nitrogen, sulfur, and metals into soils and water bodies, potentially causing acidification, eutrophication, or pollutant accumulation. Controlling urban particulate matter therefore not only improves air quality but also contributes to climate co-benefits and ecological risk management.

4.2 Human Health Risks

Particulate matter can affect the respiratory and cardiovascular systems through pathways including oxidative stress, inflammatory responses, and autonomic nervous system imbalance. The magnitude of risk depends on pollutant concentration, exposure duration, particle size, and chemical toxicity. Children, older adults, pregnant women, and individuals with pre-existing medical conditions are particularly susceptible.

Using a quasi-experimental design based on China's Huai River heating policy, Ebenstein et al. found that each 10 μg/m^3 increase in long-term PM_{10} concentrations was associated with an average reduction of 0.64 years in life expectancy, primarily because of increased cardiopulmonary mortality [4]. This result should not be interpreted directly as a $PM_{2.5}$ dose–response effect; however, it provides evidence of the causal health losses associated with long-term particulate matter exposure. Evaluations of pollution-control performance should therefore expand beyond compliance with concentration standards at monitoring stations to encompass population-weighted exposure, protection of vulnerable populations, and reductions in component-specific toxicity.

5 Targeted Control Strategies and Research Prospects

Urban particulate matter management should establish a closed-loop framework comprising identification, prediction, emission reduction, and evaluation.

First, an observational network should be established to monitor particulate matter composition, precursor pollutants, vertical profiles, and particle-size distributions. Consistent quality-control procedures should be implemented to improve comparability among cities.

Second, differentiated control strategies should be developed according to season and pollution stage. Under routine conditions, priority should be given to emission reductions through adjustments to energy, industrial, and transportation structures. During the initial stage of a pollution episode, NO_x, VOCs, SO_2, and NH_3 should be controlled simultaneously. During the persistence stage of severe pollution, coordinated regional controls should be strengthened.

Third, satellite remote sensing, ground-based monitoring, low-cost sensors, emission inventories, and atmospheric models should be integrated to produce neighborhood-scale exposure maps that can support traffic management and public-health warnings.

Fourth, meteorological normalization and counterfactual scenarios should be used to distinguish policy effects from interannual meteorological variability. Carbon reductions, changes in ozone concentrations, and health benefits should also be assessed simultaneously to prevent single-objective policies from creating pollution-substitution risks.

Future research should address three major issues. First, the formation pathways of nitrate and secondary organic aerosol under different oxidative environments should be clarified. Second, the spatial and temporal resolution of emission inventories for residential sources, agricultural ammonia, and non-exhaust traffic emissions should be improved. Third, locally relevant evidence chains linking particulate composition, toxicity, exposure, and disease outcomes should be established. Only by integrating mass-concentration control with component-specific toxicity, spatial equity, and health benefits can particulate matter management progress from reducing average concentrations to reducing actual risks.

Conclusion

Urban atmospheric particulate matter is characterized by multiple emission sources, secondary formation, regional transport, and meteorological amplification. Existing evidence demonstrates that sustained emission reductions can significantly lower baseline $PM_{2.5}$ concentrations, whereas severe haze remains strongly influenced by precursor transformation and stagnant, humid boundary-layer conditions.

The next stage of pollution control should center on restructuring emission sources and be supported by the coordinated management of multiple pollutants, joint cross-regional control, process-based early warning, and exposure management. Research on particulate matter composition and health effects should also be strengthened. A transition from concentration-oriented control to risk-oriented management is essential for consolidating and sustaining improvements in air quality.

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