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Atmospheric Microplastics and Human Health: Sources, Exposure, and Risks

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Abstract. Atmospheric microplastics, a newly recognized category of environmental pollutants, have attracted increasing attention in recent years due to their presence in the atmospheric environment. A growing body of evidence indicates that MPs are widely distributed in both indoor and outdoor air and can enter the human body through inhalation, posing potential risks to the respiratory system and overall human health. This review systematically summarizes the major sources of atmospheric MPs, their environmental distribution patterns, and their transport and fate in air. Besides, special emphasis is placed on recent advances in research on inhalable microplastic exposure levels and associated health effects. On this basis, key limitations and uncertainties in current studies are identified, and future perspectives are proposed regarding monitoring techniques, health risk assessment, and mechanistic investigations of atmospheric MPs. This study aims to provide a scientific reference for the environmental management of emerging air pollutants and the prevention and control of related health risks.

Keywords: Atmospheric Microplastics, Inhalation Exposure, Emerging Pollutants, Health Risk, Prevention and Control

1. Introduction

Since the early twentieth century, plastics have been widely recognized as indispensable materials due to their versatility, durability, cost-effectiveness, and resistance to temperature, light, and moisture. These properties have led to their extensive application in consumer products and packaging. However, rapid global urbanization and industrialization have driven plastic production to increase at a global compound annual growth rate of 8.4%, rising from approximately 2 million tons (Mt) in 1950 to 430.9 Mt in 2024, with projections reaching 1606 Mt by 2050. By 2015, global plastic waste generation had reached approximately 6300 Mt, of which only about 9% was recycled, resulting in substantial leakage into the environment [1,2]. These leaked plastics undergo physical and biological weathering processes, fragmenting into atmospheric microplastic (MPs) particle ranging from 5 mm to 100 nm in size, which have become a major focus of global environmental concern [1,3-5]. While most existing reviews have focused on the distribution and ecotoxicological effects of MPs in soil and aquatic environments, there is still a lack of studies on atmospheric microplastics, limiting the creation of effective public health policies. By analyzing existing studies, this paper explores the sources, distribution, physicochemical characteristics, and exposure features

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of inhalable microplastics, highlights critical scientific challenges, and proposes preventive strategies. Therefore, this paper contributes to providing references for future research and policy development.

2. Sources and environmental distribution of atmospheric MPs

2.1. Major sources and environmental fate

The sources of MPs can generally be divided into three primary categories. The first category, primary MPs, originates from industrial, commercial, and personal care products such as cosmetic microbeads, glitter, seed coatings, and pre-production plastic pellets. Besides, the second category, secondary MPs, is generated through the fragmentation and degradation of larger plastic items. These include synthetic fibers, fragments, foams, and films released due to improper waste disposal, and are often derived from packaging materials, fabrics, road signs, and marine coatings. In addition, the third category includes other origins such as urban dust, tire rubber particles, emissions from traffic, and debris generated by construction and renovation projects [3,6]. These sources introduce MPs into various environmental media such as air, water, and soil. Through atmospheric transport and deposition processes, MPs can be dispersed over wide areas, ultimately accumulating in marine ecosystems, terrestrial environments, or living organisms, leading to persistent environmental contamination.

2.2. Environmental distribution and influencing factors

The distribution of inhalable MPs differs between urban and rural environments. In urban atmospheres, the concentration range of suspended microplastics ranges from 0 to 274 ng m^{-3}, and the concentration range of deposited microplastics ranges from 0 to 0~925 ng m^{-2} d^{-1}, while concentrations in suburban environments are significantly lower. For instance, the atmospheric microplastic concentration in rural suburbs of Wenzhou City is 101±47 ng m^{-3}, and farmland concentrations in suburban Shanghai can be as low as about 36 ng m^{-3}. In areas with little human presence, such as mountains, oceans, and deserts, atmospheric microplastic concentrations are extremely low, with suspended microplastics ranging from 0~14 ng m^{-3} and deposited microplastics from 7~434 ng m^{-2} d^{-1} [7,8].

Existing studies have shown that atmospheric MPs exhibit pronounced vertical distribution gradients, which are consistent with the physical deposition behavior of airborne particulate matter. Influenced by gravitational settling velocity, aerodynamic drag, and turbulence within the atmospheric boundary layer, MPs tend to accumulate in the lower atmosphere, with their abundance decreasing significantly with increasing altitude. Moreover, human activities are most intensive near the ground surface, where traffic emissions, residential sources, and industrial activities substantially enhance local MP inputs, further reinforcing the accumulation of MPs in near-surface air [7,8]. The higher concentrations of MPs near ground level reflect the combined effects of physical deposition mechanisms, meteorological processes, and anthropogenic emissions.

3. Physicochemical properties and exposure characteristics

3.1. Physical properties and exposure features

The exposure characteristics of MPs are influenced by both their physical properties and environmental behavior, including factors such as particle size, shape, density, and color, along with

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the processes of atmospheric transport, deposition, and resuspension.

In particular, particle size is a key factor influencing the atmospheric behavior of MPs. Micrometer-sized (<500 μm) and nanometer-sized (<1 μm) MPs can remain suspended in air for extended periods and penetrate deep into the human respiratory tract, thus reaching the alveolar region during inhalation [9,10]. Smaller particles possess larger specific surface areas and are more significantly influenced by electrostatic forces and Brownian motion, facilitating long-range transport and inhalation exposure.

Additionally, particle shape also plays a critical role in determining atmospheric residence time and transport pathways. Fibrous MPs, because of their elongated structure, are more easily suspended and transported by airflow. Film-like MPs tend to remain airborne longer because of their rough edges and high aerodynamic resistance; whereas spherical or granular MPs, with more compact shapes and higher mass, exhibit stronger deposition tendencies [8].

Furthermore, density further affects deposition behavior. Typical MP densities range from 1.0 to 1.8 g/mL. Low-density polymers, like polyethylene (PE) and polypropylene (PP), are more likely to remain suspended and enter the respiratory tract. In contrast, high-density polymers, such as polyvinyl chloride (PVC), tend to deposit on surfaces or accumulate in indoor and outdoor dust [11,12].

3.2. Chemical properties and exposure pathways

Although physical properties primarily determine the transport, deposition, and exposure distribution of MPs in the atmosphere, it is their chemical properties that directly affect toxicological behavior within the human body and interactions with other air pollutants. In particular, MPs consist mainly of polymer matrices and various chemical additives, and polymer stability, degradation characteristics, and surface functional groups are key factors in determining toxicity [7,8].

Besides, MPs often contain multiple additives with high mobility, which can be gradually released from the polymer matrix and potentially disrupt endocrine systems or induce oxidative stress responses [11]. Moreover, due to their large specific surface area, MPs readily adsorb volatile organic compounds (VOCs), persistent organic pollutants such as PAHs and PCBs, and metal elements such as arsenic, manganese, and vanadium, forming “MP-pollutant complexes” that significantly enhance toxicity [7]. Under environmental stressors such as oxidation, ultraviolet radiation, thermal exposure, or mechanical abrasion, MPs undergo chemical weathering, leading to polymer chain scission and surface oxidation, and releasing monomers or oligomers that further amplify health risks [13].

These chemical characteristics define major exposure pathways, involving not only the deposition of particles themselves but also the combined toxic effects of adsorbed pollutants and additives entering the respiratory system. Prior studies have reported that MP surfaces can adsorb 1500-1,200,000 ng/kg of PAHs, with nanoplastics exhibiting substantially higher adsorption capacities than micrometer-sized particles [7]. Therefore, comprehensive health risk assessment of MPs must integrate both physical and chemical properties to more accurately elucidate their environmental behavior, biological interactions, and long-term health threats.

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4. Health effects and synergistic risk mechanisms

4.1. Pathological and systemic effects

The physicochemical properties of MPs facilitate their inhalation and deposition in the respiratory tract, thus leading to both localized and systemic pathological effects. In the respiratory system, MPs induce oxidative stress through increased reactive oxygen species, inflammatory responses marked by elevated IL-6 and TNF-α, and lung injury, which includes epithelial cell apoptosis and alveolar inflammation. For instance, exposure to polystyrene (PS) MPs disrupts pulmonary barrier integrity, induces fibrosis, and impairs lung function [9]. These effects are mediated by mechanisms such as phagocytosis-induced activation of the NLRP3 inflammasome, resulting in cytotoxicity.

Systemically, MPs have the ability to cross the alveolar barrier into the bloodstream, affecting the cardiovascular system, including conditions like atherosclerosis and thrombosis, as well as the nervous system, where they can lead to neuroinflammation [9,13]. MPs carrying heavy metals or VOCs further enhance toxicity, leading to endothelial dysfunction, myocardial fibrosis, and elevated blood pressure [13]. Nanoplastics (<1 μm), with stronger penetrative capacity, may disrupt endocrine function, induce metabolic disorders, and increase cancer risk [11]. Although inhalation is the primary exposure route, systemic impacts mediated by circulation substantially amplify the burden of chronic diseases.

4.2. Vulnerable populations and synergistic risks

Vulnerable populations include children, pregnant women, the elderly, smokers, and individuals with chronic diseases, all of whom have compromised immune systems or face increased exposure risks. In particular, children are at greater risk of exposure through toys, diet, and air, which could result in developmental impairments and long-term cardiovascular risks. Besides, prenatal exposure may allow MPs to cross the placental barrier, raising the risk of congenital cardiovascular abnormalities. Smokers experience higher MP exposure in the lower respiratory tract, with synergistic effects from tobacco smoke exacerbating lung damage and cardiovascular inflammation [14].

Synergistic risk mechanisms primarily arise from the carrier role of MPs. By adsorbing $PM_{2.5}$, heavy metals, and pathogens, MPs form composite pollutants that intensify oxidative stress and inflammatory cascades [11]. For example, MPs combined with black carbon can amplify the risks of cerebrovascular and cardiovascular diseases, such as stroke and myocardial infarction. Moreover, epidemiological data suggest that annual inhalation exposure among Chinese residents may reach 187,000-328,000 particles per person, with synergistic interactions with $PM_{2.5}$ contributing to increased cardiovascular mortality.

5. Preventive measures and future prospects

5.1. Preventive strategies

Prevention should prioritize source reduction and exposure control. At the policy level, governments should strengthen regulations on plastic production and recycling, promote biodegradable plastics such as PHA and PLA, and adopt advanced oxidation processes (AOPs) like Fenton-based treatments, which can degrade over 90% of MPs [13]. At the technological level, the development of high-efficiency filtration systems, such as HEPA filters for airborne MPs, and biodegradation technologies, such as enzymatic or microbial degradation of PS and PE, should be prioritized.

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Besides, the design of water filters and face masks should be optimized to reduce MP release. At the public level, public education should encourage reduced plastic use, such as minimizing single-use plastics, promoting sustainable diets with less packaged food, and improving indoor ventilation. Stricter standards for children's toys should be implemented to limit MP exposure. And previous studies have highlighted the importance of managing microplastics and their potential impacts on the environment and public health. This can be addressed through improved policy and technological solutions [15].

5.2. Research gaps and recommendations

Key research gaps include the lack of standardized sampling and analytical methods, which leads to uncertainty in exposure assessment. There are also challenges in measuring micro- and nanoplastics, a limited understanding of the effects of long-term exposure, and a lack of sufficient data on synergistic risk mechanisms and vulnerable populations. These gaps are especially clear in developing countries. In addition, the optimization and large-scale application of biodegradable and bio-based plastics remain inadequate. Future research should concentrate on quantifying MP and nanoplastic types and exposure concentrations, establishing high-resolution monitoring databases, and integrating artificial intelligence to boost detection accuracy and automation. It is also important to expand population-based exposure studies, particularly among vulnerable groups, and employ advanced data analysis techniques, such as machine learning, to improve exposure risk prediction. Furthermore, the acceleration of developing and optimizing environmentally friendly plastic alternatives will greatly enhance market competitiveness and expand application scenarios.

6. Conclusion

This study reveals that MPs have been widely detected in the atmospheric environment, with both indoor and outdoor air serving as important pathways for human inhalation exposure. Existing evidence indicates that atmospheric MPs originate from diverse sources influenced by both human activities and environmental conditions. Their size distribution and physicochemical properties determine deposition behavior in the respiratory system and associated health effects. However, substantial uncertainties remain regarding long-term inhalation exposure levels, biological effects, and underlying mechanisms. Future research should establish standardized sampling and analytical methods, strengthen exposure assessment and toxicological investigations, and incorporate atmospheric MPs into air pollution and public health risk management frameworks to more comprehensively evaluate their potential impacts on human health.

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