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Ecological and human health risks of atmospheric microplastics (MPs): a review

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Microplastics (MPs) in the atmosphere are ubiquitous and persistent emerging pollutants which have been an environmental issue of global concern. This overview summarizes the sources, morphological size and compositional characteristics, spatial–temporal distributions, transport and fates, and both ecological and human health risks of MPs in the atmospheric environment. The results suggest that atmospheric MPs could be long-range transported and deposited into aquatic and terrestrial habitats, which pose ecological risks through bio-absorption, bio-concentration, bio-accumulation, ecotoxicity and associated chemical pollution. Since a large number of small-sized MPs are present in the atmosphere, exposure to them affects ingestion, metabolism and reproduction. Human exposure to atmospheric MPs by inhalation may induce health risks, including oxidative stress and inflammatory damage. Moreover, atmospheric MPs may also serve as carriers for other harmful chemical pollutants like heavy metals. Finally, further research studies on atmospheric MPs are recommended for future work.

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Environmental significance

Microplastics have been detected in the atmosphere of cities, suburbs, and remote areas (snowy mountains, sea), indicating that MPs can be transported over long distances in the atmosphere. MPs can cause pollution in the atmospheric environment. Therefore, it is necessary to illuminate the origin, distribution, environmental fate and risks of MPs in the atmosphere. As a global environmental pollution issue, atmospheric MPs impact both ecosystems and human beings. This review explores the ecological risks and human health risks posed by various MPs in the atmosphere.

1 Introduction

Plastic pollution has become a global threat. The global demand for plastics has grown exponentially, with the global production increasing to 368 million tons in 2019.[1] Despite a growing number of strategies used to reduce plastic,[2,3] 55% of the world's plastic was discarded, followed by being incinerated (25%) and recycled (20%) in 2015.[4] Nevertheless, large amounts of plastic still accumulate in the environment.[5] Plastic particles are released from plastic products during usage and handling due to physical, chemical, and biological processes. Plastic particles of less than 5 mm in size are often referred to as microplastics (MPs)[6] (Fig. 1).

MPs enter ecosystems mainly through human activities. MPs are found in soil, air, and water environments.[7] As an emerging pollutant, it has aroused widespread concern in the society. MPs can potentially migrate and physically transfer nutrients horizontally in the environment.[8,9] MPs in the atmosphere are mostly transported by wind and enter the water and soil environments *via* dry and wet deposition.[10] MPs can travel *via* wind, soil, and water streams all the way to the ocean.[11,12] MPs in the soil environment can travel short distances through bioturbation and agricultural activities,[13] re-enter the atmosphere through wind, and enter the water environment through rain.[14] This illustrates that MPs can move in environments with different media.[15,16] Several studies have been carried out on the sources of MPs and analytical methods for their detection.[17–19] More attention is being paid to MPs present in the aquatic and terrestrial environments.[15,20] MPs may be ingested and accumulated in organisms, affecting the survival, growth, reproduction, feeding and immune system of organisms.[13,21,22] MPs enter the human body mainly through ingestion, inhalation and skin absorption. MPs have significant negative effects on human health.[23] Atmospheric MPs are considered to be an important pathway for biological and human ingestion and inhalation, resulting in ecological risks and human health risks.[24,25] Although there has been an increase in studies on atmospheric MPs in recent years, more studies on their sources, transport, and fates are needed.

The purpose of this review is to provide insight into the occurrence of MPs in the atmospheric environment, focusing on (a) using collected data to summarize the sources, morphological size and compositional characteristics, spatial–temporal distribution, transport and fates of MPs in the

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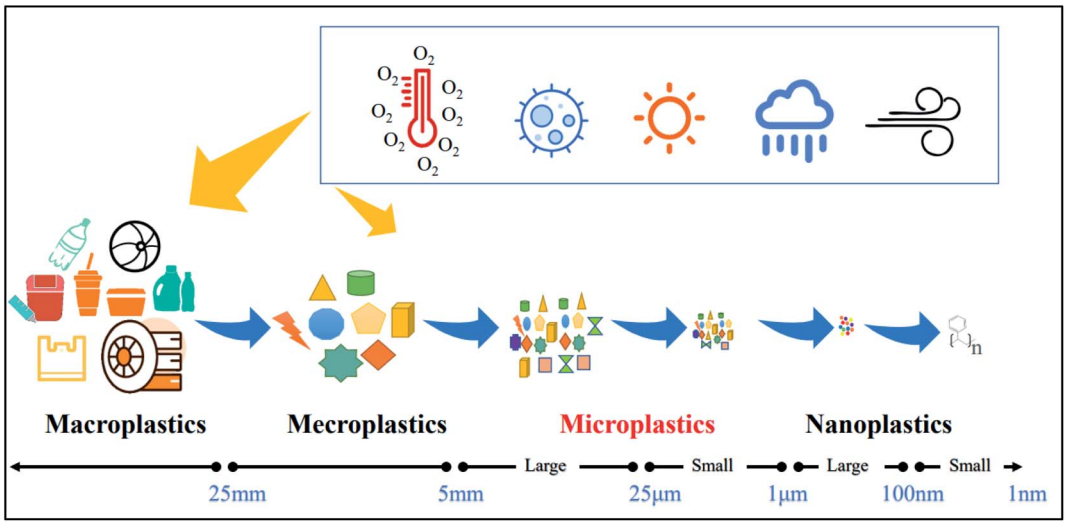

Fig. 1 Definition of plastic size classes.

atmospheric environment; (b) discussing the ecological risks of atmospheric MPs; (c) exploring the toxicological effects of atmospheric MPs on human health.

2 Microplastics in the environment

2.1 Definition of MPs

Plastic is a very important organic synthetic polymer material. Plastics are processed into various colors, sizes, and shapes according to the different needs. In addition, plastics have wide applications owing to their unique physical and chemical properties, such as durable, water-proof, lightweight, and corrosion-resistant nature. Therefore, statistics show that about 6300 metric tons (Mt) of plastic waste had been produced by 2015. However, only around 9% of them have been recycled, and 12% have been incinerated. The remaining 79% of plastics were deposited in landfills or into the natural environment.[26]

MPs are synthetic polymers with diameters less than 5 mm.[27] MPs have different colors, compositions, sizes, and shapes. They are found in diverse forms, including spheres, fragments, and fibers.[28] According to sources, they can be divided into primary MPs and secondary MPs. Primary MPs refer to plastics smaller than 5 mm that are directly generated during production and eventually released into the environment. The primary sources of MPs mainly include cosmetics, personal skin care products, products related to the medical field and water-based coatings.[1,11] Large plastic products or wastes exposed to the natural environment are broken into tiny plastic particles under

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the influence of physical, chemical and biological forces to form secondary microplastics,[29] such as debris generated by mulch breakage, particles generated by tire wear, and so on. Plastics and MPs undergo degradation to form nanoplastics (NPs). The large and diverse MPs are found in aquatic,[30] terrestrial[31,32], and atmospheric environments.[33,34] MPs have a long residence time in the environment because it is difficult to degrade them therefore this causes extensive and serious environmental pollution.

2.2 MPs in the atmosphere

MP pollution has gradually become an environmental issue that has attracted global attention. The number of publications on MPs has increased rapidly in the recent decade (Fig. 2). However, most published research focuses on their occurrence, transport, and ecological risks in the aquatic[35,36] and terrestrial[37–39] environments. There are few studies on MPs in the atmosphere, and the initial research began in 2015.[40] MPs in the atmosphere are potentially important pollutants in urban and industrial environments, which receive rare attention. In the next few years, research on atmospheric MPs will increase.

2.3 Technologies for the collection and analysis of atmospheric MPs

The choice of sampling method affects the detection of MPs in the atmosphere. Passive atmospheric deposition or vacuum pump samplers are mainly used.[41,42] The atmospheric deposition sampling method is suitable for continuous sample collection over a long period. Active vacuum pump samplers can be used to collect total suspended particulate matter (TSP) found in the atmosphere.[43]

Atmospheric MPs have been identified and quantified by macroscopic, microscopic, and spectroscopic techniques.[44–46] The size of MPs detectable by physical characterization methods such as vision and microscopy is limited. Although physical characterization methods such as infrared spectroscopy and Raman spectroscopy are more conducive to identifying common MPs with smaller sizes (down to 50 nm), they cannot identify the color and shape of MPs.[47] A growing body of research focuses on the identification and quantification of NPs in the environment.[48,49] Several mass spectrometry (MS)-based methods have been proposed to quantify and characterize polymers commonly found in MPs and NPs.[50] MS is well suited for the determination of MPs and NPs in air samples with small sample volumes that do not require complex digestion and separation,[51] but the number of polymers that can be determined is still too small.[52] MP samples can be destroyed during Raman spectroscopy identification. There are currently no well-established techniques for identifying smaller-sized MPs. There are also few studies that have measured NPs in actual samples.[53] The presence of large amounts of NPs in the atmosphere has not been identified and quantified. There is an urgent need to understand the presence of NPs in the atmospheric environment and their toxicological effects on living organisms.

3 Atmospheric MP pollution

3.1 Occurrence and distribution of MPs in the atmospheric environment

Currently, the sample types of MPs in the atmospheric environment examined include total atmospheric fallout, indoor and outdoor air, snow, and street dust. Few studies investigated the occurrence and dispersion of airborne MPs in limited sites across three continents: Europe, North America, and Asia. Since 2015, most research has focused on the composition, properties, and abundance of atmospheric MPs[40] (Tables 1 and 2). These studies suggest that sources and transport factors simultaneously influence the spatial distribution of atmospheric MPs.

3.1.1 Chemical compositions of atmospheric MPs. MPs are composed of natural and synthetic polymers in the atmospheric environment.

Regarding the composition of fibers in atmospheric environments, the vast majority are made of natural materials, such as cotton, cellulose acetate, and a small amount of wool. The remaining few fibers contain plastic polymers, one of which is a blend of polyamide (nylon) and cotton and the other fully synthetic. Many types of synthetic polymers have been detected in atmospheric MPs. The most common types include

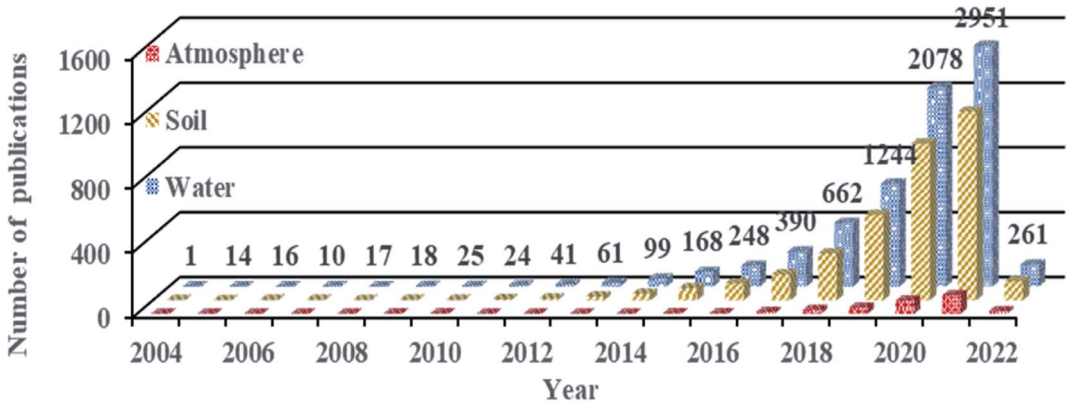

Fig. 2 The number of papers containing MPs related to the atmosphere, soil and water, respectively. The statistics are the total number of publications containing MPs each year (Data from Web of Science).

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Table 1 Available data reported on concentrations, physico-chemical characteristics and abundance of MPs in outdoor air worldwide

Environmental medium	Continent	Study area	MP abundance	MP composition	MP size (μm)	MP shape	MP color	Ref.
Total atmospheric fallout (wet and dry deposition)	Europe	Paris, France	29–280 particles per m^2 per day	N/A	100–5000	Fiber: 90%, fragment: 10%	N/A	Dris *et al.*,[40] 2015
		Paris, France	2–355 particles per m^2 per day (urban: 110 ± 96, sub-urban: 56 ± 38)	PET, PUR, PA, RY	50–600	Fiber	N/A	Dris *et al.*,[57] 2016
		Pyrenees, France	365 ± 69 particles per m^2 per day	PS, PE, PP, PVC, PET	5–3000	Fragment, film, fiber	Transparent, white, bright orange, blue, green, purple, black	Allen *et al.*,[86] 2019
		Hamburg, Germany	136.5–512.0 particles per m^2 per day	PE, EVAC, PTFE, PVA, PET	<63–5000	Fiber, fragment	N/A	Klein and Fischer,[67] 2019
		London, England	575–1008 microplastics per m^2 per day	PAN, PES, PA, PP, PVC, PE, PET, PS, PUR, AC, Pol. Petr. Res	20–2899	Fiber, film, fragment, granule, foam	N/A	Wright *et al.*,[61] 2019
	Asia	Dongguan, China	175–313 particles per m^2 per day	PE, PP, PS	200–4200	Fiber, foam, fragment, film	N/A	Cai *et al.*,[54] 2017
		Yantai, China	1.46×10^5 particles per m^2 per year	PE, PVC, PS, PES	50–5000	Fiber, foam, fragment, film	White, black, red, transparent	Zhou *et al.*,[55] 2017
		Guangzhou, China	51–178 plastics per m^2 per day	PET, PAN, PP, PA, PS, ALK, EP, ABS	50–5000	Fiber, fragment, film, microbead	Transparent/white, blue, yellow, red, orange, green, gray	Huang *et al.*,[87] 2021
Snow	Europe	Swiss Alps and Bremen, Bavaria	Arctic snow: 0–14.4×10^3 N per liter, European snow: 0.19×10^3 154×10^3 N per liter	Varnish, nitrile rubber, PE, PA	11–475	Fiber	N/A	Bergmann *et al.*,[10] 2019
Street dust	Asia	Tehran, Iran	83–605 ± 10 particles per 30 g	N/A	100–5000	Fiber, granule, sphere, hexagonal, irregular polyhedron	Transparent, red, green, blue, white, black, yellow, brown, pink, orange	Dehghani *et al.*,[59] 2017
		Asaluyeh County, Iran	Industry: 60 particles per g, urban: 16 particles per g	N/A	≤5000	Spherule, fiber, fragment, film	White-transparent, yellow-orange, black, red-pink, blue-green, black-grey	Abbasi *et al.*,[65] 2019
		Kusatsu, Japan	2.0 ± 1.6 pieces per m^2	PE, PP, PS, PET, PAK, PVS, EPC, SBR, EPDM, PU	1400 ± 947	N/A	N/A	Yukioka *et al.*,[76] 2020

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Table 1 (*Contd.*)

Environmental medium	Continent	Study area	MP abundance	MP composition	MP size (μm)	MP shape	MP color	Ref.
		Da Nang, Vietnam	19.7 ± 13.7 pieces per m^2	PE, PP, PS, PET, PAK, PVS, EPC, SBR, EPDM, PU	791 ± 530	Fragment, film/sheet, line/fiber, granule	Black, gray, red, yellow, brown, white/transparent, blue, green	Yukioka *et al.*,[76] 2020
		Kathmandu, Nepal	12.5 ± 10.1 pieces per m^2	PE, PP, PS, PET, PAK, PVS, EPC, SBR, EPDM, PU	907 ± 675	Fragment, film/sheet, line/fiber, granule	Black, gray, red, yellow, brown, white/transparent, blue, green	Yukioka *et al.*,[76] 2020
Total suspended particulates (TSP)	Asia	Shanghai, China	0–4.18 items per m^3	PET, PE, PES, PAN, PAA, RY, EVA, EP, ALK	23.1–9555	Fiber, granule, fragment	Black, blue, red, transparent, brown, green, yellow, grey	Liu *et al.*,[68] 2019a
		West Pacific Ocean	0–1.37 items per m^3	PET, PE, PP, PE-PP, PES, PAN, PMA, EP, ALK, Phe, PS, PVA, PVC, PA	20–2000	Fiber, granule, fragment, microbead	Black, blue, gray, brown, yellow, red, orange, pink, purple, white, transparent, green	Liu *et al.*,[62] 2019b
		Shanghai, China	0.05–0.07 items per m^3	PET, EP, PE, ALK, RY, PP, PA, PS	12–2191	Fiber, fragment	Black, blue, green, yellow, brown, transparent, white, pink, purple	Liu *et al.*,[69] 2019c
		North Atlantic Ocean	N/A	PS, PE, PP, PDMS	>5	N/A	N/A	Trainic *et al.*,[71] 2020
		Karimata Strait	0–0.8 items per 100 m^3	PET	382.2	Fiber	Black	Wang *et al.*,[63] 2020
		Pearl River Estuary	3–7.7 items per 100 m^3	PET, PP, PA, PEP	288.2–11182	Fiber	Black, white, red, yellow, brown	Wang *et al.*,[63] 2020
		South China Sea	0–3.1 items per 100 m^3	PP, PET, PEVA	286.1–1862	Fiber, fragment	Black, red, yellow	Wang *et al.*,[63] 2020
		East India Ocean	0–0.8 items per 100 m^3	PET, PP, PAN-AA, PR	58.6–988.4	Fiber, fragment	Black, yellow, Blue	Wang *et al.*,[63] 2020
		Five megacities of Northern and Southeast China	Northern cities: 358 ± 132 items per m^3, Southeast cities 230 ± 94 items per m^3	PE, PES, PS, PP, PA, PVC	5.9–1475	Fragment, fiber	N/A	Zhu *et al.*,[72] 2021
		Sakarya, Turkey	N/A	PA, PUR, PE, PP, PES	≤500	Fiber, fragment	Dark blue, black, blue, brown, white, transparent	Kaya *et al.*,[60] 2018

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Table 2 Available data reported on concentrations, physico-chemical characteristics and abundance of MPs in indoor air worldwide[a,b]

Environmental medium	Continent	Study area	MP abundance	MP composition	MP size (μm)	MP shape	MP color	Ref.
Indoor and outdoor air	Europe	Paris, France	Indoor: 1.0–60.0 fibers per m^3, outdoor: 0.3–1.5 fibers per m^3	PP, PA, PET, RY	Indoor: <3250, outdoor: <1650	Fiber	N/A	Dris *et al.*,[58] 2017
	America	California, America	Indoor: 3.3 ± 2.9 fibers per m^3, 12.6 ± 8.0 fragments per m^3, outdoor: 0.6 ± 0.6 fibers per m^3, 5.6 ± 3.2 fragments per m^3	PE, PET, PS, PVA, AC	Indoor: 58.6 ± 55, outdoor: 104.8 ± 64.9	Fiber, fragment	N/A	Gaston *et al.*,[56] 2020
	Asia	39 major cities in China	Indoor fiber: 17–620 fibers per mg, indoor granule: 6–184 particles per mg, outdoor fiber: 7–431 fibers per mg, out-door granule: 0–100 particles per mg	PET, PAN, NY, PE, PP, AC, PU, alkyd	50–2000	Fiber, granule	N/A	Liu *et al.*,[66] 2019d
Indoor airborne	Europe	Aarhus, Denmark	1.7–16.2 particles/m^3	PES, PE, NY, PP	11–400	Fragment, fiber	N/A	Vianello *et al.*,[70] 2019
	Asia	Shanghai, China	Dormitory: 9.9 × 10^3 MPs per m^2 per day, office: 1.8 × 10^3 MPs per m^2 per day, corridor: 1.5 × 10^3 MPs per m^2 per day	PES, RY, AC, cellophane, PP, PS, PA	50–2000	Fiber	Transparent, blue, red, black, yellow, purple, green	Zhang *et al.*,[64] 2020
	Oceania	Metropolitan Sydney, Australia	22–6169 fibres per m^2 per day	PE, PES, PET, PA, PVC	50–5000	Fiber (99%), fragment, film	Black, green, blue, red, grey, brown, transparent	Soltani *et al.*,[156] 2021

[a] N/A: not available/reported. [b] ABS: acrylonitrile butadiene styrene, AC: acrylic, ALK: alkyl resin, EP: epoxy resin, EPC: ethylene/propylene copolymer, EPDM: ethylene/propylene/diene rubber, EVA/EVAC: ethylene-vinyl acetate copolymer, NY: nylon, PA: polyamide, PAA: polyacrylic acid, PAK: polyacrylate, PAN: polyacrylonitrile, PC: polycarbonate, PDMS: polydimethylsiloxane, PE: polyethylene, PEP: poly(ethylene-*co*-propylene), PES: polyester, PET: polyethylene terephthalate, Phe: phenoxy resin, PMA: poly(*N*-methyl acrylamide), Pol. Petr. Res: polymerized petroleum resin, PP: polypropylene, PS: polystyrene, PTFE: polytetrafluoroethylene, PU/PUR: polyurethane, PVA: poly(vinyl acetate), PVC: polyvinyl chloride, PVS: polyvinyl stearate, RY: rayon, SBR: styrene/butadiene rubber.

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polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), and polyamide (PA). These synthetic polymers are utilized for various items. For example, PE and PP are mainly used in plastic bags, containers and films, PET for beverage and drinking water bottles, PS for fast food boxes, and PA for engineering plastics.

The distribution of MP types in the air is influenced by the emission type, climatic conditions, and site topography, such as the compositions of MPs measured in different cities of China. The main types of atmospheric MPs measured in Dongguan city[54] are PE, PP, and PS, while in the same year, the types of MPs measured in Yantai city[55] mainly included PE, PVC, PS, and PES.

The current determination of the composition of MPs in the atmosphere is related to technology. Micro-Raman and FT-IR paint slightly different pictures of plastic compounds in the air.[56] Micro-Raman shows that PVC dominates indoor air followed by PE, while FT-IR showed the predominance of PS followed by PE and PET. Therefore, the development of instrumental technology is crucial to the correct ongoing composition analysis of MPs in the atmosphere.

3.1.2 Morphological characteristics of atmospheric MPs

(1) Size. Plastics with a particle size of less than 5 mm are usually called MPs. The early study published regarding the size of MPs in the atmosphere[40] provided knowledge on the 100–5000 μm range in the total atmospheric fallout. So far, the generally reported size of atmospheric MPs ranged widely from 4 to 5000 μm. Limited by the available methods, the 2015–2018 studies[40,54,55,57–60] on the size measurements were not precise enough. With the development of qualitative and quantitative techniques for MPs, the research on the size of MPs has gradually narrowed to less than 2000 μm. MPs' size limits were often operationally defined by sampling and analysis methods. MPs down to 10 μm could be identified,[61] expanding the range of detectable size reported by previous studies on air samples. Many fluorescent non-fibrous particles <20 μm and smaller fibers were observed in the total atmospheric deposition in central London,[61] indicating the existence of smaller MPs in the atmosphere worthy of further study. These studies showed that MPs constitute a non-negligible fraction of atmospheric particulate matter, which can be inhaled and ingested. The studies also indicate that inhalation of MPs in the air is likely to have negative effects on human health.

There are also differences in the size of indoor and outdoor MPs in the same location, and different scholars hold different views on this topic. In a study of MPs in indoor and outdoor air in Paris,[58] France, no fibers larger than 3250 μm were observed in indoor air, while in outdoor air, it was always smaller than 1650 μm. No significant difference in fiber length was found between indoor and outdoor air in California,[56] but their data suggest that indoor fragments are half the size of outdoor ones. The size of MPs in indoor and outdoor air in Paris is larger than in California, as seen from data from the two cities, indicating that MPs in different cities may be different.

The study of total suspended MP particles in the West Pacific Ocean[62] pointed out that the size of MPs was 20–2000 μm. The size of the MPs collected over the South China Sea and the Eastern Indian Ocean is less than 2000 μm.[63] Therefore, MPs of larger size find it difficult to suspend into the air and even transmit to a longer distance.

(2) Color. MPs are composed of various colors, including white, black, red, and transparent (Fig. 3b). Judging from the reported situation, black, blue, and white account for the main part of atmospheric MPs. Color is generally considered helpful in the initial visual assessment of atmospheric MP samples. Black MPs are the most abundant, accounting for 29.9% of all atmospheric MPs in the streets of the Tehran metropolitan area.[59] We might infer from this that tire crumbs make up a large proportion of street dust.

(3) Shape. Fibrous and fragmented shapes are the most abundant shapes in atmospheric MPs. In addition, irregular shapes such as fragments, films, and spheres also exist. The study conducted in Paris[40] and in Yantai[55] confirmed the highest proportion of fibrous MPs in atmospheric deposition samples. Fibers are also the most prevalent microplastic shape collected in different indoor environments.[64] MPs in different shapes have different physical properties. Films tend to be flexible and thin, fibers tend to be very thin, and flakes tend to be thick and irregular in shape. Overall, the shape of MPs in the atmosphere depends on the original morphology of the primary MPs, the degradation and erosion processes on the surface of the plastic particles, and the residence time in the environment.[43]

In different functional areas of the same city, the shapes of atmospheric MPs are often different. For example, more film-like, spherical, and fragmented MPs were found in industrial areas while more fibrous MPs were found in urban areas.[65] Most of the street dust samples were dominated by spherical and film-like particles, with MPs mainly composed of black debris and fibrous particles of varying sizes.[66]

3.1.3 Environmental abundance of atmospheric MPs.

Most available studies focus on atmospheric MP concentrations, which can be combined with size and composition to simulate their transport in the atmosphere.

Deposition fluxes of MPs with different morphologies in the atmospheric environment vary with seasons. For instance,[55] by compiling data from the sampling points in Yantai city, atmospheric MP deposition flux in spring, summer and winter was relatively high, with a varied range of 4.84×10^2 to 6.24×10^2 particles per m^2 per day, but in autumn, it was lower, only 1.30×10^2 particles per m^2 per day. The daily deposition fluxes of different types of MPs vary widely, and there are large seasonal differences.

The average abundance of atmospheric MPs varies widely across investigated areas (Fig. 3a). In European cities, a median abundance of atmospheric MPs ranging from 136.5 to 512.0 particles per m^2 per day was observed in the metropolitan area of Hamburg.[67] In Asia, the atmospheric deposition in Dongguan city, China, comprises the concentrations of non-fibrous MPs and fibers ranging from 175 to 313 particles per m^2 per day.[54] For countries in the same continent, the concentration flux of atmospheric MPs in total atmospheric deposition in France is 29–280 particles per m^2 per day.[40] Atmospheric MPs had been measured at a deposition rate of between 575 and 1008 microplastics per m^2 per day in central London, UK,[61] and between 136.5 and 512.0 microplastics per m^2 per day in Germany.[67]

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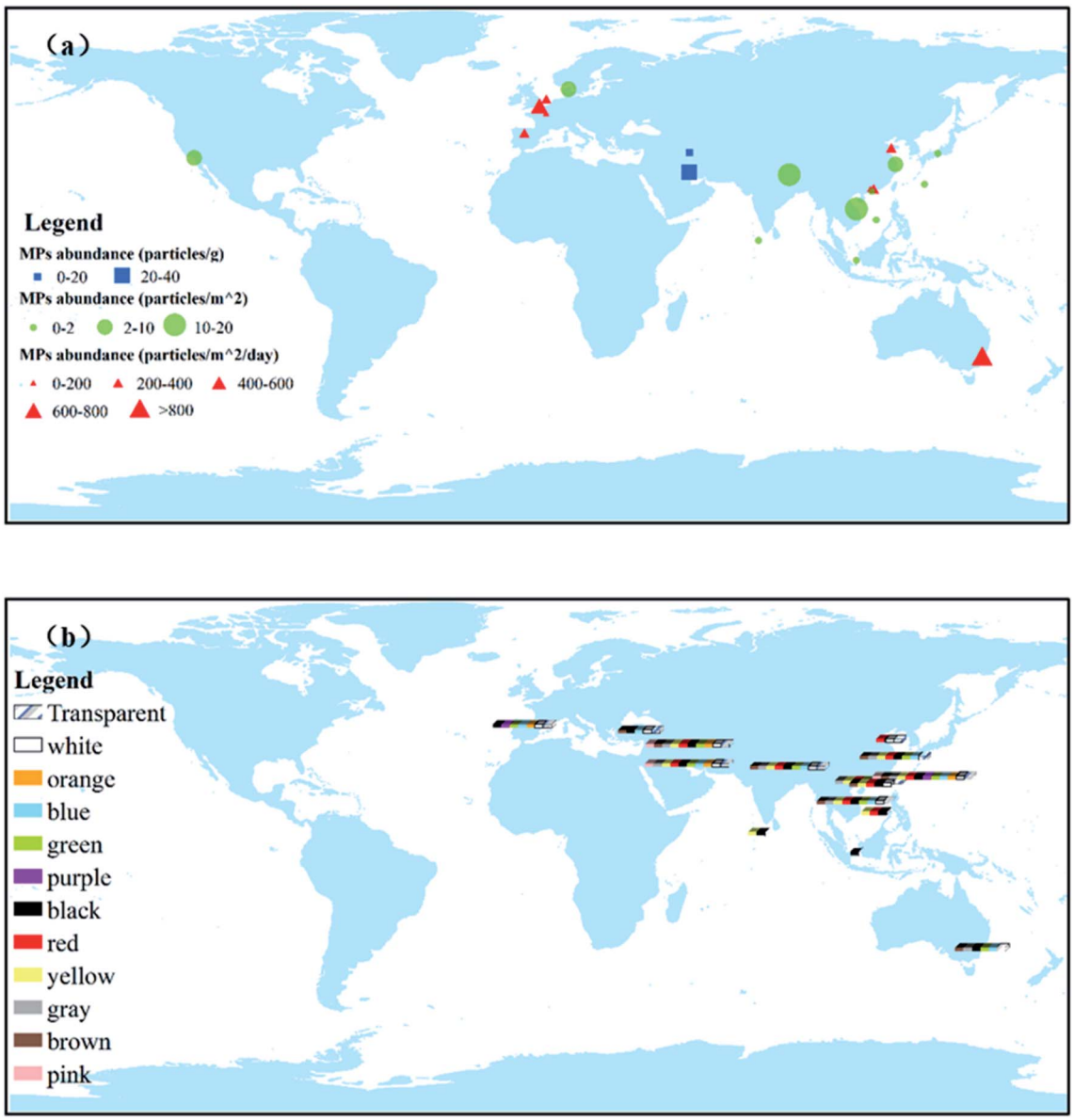

Fig. 3 The global distribution of concentration and color characteristics of MPs in the atmosphere. Panel (a) represents the concentration of atmospheric MPs monitored in the published literature surveyed. Panel (b) represents the color of atmospheric MPs detected in the surveyed published literature.

These differences may be due to different detection methods and sampling heights.

In addition, climate, population density, level of industrialization, and human activities may also affect the spatial distribution of MPs in the atmosphere. The same sampling and detection method was used to assess the intensity of exposure to MPs in the atmosphere of five megacities in China.[72] The results showed that the concentrations of MPs in the air in northern cities (358 ± 132 items per m^3) were higher than those in southeast cities (230 ± 94 items per m^3). Significant differences in the distribution of atmospheric MPs in different functional areas of the same city show that the above guesses are well-founded. According to one year of atmospheric MP monitoring in Paris, France,[57] the deposition rate of MPs in the urban atmosphere was 110 ± 96 plastics per m^2 per day, while that in the sub-urban was 56 ± 38 plastics per m^2 per day.

In small areas, human activities are an important factor affecting the distribution of MPs in the air. There are also obvious flux differences between indoor and outdoor air MPs collected in the same functional area. For example, fibers and fragments in indoor air are twice as high as outdoors in coastal buildings in California, USA.[56] Measurements in Paris, France[58] ranged from 1.0 to 60.0 fibers per m^3 for indoor MPs and 0.3 to 1.5 fibers per m^3 for outdoor MPs. Data from different regions show that the concentration of MPs in indoor air is significantly higher than in outdoor air.

The factors that influence the distribution of MPs in the air are complex. The spatial distribution of MPs in an atmospheric

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deposition is related to wind speed, wind direction, and precipitation.[56] More emphasis should be paid to the exact links between these factors in future studies. Human activities have been shown to have a significant impact on microplastic pollution. Whether indoor[64] or outdoor[60] environments, more MPs would be found in larger population densities. According to the results, we can intuitively see the occurrence and distribution of MPs and infer the source and transport in the atmospheric environment.

3.2 Sources of atmospheric MPs

3.2.1 The use, cleaning and drying process of fiber products. The source of atmospheric MPs is difficult to trace, but potential sources can be explored through the characteristics and polymer types of atmospheric MPs. The main source of airborne MPs is synthetic fibers.[72,73] Globally, more than 90 million tons of textile fibers were produced in 2016. Two-thirds of them were synthetic and plastic fibers, and the production rate has grown at around 6.6% per year over the past decade.[74] The concentration of MPs in indoor air is much greater than that in outdoor air, which may be related to the high abundance of synthetic textiles in indoor air.[56–58] The global demand for synthetic textiles (*e.g.*, clothes, blankets, and curtains) is growing. In the production process of synthetic fibers, the friction and cutting of the fibers will produce many fine fibers, and the smaller fibers can easily float into the air. In daily use, textile products are easily broken into fine particles and enter the atmosphere when subjected to mechanical wear and ultraviolet radiation.[75] MP fragments can originate from the decomposition, wear, and weathering of packaging and reusable products.

3.2.2 Dust resuspension. Dust is often seen as the fate of atmospheric MPs, but MPs in dust can be re-transported into the atmosphere by wind, so dust is a secondary source of atmospheric MPs. Smaller MPs (<100 microns), including clothing fibers and car tires, can significantly increase road dust.[76] An important source of MPs in street dust is road traffic emissions. From a quantitative study on the emission of MPs in the atmosphere from urban mining bases, tire micro-rubber is emitted the most,[77] which also confirms this view. Global per capita tire plastic emissions are about 0.81 kg per year. In the air, tire wear accounts for about 3–7% of particulate matter ($PM_{2.5}$), suggesting that it may contribute to the global health burden of air pollution.[78]

3.2.3 Landfill or incineration. Much of the plastic waste is disposed of by dumping it into landfills, significantly exposing the plastic to the atmosphere.[79] Other sources of airborne MPs may come from emissions from the recycling of plastics. Plastic waste does not decompose in landfills,[80] but degrades into MP particles over time through physical, chemical, and biological processes[6] that not only affect the environment, but also emit MPs into the air.[81] The accumulation and release of MPs in landfills is a long-term process, and landfills might not be the final sink of plastic but a potential source of MPs.[82] Large amounts of MPs are present in atmospheric suspended particulates from landfills. However, by studying MPs in lichen samples at different distances from landfills, the spatial impact of landfill emissions is limited.[83] The number of MPs decreased exponentially with distance, from 79 MP g^{-1} dw at a close range to 13 MP g^{-1} dw at 200 m and 7 MP g^{-1} dw at 1500 m from the landfill.

3.2.4 Other sources. Industry and agriculture can also generate MPs and release them into the environment.[35] Other human activities, such as the process of using building materials (paint, wallpaper) and kitchen plastic utensils (brushes, rags), release MPs during use and friction.[84] It was suggested that some MP particles in the ocean may enter the atmosphere through bubble burst jets and wave action.[85]

The source and transmission of atmospheric MPs are new contents and hot issues in the study of MPs. We can infer the type and sources of MPs from their color and shape.

3.3 Transport and fate of MPs in the atmospheric environment

The ubiquity of MPs is due to the movement of MPs in the atmosphere. Transport, diffusion, and deposition mechanisms are the driving forces for the movement of atmospheric MPs (Fig. 4).

3.3.1 Transport of atmospheric MPs. In outdoor environments, it had been demonstrated that MPs could be transported to great distances under the action of airflow. This was reflected in the detection of MPs in Arctic snow,[1] in atmospheric deposition in the pristine mountains of the remote French Pyrenees,[86] and in the suspended atmospheric particulates in the Western Pacific.[62] In indoor environments, human activity induces airflow in the room, leading to the resuspension of settled particles and increasing the concentration of MPs in indoor air.[64]

Transport is affected by the size and shape of atmospheric MPs.[43] MPs that can be transported in the atmosphere tend to be smaller. There are still many unknowns about the transport mechanism of atmospheric MPs. From the MPs detected in snow samples and in the air suspended over the sea surface, it can be assumed that fibers and debris are more easily transported.[1,63] The transport is related to the concentration of MPs in the atmosphere.

The transport of atmospheric MPs is affected by climate change. Wind provides an efficient route for the transport of atmospheric MPs. The monsoon affects the transport flux of atmospheric MPs, increasing the possibility of long-distance transport, which in turn affects their fate.[87] Atmospheric transport may lead to preferential accumulation of MPs in certain regions.[88] This affects the ecosystems in some areas, increasing the risk of organisms being exposed to MPs.

3.3.2 Fate of atmospheric MPs. MPs carried into the atmosphere by airflow have different fates depending on their size, composition, and shape. Particle size is a major factor in determining the environmental fate of atmospheric MPs. MPs enter the atmosphere and quickly combine with water vapor in the air to form aerosols. For common aerosol particles, the smaller the particle size, the longer they remain suspended in the air. While larger MPs sink under the influence of gravity,

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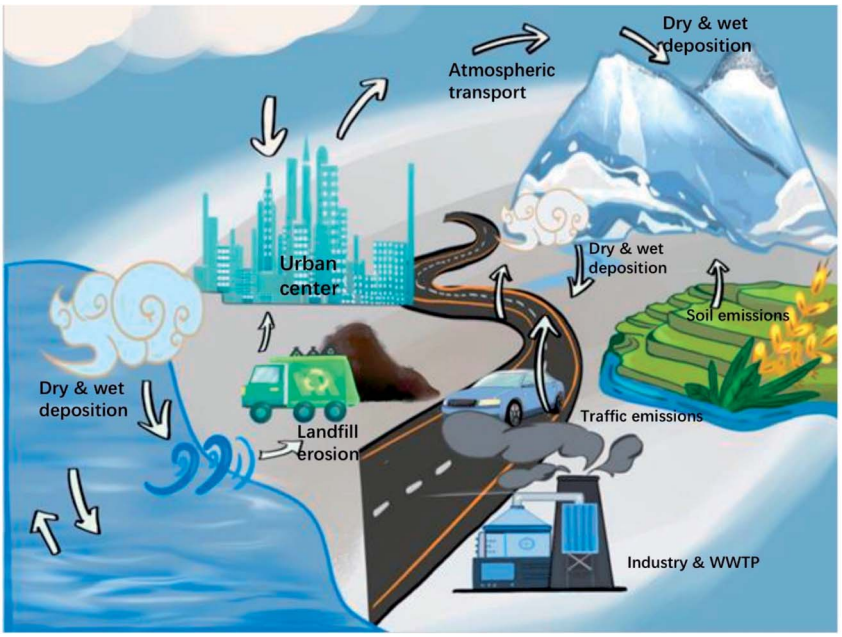

Fig. 4 Sources, transport and fates of MPs in the atmosphere.

smaller ones tend to be suspended in the atmosphere for a longer duration, transported to greater distances, or enter terrestrial or marine systems by wet deposition. This also explains the particle size <50 μm observed in the remotely transported atmosphere.[86] In an experiment,[62] the proportion of microfibers in the TSP decreased the most, and it was speculated that microfibers were more likely to sink. Meanwhile, the amount of PE collected at night was four times higher than that during the day, speculating that this may be related to the density and water absorption of the polymer. Airborne MPs with lower densities are more likely to be transported farther.[89]

Atmospheric MPs deposited into aquatic and terrestrial ecosystems may be ingested by animals, undergoing nutrient level transfer and bioaccumulation. Plant leaf surfaces can serve as potential temporary sinks for atmospheric MPs.[90] Some atmospheric MPs are temporarily stored on the surface of plant leaves and resuspended into the atmosphere under the action of wind.[91] Some nano-scale plastics may enter plants through leaves, thereby affecting the growth of plants.

Physical, chemical and biological actions further break down MPs in the atmosphere. For example, weathering can lead to the release of additives and oligomers in MPs, causing greater harm to the environment.[92] The fate of atmospheric MPs depends not only on the type and concentration of emissions, but also meteorology, topography and human activities. As the number of rainy days increases, the content of fibrous MPs collected in atmospheric deposition increases significantly.[93] Precipitation promotes the deposition of MPs in the air and is one of the important factors affecting the content of MPs in atmospheric deposition samples. Low temperature will lead to the emergence of a strong inversion layer and a low atmospheric boundary layer,[94] resulting in poor dispersion of suspended particles in the atmosphere and high concentrations of atmospheric particles over cities. The wind is a positive driver of MP deposition and increases resuspension. High wind speeds favor the atmospheric deposition of MPs. MP deposition rates and mean wind-speed high-consistence abundances in atmospheric fallout also increased with wind speed.[61] The analysis of MPs in different indoor areas showed the dynamic changes of human activities affecting MPs in the indoor environment.[64]

4 Ecological risks of atmospheric MPs

4.1 Effects of atmospheric MPs on the aquatic ecosystem

Atmospheric MPs enter aquatic ecosystems through dry and wet deposition (Fig. 5a), thereby, atmospheric deposition is a major source of MPs in the aquatic environment. MPs are persistent in aqueous environments because of their durability. Some MPs, denser than seawater, may sink to the seabed. Other MPs, lighter than seawater, frequently float on the water surface.[96] Both marine and freshwater organisms can ingest MPs.

4.1.1 Effects on aquatic animals. There are increasing research studies on the effects of MPs on aquatic animals. MPs entering the aquatic environment from the atmosphere are ingested by a variety of aquatic animals, such as invertebrates, mammals,[97] fish,[98] and shellfish.[99] Mussels effectively reflect environmental pollution. Judging from the fact that MPs in the water environment pose a great threat to survival, microplastic pollution in the North Pacific is already serious.[100] The ecological risks caused by MPs need to be taken seriously. Mammals can be exposed to MPs through direct ingestion of seawater or indirect ingestion of prey.[101] MPs can affect the gut microbiota of aquatic animals because of the associated chemicals.[95] They may accumulate in the digestive tracts of aquatic animals, clogging their guts and limiting the ability of these organisms to

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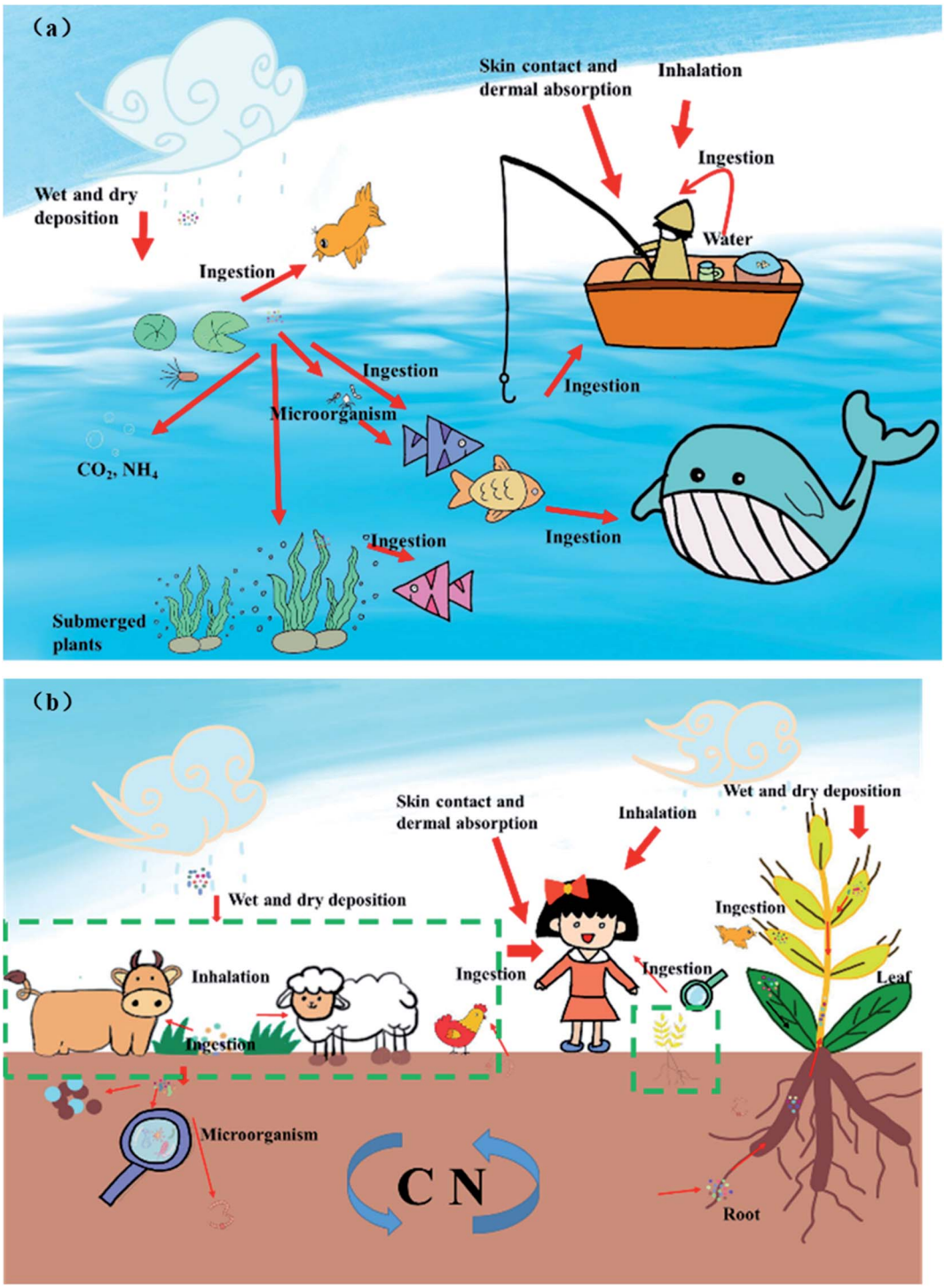

Fig. 5 Transport and exposure pathways, ecological risks and human health risks of atmospheric MPs. Panel (a) represents the terrestrial environment, and panel (b) represents the aquatic environment.

ingest and digest food.[102] This can cause toxicity and even death to aquatic animals.

Ingestion of low doses of MPs often does not cause the immediate death of organisms, and natural dietary habits[103] and histological changes[104] can serve as potential indicators of susceptibility to ingested MPs. For fish, the consumption of MPs can cause significant toxicological damage, including induction of inflammation and oxidative stress in the gut.[105] In addition to ingestion, considering the mode of adhesion increases the estimation of the bioavailability of MPs to aquatic organisms. The attachment of MPs to animals is also a way for them to move through the food web.[106] Non-aquatic animals such as seagulls[107] and penguins[108] may mistakenly ingest MPs floating on the sea surface. Because the MPs floating on the

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water are similar in size and color to their prey, they are vulnerable to active or accidental feeding by zooplankton.[109] In addition to the direct adverse effects on biota, MPs in aquatic environments may also play a potential role as carriers of hydrophobic organic chemicals and microorganisms.[110] The effects of MPs on organisms in the aquatic environment are chronic, cumulative and persistent.[97] They can accumulate in organisms, enter the food web, reach higher trophic levels, and even endanger human health.

4.1.2 Effects on aquatic microorganisms. MPs bring more organic and inorganic carbon to the aquatic environment, which stimulates the activity of microorganisms.[111] This could lead to the release of more CO_2 from the water environment, as well as to alter the CH_4 cycle. Moreover, MPs affect the structure and function of microbial communities. The invasion of MPs changed the composition and structure of bacterial communities and decreased biofilm richness and diversity.[112] On the other hand, microbes may influence the fate of MPs.[113] Changes in aquatic microbiome function affect carbon metabolism and food webs in aquatic environments. The buoyancy, hydrophobic surface and ability to transport over long distances of MPs make them novel substrates of choice for microorganisms.[114] The potential toxicity of MPs to aquatic organisms may be related to microbial pathogens.[115] MPs will act as a transfer carrier of harmful microorganisms in the water environment, affecting the colonization of microbial pathogens on the surface of MPs.[116]

4.1.3 Effects on hydrophytes. MPs floating on the water surface hinder the absorption of light by phytoplankton, which in turn prevents them from providing food and oxygen to aquatic life.[96] This view was also illustrated by the fact that MPs reduce the photosynthetic activity of Chlorella by causing physical damage and oxidative stress.[117] But it is very likely that after the algae have adapted to the presence of MPs in the water environment, they are stimulated to grow more, creating ecological risks. High concentrations of MPs can significantly alter the structure of phytoplankton communities.[118] There could be an increase in the abundance of algae in parts of the phytoplankton community. Changes in phytoplankton communities will affect food webs and ecological functions in the aquatic environment.

Many common MPs are denser than water, so they settle in aquatic environments. A large number of microfibrils were detected in Cladophora in the Great Lakes of the United States.[119] These MPs can interact with submerged aquatic plants. MPs in the aquatic environment will pose growth stress on submerged plants, including reducing plant height and chlorophyll content.[120] MPs may enter plants through the leaves or roots of submerged plants. Microfibrils were detected from the cell wall, confirming that MPs entered the plant. MPs entering plants can affect oxidative stress, antioxidant responses, and fluorescence parameters of chlorophyll in submerged plants.[121] On the other hand, submerged plants also affect the distribution of MPs in the water environment. These submerged plants that absorb MPs may be eaten by other fish, causing more serious ecological risks through the the food chain and web.

4.2 Effects of atmospheric MPs on the terrestrial ecosystem

Atmospheric transport and deposition provide the possibility for MPs to enter the terrestrial environment. Many studies have confirmed that atmospheric MPs enter the terrestrial ecosystem through dry and wet deposition.[55,57,67] Tire plastic can be released into the soil close to the road and beyond.[122] MPs that enter the terrestrial environment from the atmosphere either persist in the soil layer for a long time or degrade slowly. MPs accumulate in the soil in large quantities, posing a potential threat to terrestrial ecosystems.[123] Different types of MPs have contrasting properties and induce different impacts on terrestrial ecosystems (Fig. 5b).

4.2.1 Effects of MPs on the soil biophysical environment. The different types, shapes and sizes of MPs pose different negative effects on the soil environment. MPs, which are similar in shape and size to soil particles, have less impact on the soil structure.[124] The shape of fibrous MPs is much different from that of soil non-linear particles, which may mean that it can wrap around soil particles more efficiently. The shape of MPs has the potential to alter soil biophysical properties. A study has shown that MPs entering the soil can reduce soil bulk density and water-holding capacity and change the soil structure.[125] MP types influence the interaction of MPs and soil pore space. Polyacrylic fibers and PE fragments did not significantly reduce soil bulk density as did PES fibers. However, research has shown that PES microfibers cannot change the soil bulk density.[126] This may be caused by the differences in the experimental soils. Further research is needed to fully understand how MPs affect the soil physical environment, as well as the effects of microplastic shape, size, and composition.

4.2.2 Effects of MPs on soil organisms. The effects of MPs on soil organisms have been documented. Soil organisms include microorganisms, animals, and plants that live in the soil. MP contamination alters the physical properties of the soil, affecting soil hydrodynamics and microbial activity.[127] This may inevitably alter the composition of soil microbial communities, with implications for soil fauna and plants.

MPs influence soil microbial community structure. It was found that PE significantly changed the structure of bacterial communities and affected the succession of bacterial communities.[128] MPs affect the evolution of soil microbes by changing the soil environment.[129] MPs can serve as a source of nutrients and organic carbon in the soil, and microbiota utilizing this resource has a survival advantage. Their shape, size and concentration limit the effects of MPs on microbes. Fiber, foam and film MPs significantly affect soil bacterial composition compared to particles.[130] The change in soil microbes could lead to a change in their interaction with soil animals.

Soil animals can ingest MPs. Many studies have focused on the harmful effects of MPs on soil-dwelling animals, such as earthworms,[131] springtails,[132] and nematodes.[133] Ingestion of MPs may lead to insufficient nutrient supply, oxidative stress and intestinal damage to soil animals, thereby inhibiting their growth and reproduction.[135] Although tissue and immune system damage were evident, lower MP concentrations clearly impacted the mortality outcome of soil animals.[136] More

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research is needed in the future to identify histopathology and the immune system as potential indicators of susceptibility to ingested MPs. The size and concentration of MPs can determine how toxic they are to soil animals.[131,137] Through experiments, it was found that the addition of MPs could significantly affect the composition and abundance of microarthropod and nematode communities.[133] Likewise, exposure to MPs significantly enhanced bacterial diversity in collembola's gut.[132] The response of soil fauna to the addition of MPs can cascade through the soil food web. Changes in soil fauna and trophic structure caused by the presence of MPs can significantly affect the activity of microorganisms.[133] This indirect effect may be stronger than the direct effect of MPs on microbes. Research has provided new insights that extractable additives in MPs are the main toxic pathway for soil fauna.[134] While some specific types of MPs and the extractable additives both reduced worm growth and survival, the effects of both were not significant.

MPs in the atmosphere may enter the soil environment to affect the growth of plants and may also have an impact on plant leaves through dry and wet deposition. MPs in the atmosphere can adhere to the foliar of leaves and even enter plants through stomata. Most of the MPs that adhered to and entered the leaf were fibrous,[138] which may be related to the shape of the leaf stomata. Plant leaf stomata absorb NPs and transfer them down to the roots. Foliar absorption of MPs may affect photosynthesis in plants.[139] Foliar exposure to MPs can have a considerable impact on growth, lowering crop dry weight, plant height, and leaf area.[140] MPs deposited from the atmosphere into the soil are absorbed by plant roots and transferred to shoots.[141] MPs present in the soil can alter the rooting ability of plants. PES and PS in soil resulted in a significant increase in root biomass.[127] MPs can significantly increase the root length of plants and reduce the average root diameter. Thin, long roots increase the absorption of MPs. In the case of the aerial parts of plants, MPs also affect plant leaf shape and total biomass. Smaller size MPs may have more severe chemical toxicity in addition to their physical impact on the biota. It was thought that NPs may enter plant roots and may cause damage to plants, such as oxidative stress.[142]

4.2.3 Effects of MPs on the biogeochemical cycles of soil carbon and nitrogen. There are important links between carbon and nitrogen cycles and soil microbes that are related to greenhouse gases (GHGs) and climate change. Some studies have confirmed that MPs deposited from the atmosphere into the soil can affect carbon and nitrogen cycles in the soil by altering the composition and function of microbial communities.[143,144] A study has shown that adding MPs can significantly promote soil CO_2 emissions.[145] This could exacerbate global warming and cause even more serious environmental problems. However, no effect of adding MPs on soil NO emissions was found. MPs with different characteristics affect the diversity of bacterial communities in the soil. MPs have different effects on different soil microbes. The composition of dissolved organic carbon in the soil is affected by the size of MPs.[146] It was reported that[143] PUF and PLA promoted sediment nitrification and denitrification, while PVC inhibited it. This indicates that different MPs affect soil carbon and nitrogen cycles differently. Nitrogen availability in the soil was reduced in MP-treated soils. It is possible that MPs affect the nitrogen cycle by altering soil porosity.[144] There is also a view that MPs may alter soil nutrient cycle by altering soil bacteria or genes and enzymes associated with carbon, nitrogen and phosphorus.[147] The biological mechanism requires further studies to explain.

5 Human health risks of atmospheric MPs

Growing research studies have shown that humans are generally exposed to environmental MPs through ingestion, inhalation, and skin contact.[148]

5.1 Inhalation by respiration

The particulate toxicity of atmospheric MPs after inhalation is related to the physiological mechanisms of deposition and clearance involved in human inhalation of MPs.[149] MPs settle in various parts of the human respiratory system by gravity. The clearance mechanism can reduce the concentration of MPs in the body. Microplastic particle toxicity induced by dust overload, oxidative stress, cytotoxicity, and particulate matter translocation can all decrease the clearance mechanism,[150] thereby affecting human health.

The size of the MPs determines their respiratory potential, as only MPs smaller than 10 μm can be inhaled. Both indoors and outdoors, MPs smaller than 10 μm were detected, indicating that MPs in the air can be directly inhaled.[151] Plastic fibers were observed in human lung samples, confirming that they can be inhaled.[152] Although most of the coarse inhalable particles undergo mucociliary clearance in the upper airway, some fine particles can escape this mechanism and deposit deep in the lungs.[153] These particles (especially longer fibers) tend to avoid gaps and exhibit extreme durability in physiological fluids, where they may persist and accumulate upon inhalation. Although airborne fibers are more abundant than fragments, the smaller size consists almost entirely of fragments. Therefore, finer-sized fragments are more likely to enter the human lungs. Fragments rather than fibers are primarily transported in the air. For instance, 31 synthetic polymer particles and fibers were observed in the lung tissue of 13 of the 20 autopsies of the deceased, of which 87.5% were fragments and 12.5% were fibers,[154] confirming this idea. Most of the inhaled MPs are retained in the upper respiratory tract.

The effects of MPs on human health also depend on exposure time and concentration. Elevated concentrations of MPs in the atmosphere may significantly increase human health risks.[155] Simulating through a breathing thermal manikin, 272 MPs could be inhaled by a mannequin within 24 hours.[153] Young children tend to be at a greater risk than adults from exposure to airborne MPs.[66,156] The general population is generally exposed to low concentrations of atmospheric MPs. However, occupationally exposed practitioners may be exposed to high levels of MPs, which may lead to the accumulation of higher concentrations of MPs and occupational diseases.[149,157] Cytotoxicity is also highly influenced by the size and shape of MPs.

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NPs and MPs have potential toxicological effects on human lung cells. Exposure of lung cells to MPs inhibited cell proliferation, as well as caused significant changes in cell morphology.[158] NPs may affect the internalization, cell viability, cell cycle, and apoptosis of human lung epithelial cells.[159,160] It was demonstrated that exposure of normal human lung epithelial cells BEAS-2B to MPs resulted in inflammation and oxidative damage, as well as disruption of intercellular junctional proteins in the lung.[161] This can lead to acute and chronic respiratory diseases. Airborne MPs were also suspected of causing chemical toxicity as potential PAH carriers, plastic additives, and metals, among others.[160,162,163] Microplastic with additives tended to pose higher inflammatory potential than those without additives.[157] Airborne MPs may be toxic to organs other than the respiratory system. For example, ultrafine particles (UFPs) may reach the gut *via* inhalation and diffusion from the lungs into the systemic circulation or ingestion of inhaled particles after airway mucociliary clearance.[155]

Ingested or inhaled particles may further enter the bloodstream and may be toxic to other organs (such as liver, embryo, brain, *etc.*) after translocation.[155,164–168] Different types of MPs have varied toxic effects on human organs.[169] But no studies have clearly explained how MPs enter the bloodstream and are transported to other organs after being inhaled or ingested.

5.2 Oral ingestion

Plastics are an inevitable part of our daily lives. MPs are frequently present in human daily water and food. In addition, large amounts of MPs are found in everyday drinking bottled beverages, tap water, and alcohol.

The concentrations of MPs in different water sources vary widely. MP particles were detected in different brands of bottled water and tap water samples from around the world.[170,171] The most common MP shapes in tap water were fibers (99%).[171] In some case studies, 95% of MP particles were detected in bottled water with a size of 6 to 100 μm,[170] or 80% of MP particles were detected with a size of 5 to 20 μm.[172] This suggests that humans easily ingest MPs in drinking water. Moreover, human-caused MP pollution is also present in beer, salt, and seafood.[96,171,194] These MPs have many sources, with atmospheric emissions being a potential source.[173]

MPs transfer nutrients through the food chain. MPs can be transferred from the environment into living organisms and then, through the food web, posing a risk to human health.[174,175] Some of the MPs entering the human digestive system are excreted through feces,[176,177] and some remain in the human body.[178] The risk of intestinal exposure to MPs in infants is higher than in adults.[177] The toxicity of MPs to humans varies depending on their sources and properties.

Researchers disagreed on the health risks of MPs to the human gut. Ingestion of MPs by the human body can cause abrasions, perforations and even blockages in the digestive tract.[179] According to the effects of artificial *in vitro* digestion on 5 types of MPs, all plastic particles had high resistance to artificial digestive juices,[180] and the major stages of the human gastrointestinal tract do not break down particles. However, in a study of the digestion process of seal pups,[181] MPs break down into smaller particles in the stomach.

In vitro simulation experiments on human cells Caco-2 and intestinal flora showed that PE could weaken the cell activities and change the composition of intestinal flora, which would pose a threat to human health.[182] However, when PS of different sizes was used on Caco-2 cells, the particles did not cause damage and inflammation to the cells.[183] Oral ingestion of environmental level MPs is unlikely to represent a serious health risk to people. Most current studies on MPs in the human digestive system rely on epidemiological studies, *in vivo* animal tests,[185] and *in vitro* cell culture approaches. The consequences of MP exposure on the human digestive system are mostly unknown and necessitate detailed and more profound assessment.

Through oral ingestion, MPs that exist in the human body can accumulate in the human digestive system or translocate to other organs (*e.g.*, liver, kidney).[184] In addition to the toxicity of MPs themselves to the human digestive system, they may also act as a carrier for other toxic substances.[185–188] Most of the MP samples detected in human digestion were clear filaments,[178] probably because MPs are decolorized in the digestive tract. It is still unknown whether the MP pigments remain in the human body and cause harm to the human body. There are many more ingested routes that require our attention, such as ingesting vegetables and poultry exposed to MPs.

5.3 Skin contact and dermal absorption

Human skin is the largest organ of the human body and performs a strict barrier function to the external environment.[189] Particulate pollutants are associated with skin aging. Traffic-related particles can increase freckles on the forehead and cheeks, as well as wrinkles in the nasolabial folds.[190] Skin contact with MPs is considered a non-critical route of exposure. However, fine particulate matter is often considered a major environmental issue that causes respiratory problems and skin diseases in humans.[191] Various particulate matter in air pollution, which induce oxidative stress by producing reactive oxygen species (ROS) and secreting pro-inflammatory cytokines, can affect the development and exacerbation of skin diseases.[192] There is no available direct evidence that atmospheric MPs can penetrate the skin, and further research in this field is needed.

6 Conclusion and perspectives

Environmental risk research of MPs, particularly atmospheric MP research, is still in its early stages. MPs have been detected in atmospheric fallout,[40,54,67] indoor and outdoor air,[56,58] snow samples,[10] and street dust.[65,76] MPs in the atmosphere have various shapes, colors, sizes and compositions. The monitoring of MPs in the atmosphere is related to collection and measurement methods. Currently, there is no uniform and accurate technique to support the study of MPs in the atmosphere. Therefore, more research in the future should focus on the development of related technologies and instruments.[195] When analyzing the chemical composition of atmospheric MPs, the main focus is on the concentration, characteristics and

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composition of atmospheric MPs. The coexistence of MPs with other pollutants requires more in-depth research. Understanding the complex composition of atmospheric MPs enables better management and reduction of pollution caused by atmospheric MPs. Most detected airborne MPs ranged in size from 200 to 600 μm. Possibly affected by the method adopted, more and smaller MPs were not detected. MPs smaller than 10 μm have been found in the atmospheric environment. Smaller atmospheric MPs can be ingested and inhaled by organisms, causing more serious toxicological damage.

Atmospheric MPs are from a wide range of sources, including synthetic textiles, dust, and landfills. Most studies mainly use models or speculate on the origin of atmospheric MPs based on the characteristics of MPs. No available data can specify the detailed sources of atmospheric MPs and the contribution rate of each source to predict the future global atmospheric MP pollution. The effects of weathering and biodegradation on MP transport in the atmospheric environment need to be elucidated. Will MPs continue to break down into NPs during transport? What is the ultimate fate of NPs?

The driving forces for the movement of atmospheric MPs are migration, diffusion and deposition mechanisms. Large amounts of MPs in the atmosphere enter aquatic and terrestrial ecosystems mainly through wet and dry deposition. MPs can move in environments with different media.[196] There is value in distinguishing MPs that enter aquatic and terrestrial ecosystems from the atmosphere from those that are native to aquatic and terrestrial ecosystems. However, in practice, it is currently difficult to directly explain the ecological risks posed by MPs from the atmosphere entering other ecosystems. Few studies have been able to accurately account for the ecological risks posed by atmospheric MPs, for which there are also no guidelines, thus requiring more exploration. Possibly this is based on an accurate understanding of the source–pathway–sink relationship of atmospheric MPs in various environmental media.

The published literature investigated the human health risks posed by atmospheric MPs through *in vitro* cell cultures and models.[193] Researchers hold different opinions on the risks MPs pose to human health. Ingestion or inhalation of MPs (especially NPs) is widely believed to be toxic to human organs. There is currently no research on how micro–nano plastics enter the human body and what damage they do to various human body organs. The toxicological effects of various types, sizes and shapes of micro–nano plastics on human cells also need attention. Knowledge gaps remain on the environmental exposures, bio–nano interactions, and potential risks of MPs.[197] More scientifically reliable data are needed to explain the presence of atmospheric MPs and the resulting ecological and human health risks.

After understanding the pollution of MPs in the atmospheric environment, policies to help reducing MP pollution need to be implemented in the future. Strictly controlling the way MPs enter the environment and selecting MPs that pose less ecological and human health risks have become an urgent goal.

Conflicts of interest

There are no conflicts to declare.

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