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A brief global overview of plastic waste and the key role of the atmosphere: Sources, transport and impacts

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Abstract

Plastic waste in the atmosphere, particularly microplastics (MPs), has emerged as a critical environmental issue due to their capacity to remain temporarily suspended in air. Over the past decade, significant advancements have been made in understanding their sources, atmospheric transport, environmental fate, and associated impacts. Early studies primarily examined their deposition in urban areas, while recent research has identified additional emission sources, long-range atmospheric transport, the occurrence of suspended MPs and their impacts. MPs may influence atmospheric processes, such as ice nucleation dynamics, and pose risks to respiratory health in air-breathing organisms, including humans, by potentially damaging lung tissue. Furthermore, MPs could act as vectors for microorganisms, facilitating the spread of viruses and bacteria. Despite these advancements, further research is needed to standardize methodologies and deepen our understanding of their atmospheric transport, their role in ice nucleation, and their function as microbial carriers, ultimately mitigating their potential 'One Health' impacts.

1. A brief global overview of plastic waste: Does the atmosphere play a role?

Plastic pollution is a growing global concern[1], with its production continuing to rise each year[2], prompting the governments worldwide to take significant action[3,4]. In 2023 alone, more than 400 million tons of plastic were produced worldwide, excluding those used in textiles, adhesives, and medical applications[5]. Due to their durability, versatility, and low cost, plastics are utilized across various industrial sectors[6]. In 2021, the primary uses include packaging (44%), construction (18%), automotive (8%), electronics (7%), and agriculture, farming and gardening (4%)[7]. However, most plastics are employed in short-lived applications, such as packaging (lasting weeks) or agricultural films (lasting months), despite their persistent nature, often remaining in the environment for decades[8]. At the end of their useful life, plastics become waste. A portion of this waste is managed through recycling and the majority of plastic waste is either sent to landfills or used for energy recovery[9]. Plastics that are not properly managed, or those that undergo accidents during handling (such as the recent case of pellets washing up on Galician beaches), may end up in the environment[10]. The global macroplastic waste emissions are estimated at 52.1 Mt per year[11]. Once in nature, plastic waste undergoes fragmentation and abiotic and/or biotic degradation processes, influenced by local environmental conditions and modulated by the physical and chemical properties of the polymer material. Fragmentation is driven by physical processes such as weathering, freeze-thaw cycles, pressure changes, water turbulence and biological activity. Abiotic degradation mechanisms include hydrolysis, redox reactions, thermal degradation, or photo-oxidation, while biotic degradation involves the action of individual or communities of microorganisms (fungi, bacteria, and others). These processes result in the progressive breakdown of plastic waste into smaller particles, resulting in microplastics (MPs; particles <5 mm in size), nanoplastics, oligomers, and eventually greenhouse gases. Plastics generated through the degradation of larger items are classified as secondary plastics, whereas plastics intentionally manufactured at small scales are termed primary plastics. Since the 1970s, plastic waste has been detected across various environmental compartments. Initial findings reported plastics in the marine environment, such as in seabirds and seawater[12–14]. In recent decades,

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MPs have also been identified in humans[15,16] and across all major environmental compartments, including the biosphere[17], lithosphere[18], cryosphere[19], and atmosphere[20]. Even the most remote regions of the planet are not exempt from plastic contamination. MPs have been discovered in high-altitude atmospheric layers[21], Antarctica[22−23], and mountain peaks, including Mount Everest[24]. Recently, plastic waste has also been identified as contributing to the formation of novel geological materials[25−26].

Plastic waste has been shown to cause significant damage to the environment, wildlife, and humans through several mechanisms, therefore, in One Health (a holistic framework that addresses the complex interconnections among animals, human, and environmental health). Physically, large plastic waste can cause entanglement, trapping animals and hindering their movement, which can affect their feeding or survival. Both macroplastics and MPs can be ingested, leading to blockages and injuries in digestive systems, and subsequent potentially adverse impacts on the health and survival of organisms. At the nanoscale, due to their small sizes, nanoplastics can penetrate cellular membranes, causing cellular damage and disrupting critical biological functions[27]. MPs also act as vectors for pollutants[28]. They can have sorbed toxic chemical contaminants, including antibacterial agents, onto their surfaces during environmental transport[29−30]. Once deposited, these pollutants may desorb, introducing toxic substances into previously pristine environments. MPs also leach additives such as flame retardants, plasticizers, and UV stabilizers, which are incorporated during plastic manufacturing[31]. These additives, once released, can pose additional risks to native organisms by disrupting local ecosystems. Another concern is the role of MPs as microbial vectors. MPs can transport microorganisms, including invasive or pathogenic species attached to their surfaces[32−33]. This can facilitate the introduction of new microbial species into fragile ecosystems, with potentially severe consequences for local biodiversity and ecosystem function. In a broader scale, plastic pollution contributes to climate change through several mechanisms[34]. For instance, the slow degradation of plastics releases greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4)[35]. With approximately 8% of global oil production allocated to plastic manufacturing, the cumulative degradation of these materials represents a non-negligible source of greenhouse gas emissions[36]. In aquatic systems, MPs may disturb the biological carbon pump, a key process in oceanic carbon sequestration, and in terrestrial environments, they may alter soil respiration rates, further contributing to the carbon cycle's imbalance[34]. Furthermore, small plastics may influence atmospheric ice nucleation and, if they were present in sufficiently high concentrations, could impact cloud formation and local climate patterns[37−38]. In this context, airborne MPs could play a key role by influencing atmospheric processes, acting as vectors for microorganisms, or causing physical impacts on animals and humans.

2. The role of the atmosphere: Airborne plastic wastes

Recently, research focuses on the plastic cycle, including the mechanisms governing its transport between environmental compartments (Fig. 1)[39−42]. Among these compartments, the atmosphere has recently emerged as a potentially critical pathway. Although atmospheric plastics were only discovered in 2015[20], growing evidence suggests that this compartment could play a significant role in the global distribution of plastic waste, especially MPs[43]. Atmospheric transport enables the deposition of MPs over vast distances, reaching remote areas such as polar regions and high-altitude environments[21,44]. Understanding the atmospheric contribution to the plastic cycle is crucial, as it facilitates the transfer of plastic waste between compartments while influencing its sources, transport, fate, and impacts on the environment, wildlife, and human health.

2.1. Sources

Atmospheric MPs originate from a wide range of sources. In urban areas, MPs are released from synthetic fibers due to washing, drying, and general wear of textiles[45−46]. For instance, it has been estimated that a single 6 kg load of acrylic fabric in a domestic washing machine releases approximately 700,000 fibers[47], while mechanical drying of synthetic textiles contributes to MP emissions in indoor environments[48]. Industrial activities could also represent a significant contributor to airborne MPs, releasing large amounts of particles through the manufacturing, recycling, and incomplete incineration of plastic products[45,46,49]. Other sources include the weathering and abrasion of the painted surface (paints contains binders that are usually made of plastic polymers) and wind erosion of landfills, all of which may contribute to the release of airborne MPs[45].Transport-related emissions are another significant factor, with tire wear, brake pad abrasion, and road dust accounting for a substantial proportion of atmospheric MPs, especially in densely populated and high-traffic regions[49−51].

In agricultural settings, practices such as the use of plastic mulch films, greenhouse covers, irrigation wa-

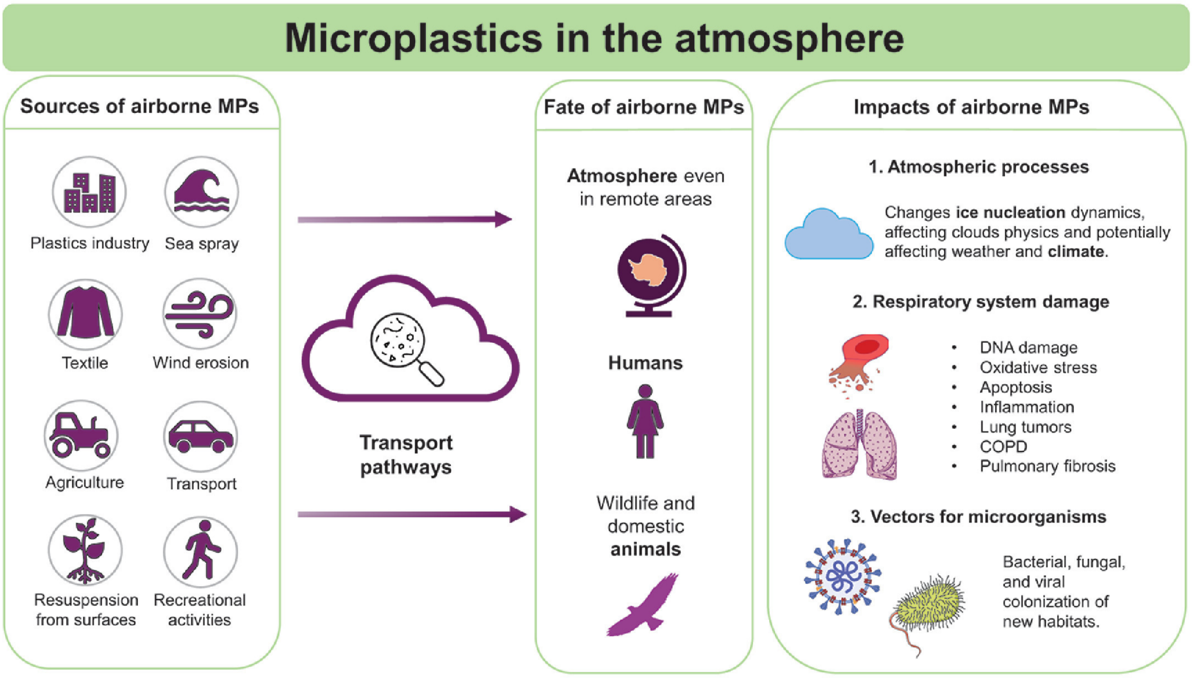

Figure 1: *Sources, fate and impacts of atmospheric microplastics.*

ter, and the application of sewage sludge as fertilizer contribute to MPs entering the atmosphere through wind erosion, mechanical degradation, and other farming activities[45,46,49,51,52]. Furthermore, plants can also act as both a sink and a source of airborne MPs, which can temporarily adhere to leaves (and subsequently released), with measured abundances ranging from 0.06 to 25 items/cm^2 [53–56]. This adherence varies depending on plant leaf micromorphological structures and MP accumulation displays diurnal fluctuations[53]. Once deposited, MPs may be resuspended into the atmosphere by wind or transferred to other compartments when leaves fall or are washed away by runoff[55,57]. Also, the ocean acts as a source of MPs through processes such as sea spray[58–60], where bubble bursting and wave action transfer MPs from the surface of the water into the atmosphere, particularly in coastal regions[46]. In remote areas, tourism, recreational activities and long-range atmospheric transport of small MPs may also introduce MPs into the air.

2.2. Transport

Different processes significantly contribute to suspension, horizontal transport, deposition and even resuspension of MPs. Particles that have settled on surfaces such as soil, vegetation, or sand can be reintroduced into the atmosphere by wind or anthropogenic activities (e.g., agriculture) and those present in the oceans can be resuspended by sea surface spray wave breaking[45,49,55]. This dynamic interplay gives rise to complexity of atmospheric transport of MPs. The transport of atmospheric MPs in the environment remains poorly characterized and highly variable. It seems to depend on the size, shape, length and density of the MP[45,61–63], as well as meteorological parameters such as wind speed, wind direction, precipitation, humidity and air temperature[44,45,50,61]. Although in the case of small fractions, some of these parameters (for instance, the relatively high density of some small fibers of polyethylene terephthalate) does not seem to prevent their resuspension from the ground to the atmosphere via vertical winds[64].

Despite its importance, only a limited number of studies have evaluated the transport pathways or trajectories of MPs in the atmosphere. Most of these studies have employed the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT)[45]. Initial studies on atmospheric MP transport demonstrated that air masses transported MPs over distances of approximately 100 km[61,65] and that no significant differences were observed in the transport fluxes of fibers and fragments, at least in urban environments[64]. Recent studies suggest that MPs can even be transported over larger distances (hundreds of kilometers) than previously expected[44]. However, further research is urgently needed to better understand the sources, transport mechanisms, and fate of atmospheric airborne MPs. Well-known atmospheric models (e.g., LAGRANTO, FLEXPART, CESM or MILORD), which are widely used to model the transport of atmospheric pollutants, could be used for these purposes[45,61].

Table 1. Summary of selected studies on MPs in the atmosphere.

Reference	O/I	Place	Identification	V (m^3)	items/m^3	Filter	Size (µm)	Morphology	Composition
Liu et al.[67]	O	East China Normal University	µFTIR	72-144	0.06±0.01	Glass fiber 1.60 µm	12-2191	Fibers 43%; fragments 48%	PET (51%), EP (19%), PE (12%); cellulose not mentioned
Liu et al.[68]	O	West Pacific Ocean	µFTIR	n.a.	0-1.37 (0.06±0.16 average)	Glass fiber 1.60 µm	16-2087	Fibres 42-58%	PET (57%), EP (10%), PE-PP (6%); cellulose (24%)
Liu et al.[64]	O	Shanghai	µFTIR	6	0-4.18 (average 1.42±1.42)	Glass fiber 1.60 µm	23-9555	Fibres 67%; fragments 33%	PET, PE, and PES (46% altogether); cellulose (49%)
Dris et al.[75]	O	10 km from Paris city center	µFTIR	2-5	0.3-1.5 (median 0.9 only fibers)	Glass fiber 1.60 µm	50-1650	Only fibers	n.a.
	I	Two private apartments and one office	µFTIR	2-5	0.4-59.4 (median 5.4 only fibers)	Glass fiber 1.60 µm	50-3250	Only fibers	Cellulose (67%), synthetic (33%)
Sharaf-Din et al.[87]	I	Islamabad University Campus	µRaman	8.64	4.34±1.93	Whatman's quartz filter paper 1.2 µm	2.7-938 (mean 144)	Fibers 57.6%	PET (52.2%), PE (22.2%), and PP (10%); cellulose not mentioned
	O	Islamabad University Campus	µRaman	23.0	0.93±0.32	Whatman's quartz filter paper 1.2 µm	4.1-893.2 (mean 87.8)	Fibers 66.3%	PET (42.2%), PE (30.0%), PS (14.4%); cellulose not mentioned
Maurizi et al.[88]	I	Meeting room, workshop, and two apartments in Aalborg (Denmark)	µRaman	2.9	58-684 (median 212)	1 µm pore	Approx. 45% in the 1-5 µm range	Fragments 99.4%, fibers 0.6%	PA (21%), PV (polyvinyl polymers, 18%), PE (16%), PS (11%), and PEST (8%); most non-plastic particles were cotton-cellulose
Ding et al.[89]	O	Northwestern Pacific Ocean	µFTIR	1512	0.0046-0.064 (average 0.027±0.018)	Glass fiber filters 1.60 µm	10-4556 (average 853, median 645)	Fibers 88-100%	Rayon (63%), PET (23%), cellophane, PE, PES, PVC-PVA copolymer, and others
Choi et al.[90]	I	Residential houses in Seoul	µFTIR	20.16	0.49-6.64 (3.02±1.77)	CN membrane filters 5 µm	20.1- 6801 (166 average)	Fibers 10.2%	PE (40%), PP (24.6%), PES (13.6 %)
	O	Rooftop in Seoul	µFTIR	20.16	0.45-5.16 (1.96±1.65)	CN membrane filters 5 µm	20.3-4497 (116 average)	Fibers 3.6%	PE (34.7%), PP (33.3%), PA (10.6%)
Perera et al.[91]	O	Different sites in Sri Lanka	µFTIR	10	0.01-0.23	Stainless-steel 1 µm	Mostly in the 100-1900 µm range	Fibres 98%	Natural (59%), semisynthetic (29%), synthetic (12%)
	I	Indoor places in Sri Lanka	µFTIR	10	0.13-0.93	Stainless-steel 1 µm	Most abundant class 100-300	Fibers 98%	Semisynthetic 70%, synthetic 16%, natural 13%
Abbasi et al.[92]	O	City of Ahvaz, Iran	µRaman	1872	0.002-0.017	Glass fiber 1.6 µm	75% < 1000 µm	Fibres 100%	PET, PA and PP
Dong et al.[93]	O	Campus of the Lhasa, Tibet	µFTIR	5-300	0.15-0.63	Glass fiber 1 µm, and PC 1 µm	10-100 (40%)	Fibres 44-54%	Cellophane comprises the majority particles; other polymers PES and PA

Table 1. *Summary of selected studies on MPs in the atmosphere (cont.).*

Reference	O/I	Place	Identification	V (m^3)	items/m^3	Filter	Size (μm)	Morphology	Composition
Wang et al.[69]	O	Atmosphere over the Pearl River Estuary, South China Sea, East Indian Ocean	μFTIR	53-259	0-0.077	Glass microfiber filters 1.6 μm	59-2252	Fibres 88.9%, fragments 11.1%	Plastics (21.05%): PET (50%), PP (22%) and others (28%) including PEVA, PET, PEP, PAN-AA, PR and PA; artificial fibers (4.2%): rayon and cellophane; natural fibers (76.8%): cotton and cellulose
Vianello et al.[94]	I	Indoor air of apartments (Aarhus, Denmark)	FPA-μFTIR	16.8 per sample	1.7-16.2	Silver membranes 0.8 μm	4-398	Fibers 13%, fragments 87%	PES (81%), PE (6%), PA (5%), PP (2%); other polymers (6%): PS, ACR, PU, EPDM, PVAC, EVA, EP, PR, CA, PLA, PC, PU, AR
Syafei et al.[95]	O	Streets in Surabaya, Indonesia	FTIR	0.64	55.9-75.0	Glass fibre 1.6 μm	1000-1500	Fibers 97.5%, fragments 1.27%, films 1.27 %	PES (including PET, 41.7 %); cellophane 58.3%
O'Brien et al.[48]	I	Near domestic laundry dryers	FTIR and Pyr-GC/MS	18.3	1.6±1.8	Glass fibrer 1.6 μm	19-3948	Fibers 100%	PES (100%)
Abbasi et al.[77]	O	Street dusts in Asaluyeh, Iran	Fluorescence, polarized light, SEM	24	0.3-1.1	PTFE filter papers 2 μm	2-100	MPs: Spherules (74%), films (14%); microrubbers: fragments (61%), fibers (36%)	MPs (not differentiated) and microrubbers
Liao et al.[96]	O	Wenzhou, China	μFTIR	63	189±85	Glass fiber 0.70 μm	5-5000	Fragments 89.7-96.3%)	PE (26.8%), PS (17.8%), PES (17.2%)
	I	Wenzhou, China	μFTIR	39	1583±1180	Glass fiber 0.70 μm	5-5000	Fragments 83.5-94.2%	PET (28.4%), PA (20.54%), PP (16.3%)
Zhu et al.[97]	O	Five Megacities of Northern and Southeast China (Beijing, Tianjin, Hangzhou, Shanghai, Nanjing)	μFTIR	75	104-650	Glass fiber 0.70 μm	5.9-1475	Fragments 88.2%	PE (26.6%), PET (16.0%), PS (14.9%), PP (13.6%), PA (7.3%), PVC (6.6%)
Akhbarizadeh et al.[98]	O	Bushehr Port, Iran	Fluorescence analysis and μRaman	2160	0-14.2	Quartz fiber 2.5 μm	<2.5-1000	Fragments 63%, fibers 27%, films 10%	PET (33%), PE (29%), PA (22%), PS (10%), PP (6%)
Chen et al.[99]	O	Outdood nail salons in Taiwan	FTIR	5.08	28±24	Silver membrane 0.2 μm	<50-100	Fragments 99%, fibers 1%	ACR (40 %), rubber (13%), PVC (12%), PU (2%), PEI (2%), PVA (3%), others (28%)
	I	Inside nail salons in Taiwan	FTIR	5.43	46±55	Silver membrane 0.2 μm	<50-200	Fragments 99%, fibers 1%	ACR (27%), Rubber (21%), PU (13%), PVC (9%), PVA (5%), PEI (5%), PCL (6%), other (14%)
Ferrero et al.[100]	O	Poland, Baltic Sea and Gotland Island, Sweden	μRaman and FTIR	n.a.	0-301	n.a. (Glass microscope slide substrates)	Average length and width of 427±59 and 17±2 μm	Fibers 98%, fragments 2%	PC (35.5%), PE (11.8%), PET (5.3%), PU (5.3%), PA (2.6%)

Table 1. Summary of selected studies on MPs in the atmosphere (cont.).

Reference	O/I	Place	Identification	V (m^3)	items/m^3	Filter	Size (μm)	Morphology	Composition
Kernchen et al.[101]	O	Weser River Catchment in Northwest and Central Germany	Raman (active sampling only)	0.56-1.62	37-121 (active sampling only)	Aluminum oxide 0.2 μm	4.1-33 (active sampling only)	Fragments 79%, spheres 21% (active sampling only)	PE (78%), PMMA, PS, EVAc, PP, PVC, PET, PHB
González-Pleiter et al.[21]	O	Rural and urban areas in Spain	μFTIR	8.78	1.5-13.9	Stainless steel 25 μm	42-1709	Rural: fibers (84%) and fragments (16%); urban: fragments (67%) and fibers (33%)	PES, ACR, PA, PU, PS, and polyolefins
Allen et al.[82]	O	Pic du Midi, France	μRaman	7880	0.09-0.66	Quartz fiber 2.2 μm	3.5-53	Fragments 70%, and 30 %	PE (44%), PS (18%), PVC (15%), PET (14%) and PP (10%)
Chang et al.[102]	O	Urban forest, business center, commercial areas, and a public transportation hub in Seoul	μFTIR	24.0± 0.2	0.33-1.21	CN filter 0.45 μm	24.4–2278	Fragments 87.4%), fibers 12.6 %	PP (54%), PET (11%), PE, PEVA, PA, PU, ACR and others
Gaston et al.[103]	O	California, USA	μFTIR or μRaman	4,615	12.0±3.4	Glass fiber 1.60 μm	20-8961	Fragments and fibers	PET (n=1), PS (n=1), Acrylic (n=1), PVC-heat stabilizer (n=12), PS (n=2), polymeric additives (n=2)
	I	California, USA	μFTIR or μRaman	4,615	12.8 ± 4.0	Glass fiber 1.60 μm	20-8961	Fragments and fibers	PS (n=4), PET (n=3), PVC-heat stabilizer (n=7) polymeric additives (n=6), PE (n=2)
Torres-Agullo et al.[104]	I	Barcelona, Spain	μFTIR	n.a.	4.2±1.6 and 17.3±2.4	Nylon net 20 μm	20-23,565	Fibers 53±24% and 73±9%), fragments (balance)	PES (48%), PA (51%) and PP (1%)
Allen et al.[58]	O	French Atlantic Sea	μRaman	18 and 6401	0.06±0.05	Quartz filters	5-140	Films, fiber, fragments	PVC, PS, PP, PET, PE
Xumiao et al.[105]	I	Aveiro, Portugal	Fluorescence microscopy	7.2	0.6-3.9	Quartz fiber 2.2 μm	MPs: 9.6-21, synthetic fibers: 37-10822	MPs: fragments 71.4%, spheres 28.6%. Synthetic fibers also found	n.a.
Xie et al.[106]	O	Shanghai, China	Raman	10	15.9-38.5	Alumina 0.22 μm	2.40-2181	Fragments >85%, beads and fibers	PE (73.8%), PES (9.2%), PVC (3.1%), PP (0.57%), PU (0.34%) and rubber (0.18%);
	I	Shanghai, China	Raman	10	15.6-93.3	Alumina 0.22 μm	2.40-2181	Fragments >85%, beads and fibers	phenolic resins (9.1%) and cotton (1.4%)
Jiang et al.[107]	O	Harbin, China	Raman	0.14	12.8±5.5 and 162.4 ± 44.6	PTFE filter 0.45 μm	6.8-1665	Fibers 69.4%), fragments and spheres	PES (43%), PE (16%), PA (12%), PP (9.0%), PS (11%), and PVC (5.8%)

I: indoor; O: outdoor; n.a.: not applicable or not specified; ACR: acrylic polymers; AR: alkyd resins; CA: cellulose acetate; CN: cellulose nitrate; EP: epoxy resin; EPDM: ethylene-propylene-diene-monomer; EVA: ethylene vinyl acetate; EVAc: ethylene vinyl acetate copolymer; FPA: focal Plane Array; PA: polyamide; PAN-AA: poly(acrylonitrile-co-acrylic acid); PC: polycarbonate; PCL: polycaprolactone; PE: polyethylene; PEI: polyethylenimine; PEP: polyethylene-co-propylene; PES: polyester; PEST: poly-butylene-terephthalate, poly-ethylene-terephthalate; PET: polyethylene terephthalate; PEVA: polyethylene-co-vinyl acetate; PHB: polyhydroxybutyrate; PLA: polylactic acid; PP: polypropylene; PR: phenoxy resin; PS: polystyrene; PTFE: polytetrafluoroethylene; PU: polyurethane; PV: polyvinyl polymers; PVA: polyvinyl alcohol; PVAC: polyvinyl acetate; PVC: polyvinyl chloride; Pyr-GC/MS: pyrolysis-gas chromatography-mass spectrometry; SEM: scanning electron microscope; μFTIR: Fourier-transform infrared microspectroscopy; μRaman: Micro-Raman spectroscopy.

2.3. Fate: Spatial distribution, concentration, characteristics and types

Environment. Regarding the occurrence and spatial distribution of MPs the atmosphere remains one of the least studied environmental compartments. Until recently, when the first direct evidence of MPs in the atmosphere was obtained through air sampling above ground level (within and above the planetary boundary layer) most evidence of their presence in the atmosphere have been conducted near ground level from atmospheric deposition studies (passive methods) or air sampling using suspended particulate samplers or vacuum suction devices (active methods)[64,66−71]. Recently, the presence of MPs in rural and urban areas has been extensively studied. Table 1 summarizes the characteristics of MPs in the atmosphere. MPs have been detected in rural and sub-rural areas, such as Nottingham, (England),72 Paris (France)73 and Hamburg (Germany)[72−74]. Regarding urban regions, MPs have been identified in cities like Paris (France), Hamburg (Germany), Adapazarı (Turkey), Asaluyeh (Iran) and Dongguan and Yantai (China), Shanghai, as well as in several cities in England, Ireland, and Spain[20,66,73−81]. Remote areas including the French Pyrenees[82], the Tibetan Plateau and the air on the Pacific Ocean, South China Sea, East Indian Ocean have shown the presence of MPs. Most recently, MPs were also identified in polar regions [67,69,70,82−86].

Regarding its abundance, studies using suspended particulate samplers have reported atmospheric MP concentrations ranging from 0 to hundreds of MPs/m^3 (Table 1). Atmospheric deposition studies have indicated deposition rates ranging from 0 to thousands of MPs m^{-2} day^{-1} [81−108]. Sampling performed several hundred meters above ground level revealed MP concentrations between 1.5 MPs m^{-3} and 13.9 MPs m^{-2} [21]. Fibers appear to be the dominant shape of MPs detected, followed by fragments and, to a lesser extent, microbeads, films, foams, and granules[45,46,49−51]. Atmospheric MPs ranged in size from >1 µm to <5000 µm[20,21]. Identification methods that are commonly used, FTIR and Raman spectroscopy and mass spectrometry revealed that polyester (PES) seems to be the most abundant atmospheric MP, particularly among fibers[45,46,49−51]. PES accounted for an exceptionally high percentage of MPs in certain locations, including the air over the Pacific Ocean the Pacific Ocean[68]. Other detected MP types include polyethylene (PE), polyacrylonitrile (PAN), and poly(N-methyl acrylamide) (PAM). To a lesser extent, MPs composed of polypropylene (PP), polyamide (PA), polyvinyl chloride (PVC), poly(vinyl acetate) (PVA), rayon, epoxy resin, alkyd resin, phenoxy resin, and copolymers such as polyethylene-polypropylene have also been identified[45,46,49−51].

Fauna. MPs have been identified in the respiratory systems of a wide range of wild, domestic, marine, and terrestrial animals (Table 2). Numerous studies have reported the presence of MPs in the respiratory tissues of various wild bird species, including rock doves (*Columba livia*), barn swallows (*Hirundo rustica*), common buzzards (*Buteo buteo*), black kites (*Milvus migrans*), Eurasian sparrowhawks (*Accipiter nisus*), northern goshawks (*Accipiter gentilis*), common house martins (*Delichon urbicum*), common swifts (*Apus apus*) and white-breasted kingfishers (*Halcyon smyrnensis*) [109−112]. In terrestrial animals, MPs have been detected in the lung tissue of domestic pigs, as well as in dogs and cats[113−114]. In the marine environment, MPs have even been identified in the exhaled air of bottlenose dolphins (*Tursiops truncatus*)[115].

The concentration of MPs in birds has been reported to range from 0.13 to 0.40 MPs/g[111]. In domestic pigs, MP concentrations in lung tissues were measured at 180 particles/g for adults and 97 particles/g for fetal pigs. Interestingly, MPs found in the lungs of fetal pigs are thought to have been transported through the placenta from MPs inhaled or ingested by the mother[113]. In positive samples from dogs and cats, MP concentrations in lung tissues ranged between 4 and 20.5 MPs/g[114]. For other species, the concentration of MPs has not yet been quantified.

Various MP morphologies have been identified in animal respiratory systems, including fragments, fibers, and films[110−112,115]. Among these, fibers are consistently the most prevalent morphology, particularly in the lungs of pigs and birds, aligning with the dominance of fibers among airborne MPs[111−113]. In birds, MP sizes ranged from 28 µm to 2157 µm[110,112]. In cetaceans, particles were all smaller than 500 µm, while fibers measured less than 1.70 mm[115]. In pigs, MP sizes varied between 20.3 µm and 1370 µm[113]. In cats and dogs, MPs ranged in size from 5.5 µm to 8.1 µm[114]. The polymers identified in bird lung samples included PP, PE, ethylene-vinyl acetate (EVA), PES, and acrylic[110−112]. In cetaceans, the most prevalent polymers were polyethylene terephthalate (PET), PE, PA, polybutylene terephthalate (PBT), and polymethyl methacrylate (PMMA)[115]. In adult pigs, the identified polymers included PA, PP, PE, PVC, polycarbonate (PC), and PET, while in foetal pigs, the detected polymers were PC, PP, PVC, PA, PE, and polyurethane (PU). Notably, PU was absent in adult pig lungs[113]. In cats and dogs, PP and PET were the main polymers detected [114].

Table 2. *Summary of selected studies on MPs in wildlife and domestic animals.*

Reference	W/D[a]	Species	Place	Sample treatment	Filter	Identification	MPs/specimen	MPs/g of lung	Morphology	Size (µm)	Composition
Qaiser et al.[109]	W	White-breasted kingfisher *Halcyon smyrnensis*	Water bodies in Pakistan	10% KOH overnight	Not specified	Hot needle test	0-2	Not specified	Not specified	Not specified	Unknown
Tokunaga et al.[110]	W	Rock doves *Columba livia*	Tokio and Ise Bays, Japan	Enzymatic digestion (Proteinase K)+ Oxidative digestion (H_2O_2)+Flotation (NaI)	Alumina 0.2 µm	ATR-µFTIR	0-2	0-1.83 (calculated)	Fragments	28.0-31.8	PE (50 %) and PP (50 %)
		Black kites *Milvus migrans*					-[b]	-[b]	-[b]	-[b]	-[b]
		Barn swallows *Hirundo rustica*					0-2	0-25.6 (calculated)	Fragments	69-71	EVA
González-Pleiter et al.[111]	W	Common Buzzard *Buteo buteo* Black Kite *Milvus migrans* Eurasian Sparrowhawk *Accipiter nisus* Northern Goshawk *Accipiter gentilis*	Madrid, Spain	Digestion (10% KOH, 48 h at 50 °C and 80 rpm)]	Stainless steel 25 µm mesh	µFTIR	n.a.[c]	0.13-0.4 (median values)	Mostly fibers. One fragment	239-255	PES, acrylic, PE, PP, PVC, PS. Also artificial cellulosic particles
González-Pleiter et al.[112]	W	Common House Martin *Delichon urbicum*	Madrid, Spain	Digestion (10% KOH, 48 h at 50 °C and 80 rpm)	Stainless steel 25 µm mesh	µFTIR	1.12±0.45	n.a.[c]	Fibers	120-2157	PES (79%), ACR (14%) and PE (7%). Also, artificial cellulosic fibers
		Common Swift *Apus apus*					0.75±0.30				
Li et al.[113]	D	Adult pigs *Sus scrofa*	Shenyang, China	n.a.[c]	Metal 10 µm pore	PLM[d]	0-1	12	Fibers	115-1370	n.a.[c]
				Predigestion (10 % KOH, 40 °C, 8 h) + Enzymatic digestion (cellulase, 6 h)		LDIR[e]		180		20.3-916	PA (46.1%), PP (21.1%), PE (17.2%), PVC (6.1%), PC (4.4%), PET (2.2%), others (2.8%)
Li et al.[113]	D	Fetal pigs	n.a.[c]	n.a.[c]	n.a.[c]	PLM[d]	n.a.[c]	6	Fibres	139-438	n.a.[c]
			n.a.[c]	Predigestion (10 % KOH, 40ºC, 8 h) + Enzymatic digestion (cellulase, 6 h)	n.a.[c]	LDIR[e]	n.a.[c]	97	Fibres, fragments and irregular shapes	20.3-501	PC (33%), PP (15%), PVC (15%), PA (14%), PE (11%), PU (4.1%), others (6.2%)
Prata et al.[114]	D	Cats *Felis catus* and dogs *Canis familiaris*	Porto, Portugal	10% KOH), filtration, Nile Red Staining	Glass fiber filter 0.2 µm	µRaman	n.a.[c]	0-20.5	n.a.[c]	5.5-8.1	PP, PET
Dziobak et al.[115]	W	Bottlenose dolphins *Tursiops truncatus*	Sarasota Bay (Florida) and Barataria Bay (Los Angeles)	n.a.[c]	Glass fibre filters, 1.6 µm	Hot needle test and µRaman	2-11	n.a.[c]	Fibers (58%), films (42%)	0.24-1704	PET (53%), PES (24%), PA (12%), PMMA (6%), PBT (6%)

[a]: W, wild; D, domestic. [b]: No MPs found. [c]: n.a., not applicable or not specified. [d]: PLM, polarized light microscopy. [d]: LDIR, laser direct infrared imaging. ATR: attenuated total reflectance. µFTIR: micro Fourier transform infrared spectroscopy. µRaman: Micro-Raman Spectroscopy. EVA: ethylene vinyl acetate; PA: polyamide; PBT: polybutylene terephthalate; PC: polycarbonate; PE: polyethylene; PES: polyester; PET: polyethylene terephthalate; PMMA: polymethyl methacrylate; PP: polypropylene; PS: polystyrene; PU: polyurethane; PVC: polyvinyl chloride.

Humans. Humans are continuously exposed to airborne MPs, with inhalation rates estimated to reach up to 174 MPs kg_{bw}^{-1} day^{-1} [116]. Exposure to airborne MPs is influenced by factors such as geographical location, age, and occupation. Individuals from urban areas typically exhibit higher MP concentrations due to increased time spent indoors, where MP levels tend to surpass those in outdoor environments[16] Certain occupational settings exposure to airborne MPs lead to increased deposition in the respiratory tract[117−118]. Furthermore, older individuals are more likely to accumulate higher MP concentrations in their respiratory systems, as fibers tend to persist and accumulate with age[119−120]. Once inhaled, MPs can distribute throughout the respiratory system potentially accumulating in different parts[121−122]. MPs have been detected from the upper airways (nose, mouth, and throat) to the lower respiratory tract, including the lungs[121,123]. MP exposure via inhalation can be assessed through various biological samples including saliva, bronchoalveolar lavage fluid (BALF), sputum, pleural fluid, lung tissue biopsies, or cadaver autopsies[118,119], as well as, using experimental setups, such as breathing thermal manikins, for indoor air sampling[124]. MP concentrations in BALF range from 0.2 to 140.9 MPs/g[125,126], while lung tissue concentrations vary between 0.69 ± 0.84 MPs/g and 14.2 ± 14.6 MPs/g[123,127].

A variety of MP morphologies have been identified in the human respiratory system, including fibers, fragments, spheres, and films. Particle dimensions range from 1.6 µm to 4760 µm [16,119,123,125]. MP deposition within the respiratory system is influenced by particle size, density, and shape. Larger particles are typically cleared by the mucociliary mechanism in the upper airways, whereas smaller and lighter MPs can bypass these defenses and deposit in deeper regions of the lungs, including terminal bronchioles, alveolar ducts, and alveoli[120,124]. Interestingly, fiber width, rather than length, determines whether and where fibers deposit within the respiratory tract[16,120,128]. Once deposited in the lungs, MPs may persist for extended periods or translocate to other tissues or organs[129] Fiber persistence increases with length but decreases with higher dissolution or fragmentation rates[119,130]. Several polymer types have been identified in the human respiratory system, including high- and low-density polyethylene (HDPE, LDPE), PA, polyesters (e.g., PET), PU, PP, polystyrene (PS), PVC, and synthetic copolymers such as polystyrene-co-polyvinyl chloride[16,123,124].

2.4. Impacts

Airborne MPs may pose a risk to environmental, animal, and human health due to both the effect of MPs themselves and the potential release of microorganisms or pollutants previously attached to their surfaces. The impacts of MPs are influenced by several factors, including their size, shape, density, concentration, polymer type, chemical leachates, environmental adsorbents, and the level and duration of exposure[121−123]. However, more research is needed to clarify their impacts, as there is still limited literature in this regard.

Atmospheric processes. The presence of the MPs in the atmosphere above ground level has the potential to influence atmospheric processes, particularly through their potential capacity to act as ice nucleating particles[37,38,131,132]. A recent investigation explored the ice-nucleating activity of four common MP types (LDPE, PP, PVC and PET) under pristine and aged conditions including exposure to UV radiation, ozone, sulfuric acid, and ammonium sulphate[38]. All tested MPs exhibited some degree of ice-nucleating activity, although the effects of aging varied markedly among polymer types. For example, while the aging of LDPE, PP, and PET generally resulted in either unchanged or reduced ice nucleating activity compared to the pristine MPs, LDPE aged with ammonium sulphate displayed a significantly enhanced ice nucleating activity. In contrast, PVC showed either no change or an increase in ice nucleation activity after most aging treatments. Notably, some MPs demonstrated ice nucleating activity comparable to mineral dust particles (kaolinite, a well-known natural ice nucleator in the atmosphere). Furthermore, PP needles (commercially produced) and fibers generated from the breakdown of PP and PET in the laboratory setting were frozen heterogeneously with median freezing temperatures between -20.9 °C and -23.3 °C[131]. These MPs exhibited a number of ice nucleation sites per surface area comparable to volcanic ash and fungal spores. Aging processes, such as exposure to ozone or photooxidation treatments, were found to reduce the ice nucleation activity of PP needles and PET fibers. Additionally, MP fibers from clothing textiles were identified as effective ice nucleators, probably due to biological particles (i.e., cells) attached to their surfaces and enclosed in an extracellular polysaccharide[132]. Treatments with lysozyme and hydrogen peroxide were observed to strip these fibers of their ice nucleation properties, highlighting the role of biological particles in this activity. PE MPs have also been shown to induce heterogeneous ice nucleation via immersion freezing under atmospherically relevant conditions, with their ice nucleation ability being intrinsically linked to their underlying chemical composition.37

In general, many atmospheric particles capable of acting as ice nucleators impact the microphysical and radiative properties of clouds, influencing the Earth's radiative balance[132]. These particles can also influence the lifetimes and optical properties of clouds, with implications for the cloud albedo effect[131]. MPs, with their heterogeneous physicochemical properties, introduce uncertainties into these processes. Recent freezing data indicate that MPs may facilitate ice formation within cloud droplets, a feature that could be integrated into atmospheric models. The potential for MPs to nucleate ice and subsequently participate in precipitation processes may also influence their long-range transport and global distribution[37] Furthermore, MP fibers carrying biological particles warrant special consideration in cloud modelling due to their potential impacts on cloud ice, droplet formation, and precipitation dynamics[132].

However, caution is necessary when extrapolating laboratory findings to larger atmospheric systems. These results emphasize the need to links between MPs and atmospheric processes. For instance, the influence of MP morphology (e.g., fibers, films) or additives on ice nucleating activity remains poorly understood[38]. Additionally, field studies are essential to quantify atmospheric MP concentrations, lifetimes, and the impacts of aging processes on the ice nucleation efficiency of MPs and associated biological particles[132]. Further research is needed to determine whether increasing MPs levels in the atmosphere could significantly change any atmospheric processes.

Respiratory system damage. Airborne MPs are ubiquitous in outdoor and, particularly, indoor environments where humans are exposed to them daily. One of the most fundamental activities humans perform is breathing, which inevitably involves inhaling MPs (Section 2.3.1). The potential risks of airborne MPs to human health have been recognized since the 1980s[117,133,134]. An epidemiological study on workers exposed to PVC dust reported an association with reduced lung function, mild abnormalities in chest radiographs, and complaints of slight dyspnea[133]. Another study identified plastic fibers as potential agents contributing to lung cancer risk[134]. Workers in the nylon flocking industry were shown to have a substantially elevated risk of occupational interstitial lung disease, with a 48-fold or greater increase in the sex-adjusted incidence rate among a 165-member cohort[117]. Currently, it is well-established that certain occupational settings serve as significant sources of airborne MPs, posing substantial risks to worker health. Industries with high MP exposure levels include the synthetic textile sector, the flocking industry, and PVC manufacturing[135]. Other high-risk environments include facilities where plastic substrates are ground or drilled, waste management and recycling facilities and extrusion-based 3D printing operations[136,137]. For instance, PC filaments and acrylonitrile butadiene styrene (ABS) have been detected in workplace air during industrial-scale additive manufacturing[132]. Additionally, occupations requiring frequent use of face masks or respirators may also lead to heightened MP exposure[132]. These findings highlight the need to assess respiratory risks in workers ,exposed to MPs during plastic product manufacturing and related industries[137−139].

In addition to occupational exposures, numerous studies in laboratory conditions have shown that inhaling airborne MPs could increase the risk of developing lung diseases. Research conducted using human cell cultures, in vitro models, in vivo animal studies, and human subjects has revealed various adverse effects. Studies in human cells have shown that MP exposure can lead to morphological changes, altered metabolism, cytotoxicity, inflammation, inhibition of cell proliferation, DNA damage, and increased reactive oxygen species (ROS) production, contributing to oxidative stress[121,121]. In lung-related cell lines, PVC has been shown to induce cellular senescence via ROS production, while PS causes pulmonary cytotoxicity and inflammatory responses by promoting ROS accumulation, both of which increase the risk of lung diseases[122,140]. In vivo studies have shown that inhalation of MPs leads to pro-inflammatory responses, granuloma formation, ROS-induced cellular senescence, alveolar destruction, and pulmonary fibrosis, with these effects being dose- and size-dependent[140,141]. Associations have also been found between microfiber concentrations and radiological abnormalities, pathological microbial growth, and reduced lung function[119]. MPs have been implicated in the development of tumors, pulmonary ground-glass nodules, chronic obstructive pulmonary disease and interstitial lung disease[117,120,122]

Few studies have investigated its effects on animals beyond mammals, highlighting a significant gap in understanding its broader ecological impact. Lung tissues of chickens exposed to PS MPs showed upregulation of Bax/Bcl-2 expression and increased activity of the Caspase family, alongside elevated phosphorylation levels within MAPK signaling pathways (p38, ERK, and JNK), ultimately promoting apoptosis. Additionally, MPs activated the antioxidant defense system, but an imbalance in this system modulated the Caspase family and triggered the PTEN/PI3K/AKT pathways, initiating apoptosis and autophagy processes that collectively contributed to lung tissue damage in chickens[142].

Vector for microorganisms. MPs can act as vectors for microorganisms, facilitating the spread of microbial populations and enabling the colonization of new habitats. These particles are capable of transporting both non-pathogenic and pathogenic microorganisms, thereby posing potential risks to human and animal health. The surface properties of MPs enable the adsorption of nutrients and water, creating a nutrient-rich microenvironment conducive to microbial growth. Despite the increasing recognition of the presence of airborne MPs, only a limited number of studies have focused on microorganisms attached to these particles in the atmosphere[143−147].

A study has demonstrated that fibers colonized by viable microorganisms can be found at altitudes hundreds of meters above ground level[145]. At ground level, concentrations of airborne microorganisms, including bacteria and fungi, have been positively correlated with the presence of MPs[107]. Notably, the characteristics of airborne MPs and the pathogenicity of airborne bacterial communities exhibit significant positive correlations, particularly with MP size and the immune-mediated disease risks associated with atmospheric microbes. Among these, *Sphingomonas* has been identified as a potential key mediator[143]. Additionally, the abundance of certain bacterial phyla, such as Actinobacteria, has shown positive correlations with specific types of airborne MPs (i.e., PA, PET and PP) in indoor environments, where evidence further suggests that the abundance of airborne MPs is positively associated with the abundance of antibiotic resistance genes[146]. Airborne MPs have also been implicated in the spread of viruses; for example, suspended MPs have been positively correlated with the quantification of SARS-CoV-2 envelope genes[147]

3. Conclusions

Taken together, the atmosphere remains the least studied environmental compartment in terms of the occurrence, spatial distribution, and consequences of MPs. Despite recent advancements, significant knowledge gaps persist, hindering our understanding of the full life cycle of airborne MPs, including their sources, transport mechanisms, environmental fates, and impacts. As this is an emerging field of research that has been active for less than a decade, the development of new methodologies and innovative approaches is essential to address the following unresolved challenges. First, global standardization of data collection protocols148 and analytical methods for suspended and deposited MPs in environment, humans[149] and animals as well as standardized elution protocols to evaluate microorganisms attached to airborne MPs[150], are urgently needed to ensure consistency and comparability across studies and regions. Second, a deeper understanding of ice nucleation processes involving airborne MPs is imperative, given their potential to influence cloud formation. Third, improvements of the atmospheric transport are necessary to incorporate long-range MP transport from lower altitudes, as well as resuspension processes from soil and water sources[151]. Addressing these research gaps is vital for advancing our understanding of atmospheric MPs and their broader implications for environmental and human health, particularly within the context of the "One Health" framework.

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