Airborne Microplastics: Occurrence, Sources, Fate, Risks and Mitigation

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Abstract

This paper serves to enhance the current knowledge base of airborne microplastics which is significantly smaller than that of microplastics in marine, freshwater and terrestrial environment. It systematically presents the prevalence, sources, fate, risks and mitigations of airborne microplastics through the review of more than 140 scientific papers published mainly in the last 10 years. Unlike the extant review, it places an emphasis on the indoor microplastics, the risks of airborne microplastics on animals and plants and their mitigations. The outdoor microplastics are mostly generated by the wear and tear of tyres, brake pads, waste incineration and industrial activities. They have been detected in many regions worldwide at concentrations ranging from 0.3 particles/m^3 to 154000 particles/L of air even in the Pyrenees Mountains and the Arctic. As for indoor microplastics, the reported concentrations range from 1 piece/m^3 to 9900 pieces/m^2/day, and are frequently higher than those of the outdoor microplastics. They come from the wear and tear of walls and ceilings, synthetic textiles and furniture finishings. Airborne microplastics could be suspended and resuspended, entrapped, settle under gravity as well as interact with chemicals, microorganisms and other microplastic particles. In the outdoors, they could also interact with sunlight and be carried by the wind over long distance. Airborne microplastics could adversely affect plants, animals and humans, leading to reduced photosynthetic rate, retarded growth, oxidative stress, inflammatory responses and increased cancer risks in humans. They could be mitigated indirectly through filters attached to air-conditioning system and directly through source reduction, regulation and biodegradable substitutes.

Keywords: Airborne microplastics; indoor; outdoor; transport; deposition; suspended

1. Introduction

Over the past decades, microplastic(s) (MPs) have become an emerging concern globally. As an entirely anthropogenic type of pollution, they are regarded as the by-products of the era of human dominance on planet Earth (Gasperi et al., 2018; Shao et al., 2022). The term microplastics was first introduced by Thompson et al. (2004) and it means very small plastic particulates and fibers. The National Oceanic and Atmospheric Administration (NOAA) defines MPs as tiny ubiquitous plastic particles less than 5 mm in diameter (Arthur et al., 2009). Frias and Nash (2019) proposed a more detailed definition of MPs which states that they are any synthetic solid particles or polymeric matrices, with regular or irregular shapes and with sizes ranging from 1 μm to 5 mm.

MPs could either be of primary or secondary origin and they are insoluble in water. During the process of waste generation, collection, transportation, and treatment, primary MPs are discharged directly into the environment through mechanical actions, including compressing, stirring, and reception (Cole et al., 2013). Secondary MPs are generated by the photochemical effects, wind erosion, and biodegradation of bulk plastics (Devriese et al., 2015). Airborne MPs are contributors to MPs pollution in aquatic and soil environments (Wang et al., 2021a). Polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyethylene terephthalate (PET) are the dominant polymer components of MPs in atmospheric fallout (Chen et al., 2022).

According to Prata (2018a), the most important sources of airborne MPs consist of wear and tear of synthetic textiles, abrasion of synthetic rubber tires, as well as urban and household dust (Dris et al., 2016 & 2017). Other sources of airborne MPs may include construction materials, waste incineration, landfilling (Dris et al., 2016), industrial outflows, roadway particles, resuspension of particles (Devriese et al., 2015), and synthetic particles such as PS peat which is applied in horticulture (Prata, 2018a, 2018b).

Normally, airborne MPs occur as films and fibers. Fibrous MPs are generally produced from textiles, and a large number of fibers is produced during mechanical processes, such as washing clothes (Fu and Wang, 2019). Film MPs are typically generated during the degradation of plastic bags. Since they are directly produced in primary sources and do not undergo secondary decomposition in the air environment, the particle sizes of film MPs are generally large (Hu et al., 2022). The fate and dispersal of MPs in the air environment depend on particle characteristics such as density, length, and diameter, as well as environmental factors that include wind, air currents, and precipitation. Zhang and Wu (2022) found that MPs features, aerodynamics, and their sources collectively determine the pollution characteristics and transport of MPs in the atmosphere. The abundance of airborne MPs is associated with human activities, population density, and industrialization level (Liu et al., 2019a).

Researchers found that airborne MPs may pose a greater risk to public well-being than those in water, food, or soil (Pauly et al., 1998; Prata, 2018a). This is because airborne MPs could gain access to the human body through both inhalation and ingestion. Once MPs are ingested by organisms, serious physical and physiological threats may occur in their bodies, including obstruction, inflammation, reduced growth rate, oxidative stress, and reproductive complications (Alomar et al., 2017; von Moos et al., 2012; Wright et al., 2013). In addition, contaminants such as heavy metals and toxic chemicals, as well as microorganisms tend to adsorb onto MPs surfaces due to the large specific surface area and stronger sorption capacities of MPs (Koelmans et al., 2013; Reisser et al., 2014). MPs are easily transferred and bioaccumulated through the food chain, and may eventually be transferred to humans, posing a potential threat to human health (Rochman et al., 2015; Seltenrich, 2015).

The physical characteristics, polymer types, and concentrations of airborne MPs are typically determined using a stereomicroscope and Fourier Transform Infrared Spectroscopy (FTIR). Analytical progress in MPs detection and quantification has permitted studies on the estimation of the inhaled MPs in different microenvironments (Torres-Agullo et al., 2022), and the occurrence and ecological effects of MPs in water and soil to be conducted (Wang et al., 2021a). Besides, there has been substantial research into the occurrences of MPs in the marine environment, freshwater systems, and terrestrial environment (Alfaro-Núñez et al., 2021; Dobaradaran et al., 2018; Stanton et al., 2020; van Cauwenberghe et al., 2013) including remote areas (Lusher et al., 2015; Stanton et al., 2020). However, there is still a large knowledge gap around the airborne MPs particles, particularly their emission factors, size distribution, atmospheric transport and fate, and the interaction between the urban and oceanic environments on the environmental behaviors of MPs (Coleman et al., 2017; Keeney and Raiffa, 1979). The majority of studies about airborne MPs published so far focused on atmospheric deposition. Several studies are longitudinal in nature, extending over multiple seasons up to 12 months (Dris et al., 2016; Klein and Fischer, 2019).

Due to the relatively limited studies on airborne MPs, there is currently a lack of reviews on airborne MPs. The extant reviews center on the analysis, outdoor occurrence, transport, and human risks of airborne MPs (Chen et al., 2020a; Enyoh et al., 2019; Huang et al., 2020). There is a need for a comprehensive review capturing the latest progress in airborne MPs, particularly that which also includes their indoor occurrences since indoor airborne MPs have been reported in multiple scholarly papers, as well as their risks on plants and animals (Liao et al., 2021; Huang et al., 2021a). Airborne MPs have been reported to gain access to plants and animals, bringing potential impacts on their health and that of the ecosystem as a whole (Campanale et al., 2022). However, these dimensions of airborne MPs are rarely covered in the extant review. The present literature review, therefore, aims to systematically present the most recent progress in the studies of airborne MPs, particularly their occurrences and distributions in different parts of the world, their sources, and fate in the environment encompassing transport and transformation, as well as the risks of airborne MPs to plants and animals. This review also proposes methods for mitigating airborne MPs. Different from the previous reviews, this review covers the occurrences of indoor MPs and the impacts of MPs on plants and animals. It places an emphasis on the mitigation of airborne MPs which is crucial to reduce their prevalence in the atmosphere to safeguard public health.

2. Prevalence of Airborne MPs

Airborne MPs have been detected in both indoor and outdoor environments. While there are comparatively more studies on outdoor airborne MPs, studies related to their indoor presence are increasing. There are increasing evidences that indoor air contains higher concentrations of MPs than outdoor air, and in some cases, by an order of magnitude (Liao et al., 2021) . This section presents the prevalence of outdoor and indoor MPs in the air environment.

2.1. Outdoor Airborne MPs

In recent years, atmospheric MPs transportation and prevalence have been considered as important factors, that may cause MPs accumulation in terrestrial and aquatic environments. One study has suggested that marine MPs pollution stems from MPs in the terrestrial environment and atmosphere in Shanghai and the west Pacific Ocean regions. For atmospheric sources, atmospheric deposition (wet deposition and dry deposition) and suspended atmospheric particles are two main contributors to marine MPs pollution. Collecting and collating relative atmosphere MPs distribution and quantity data in the world is crucial to gain insight into the latest situation of the MPs pollution around us.

MPs in the atmosphere are all from anthropogenic activities and can be subdivided into industrial, domestic, and agricultural sources (Abbasi et al., 2019; Dris et al., 2016) . PE, PP, and polyester (PES) are the raw materials widely used in the plastic industry. PE can be used to manufacture agricultural films, which are extensively used in the field to protect the growth of crops. It can also be used to make containers and bags. PET is a significant raw material, which is widely used in the textile industry to manufacture cloths (PlasticsEurope, 2018). Nylon is another highly abundant MPs found in the atmosphere due to its versatile uses, such as in wheels, textiles, and ropes.

Because anthropogenic activities occur throughout the world, almost all places including the remote and unfrequented regions have MPs detected. The latest research has revealed that atmospheric transportation can spread MPs to remote regions without any local sources (Allen et al., 2019) . In Pyrenees Mountains located between France and Spain, the average deposition rate of MPs particles was 365/m^2 d, and the predominant sizes of MPs fibers were under 300 nm (Table 1). The region also had a large number of MPs fragments, and more than 70% were less than 50 nm (Allen et al., 2019). Besides, film MPs were also detected in the region with sizes ranging between 50 and 200 nm (Allen et al., 2019). In the arctic region, the number of MPs deposited in melted snow samples is between 0 and 14400 particles/L, compared to European cities' samples with 190 to 154000 particles/L (Bergmann et al., 2019)(Table 1). This indicates that the arctic MPs concentrations could be higher than some European cities, though the Arctic is located far from the urban and industrial areas. A comparison of the arctic MPs abundance with those in Dongguan, China (Cai et al., 2017) and Paris, France (Dris et al., 2017) shows that the abundance of arctic MPs is over 4 orders of magnitude higher than those in the two cities (Table 1) (Bergmann et al., 2019). However, it is likely to have some uncertainties in the results due to the different sampling and quantification methods used in those studies and the removal of aerosol particles by rain and snow. To be specific, the arctic study set 11 μm as the lower size limit of MPs particles, but in the other two studies, the lower limits of particle size were higher at 50 and 200 μm respectively. In addition, snowfall and rainfall are effective ways to eliminate aerosol particles, leading to the sedimentation of a large number of particles during the process. (Zhang et al., 2020a). The MPs particle sizes are also reported to be different between snow samples in Europe and the arctic region. In the European study, about 80% of the detected microplastics were smaller than 25 μm, while in the arctic study, over 98% of MPs diameters were distributed in the range of lower than 100 μm (Bergmann et al., 2019) . This implies an inverse relationship between the diameter and abundance of MPs, which forms a significant feature in the studies of atmospheric MPs (Bergmann et al., 2019). Plastic fibers also demonstrate such relationship. According to the same study in Europe, the length of fibers ranged from 65 to 14314 µm, and 97% of them could be classified as MPs (97% <5mm) (Bergmann et al., 2019). The counts of these microfibers showed an increasing trend with decreasing lengths. Besides, having compared the fibers in the snow of Europe and the Arctic, the study revealed that European fibers were significantly longer than the arctic ones (with maximum fiber length excluded) (Bergmann et al., 2019).

Table 1: The prevalence of outdoor MPs in different regions

Country/Region	**Type of MPs Samples**	**Concentration of Airborne MPs**	**Reference**
Paris	Dry and wet deposition	118 MPs/m^2 d	Dris et al., 2017
	Suspended MPs particles	0.3 – 1.5 MPs/m^3	
Hamburg	Dry and wet deposition	275 MPs/m^2 d	Dris et al., 2016
Pyrenees Mountains	Atmospheric deposition	365 MPs/m^2 d	Allen et al., 2019
Other European cities	Wet deposition (snow)	190 – 154000 MPs/L	Bergmann et al., 2019
Dongguan	Atmospheric deposition	36 MPs/m^2 d	Cai et al., 2017
Shanghai	Suspended MPs particles	0 – 2.84 MPs/m^3	Liu et al., 2019c
Yantai	Atmospheric deposition	602 MPs/m^2 d	Zhou et al., 2017
Asaluyeh	Street dust	60 MPs/g	Abbasi et al., 2019
	Suspended MPs particles	0.3 – 1.1 MPs/m^3	
Arctic	Wet deposition (snow)	0 – 14400 MPs/L	Bergmann et al., 2019

It was also found that the atmosphere above cities often has a higher abundance of MPs particles due to the effects of industry and human activity. In Yantai city, a coastal city in China, the atmospheric deposition of MPs was reported to be 602 particles/ m^2 d (Table 1)(Zhou et al., 2017). It is the highest abundance of MPs reported in China. The main particle diameters were smaller than 500 μm, accounting for 50% of total MPs particles detected. The predominant types of microplastic polymers were PS foams, PE fragments, PET fibers, polyvinyl chloride (PVC) fibers and films. Fiber was the predominant shape of the MPs particles, which accounted for over 60% of all MPs particles detected (Zhou et al., 201).

Shanghai, another coastal city in China located in the south of Yantai, has similar weather and geographical conditions as Yantai. A study revealed that the number of suspended MPs particles in the air of Shanghai was 1.42 ± 1.42/ m^3, and it could go up to as high as 4.18 particles/ m^3 (Table 1)(Liu et al., 2019c). Compared to the abundance of MPs fiber of 0.3 to 1.5 particles/ m^3 in Paris, Shanghai has a much higher concentration of MPs particles due to the larger population size, greater industrial density and higher anthropogenic activities. The dominant shape of MPs in Shanghai was similar to that of other cities in China, namely Dongguan and Yantai, where fiber was the major shape. In Shanghai, the proportion of fiber-shaped MPs particles in atmospheric deposition was 60%. In terms of the length of the MPs fiber, 30% of them were in the range of less than 500 μm (Liu et al., 2019c).

In the European city of Hamburg, the average rate of atmospheric MPs deposition was 275 particles/ m^2d, while in Paris, it was 118 particles/ m^2d (Table 1) (Dris et al., 2016). In Hamburg, the dominant shapes of microplastics were different from China. Among MPs particles of all shapes, there were 95% fragments, and the remaining 5% were fibers. 60% of the MPs fragments were less than 63 μm, and 30% of them were between 63 to 300 μm. As for fibers, the dominant diameters were in the range of 300 to 5000 μm (Klein and Fischer, 2019). This is longer than the predominant fiber diameter of 500 μm in Yantai and Shanghai (Liu et al., 2019c). In Hamburg, Germany, the predominating types of MPs were PE and EVA (ethylvinyl acetate), at the percentages of 48.8% and 22.0% respectively. The MPs types were distinctly different from other regions in the world where EVA is less commonly reported (Klein and Fischer, 2019).

Asaluyeh is a city in the southern coastal region of Iran with the Persian Gulf in its southwest, and mountains in its northeast. Due to the geographical location, Asaluyeh has poor ventilation and poor air quality (Jafarigol et al., 2016). Analysis of the samples of street dust and atmospheric dust of the city revealed that the highest concentration of MPs in street dust was 66.7 particles/g, and the lowest was 3.3 particles/g. On average, there were 60 MPs particles/g of street dust (Table 1)(Abbasi et al., 2019). The dominant shapes of MPs in street dust were spherules and films, at the proportions of 74% and 14% respectively. In terms of the distribution of MPs by shape, film, spherical and fragmented shapes were more likely to appear in industrial regions, while fibrous shape was more common in urban regions (Abbasi et al., 2019). With regards to MPs sizes, all MPs particles except those of spherical shape followed the normal distribution with sizes in the range from 100 to 250 µm having the highest prevalence. For spherical particles, there were about 98% of them distributed in the smallest size range of < 100 µm, instead of 100 to 250 µm (Abbasi et al., 2019). As for suspended MPs in Asaluyeh, 8-day sampling in urban and industrial regions retrieved a total of 220 particles, and the abundances of particles were almost equal in the urban and industrial regions. The average number of MPs particles was in the range of 0.3 to 1.1 per cubic meter (Abbasi et al., 2019). Because the suspended MPs particles are extremely tiny (less than 10 µm and some even less than 2.5 µm) and brittle, accurate identification of their shapes and numbers was a limitation (Abbasi et al., 2019).

2.2. Indoor Airborne MPs

In indoor environment, MPs are emitted into the atmosphere by various sources such as synthetic clothing and house furniture (Patil et al., 2021). Microfibers are abundantly present in the atmosphere. Due to their low densities and small sizes, they disperse quickly and can reach the respiratory tracts (Tunahan Kaya et al., 2018). The behaviour and concentrations of MPs in the atmospheric environment depend on their size, density, and local atmospheric conditions (Batool et al., 2022).

The health risk caused by ubiquitous airborne MPs should not be neglected as the maximum annual outdoor exposure of airborne MPs can reach 1 million/year, and indoor exposure may be even higher due to higher indoor airborne MPs concentrations (Liao et al., 2021) . It has been reported in multiple studies that the prevalence of indoor MPs is significantly higher than that of outdoor. Dris et al. (2017) evaluated the indoor and outdoor air for airborne fibers. The study sites consisted of private apartments and offices (for indoor) while outdoor air samples were taken just outside the apartment. Results revealed that indoor environment had higher deposition rate and concentrations of microfibers than outdoor environment, probably due to factors such as partition, ventilation, and airflow in enclosed spaces favoring indoor deposition rate (Table 2).

Thirty-two airborne indoor deposited dust samples were collected in glass Petri dishes from Sydney (Australia) homes, over one month in 2019 (Table 2). The samples were analysed using a stereomicroscope, a fluorescent microscope and micro-FTIR spectroscopy for their colour, size, shape and composition. The study revealed that the deposition rates of fibrous MPs ranged from 22 to 6169 fibres/m^2/day (Table 2). Deposited dust comprised 99% fibers. The highest proportion of fibers (19%) was 200–400 µm in length. Majority of the fibers were natural (42%); 18% were transformed natural-based fibers; and 39% were petrochemical-based. A significant difference was observed between MPs deposition rate and the abundance of different polymer types of MPs on main floor covering ($p < 0.05$). PE, PES, polyamide, polyacrylic, and polystyrene fibers were found in higher abundance in homes with carpet as the main floor covering. Where carpet was absent, PVA fibers were the most dominant type of petrochemical fiber, indicating the role of flooring materials (e.g. wood varnishes) in determining MPs composition. Vacuum cleaner use was significantly related to MPs deposition rates (Soltani et al., 2021) 2021).

Table 2: The prevalence of indoor MPs in different regions

Country/ Region	**Type of MPs**	**Concentration of Airborne MPs**	**Reference**

Paris, France	Fibers	1 – 60 m^{-3} (Mean = 5.4)	Dris et al., 2017
Shanghai, China	Particles	500 – 29000 m^{-2} day^{-1}	Zhang et al., 2022
California, USA	PS, PE, and PET	3.3 ± 2.9 fibers m^{-3}	Gaston et al., 2020
	PVC and PE	12.6 ± 8.0 fragments m^{-3}	
Shanghai, China	PES and RY	9.9 × 10^3 MPs/m^2/day(dormitory)	Zhang et al., 2020b
		1.8 × 10^3 MPs/m^2/day(office)	
		1.5 × 10^3 MPs/m^2/day(corridor)	
Aarhus, Denmark	PES, PE, and NY	1.7 – 16.2 MPs/m^3	Vianello et al., 2019
Eastern coast, China	-	1583 ± 1180 MPs/m^3	Liao et al., 2021
Edinburgh, UK (Europe)	PET, PUR	5 ± 3.3 to 10 ± 4.2 MPs/m^3	Catarino et al., 2018
Sydney, Australia	PE, PES, NY, PAA, and PS	22 to 6169 fibers/m^2/day	Soltani et al., 2021
Bushehr port and Shiraz, Iran	PE	90.8 and 80.8 MPs/mg	Kashfi et al., 2022
Barcelona, Spain	ES, PA, and PP	8 ± 1.9 MPs/m^3 in subways, 17.3 ± 2.4 MPs/m^3 in buses, 4.8 ± 1.6 MPs/m^3 in houses	Torres-Agullo et al., 2022

In another study, levels and characteristics of MPs in the indoor dust of buildings with different uses including residential houses, mosques, hospitals, kindergartens, and universities in two cities namely Bushehr Port and Shiraz in Iran, were determined. Thirty dust samples from various buildings were collected. The average numbers of MPs in the indoor dust of the buildings in Shiraz and Bushehr were 90.8 and 80.8 items/mg, respectively (Table 2). Fiber and polyethylene (PE) were the most common shape and polymer type of identified MPs, respectively. The highest number of MPs was observed in the indoor dust of kindergartens with a mean number of 121 items/mg in Bushehr and 104 items/mg in Shiraz. Except for mosques, a significant difference was not observed between the MPs levels in buildings with similar purposes in Bushehr and Shiraz cities. In addition, high daily intake of MPs via indoor dust ingestion and inhalation was found among infants in kindergartens and mosques (Kashfi et al., 2022).

In Barcelona, Spain, MPs concentration in buses was reported to be significantly different from other micro-environments ($p < 0.001$). Buses and subways are often crowded, which means that there are many fibers and particles contributed by synthetic textiles, and this correlates with the concentrations of airborne MPs in those micro-environments. However, higher MPs concentrations were observed in buses compared to the subway. A factor that could influence the difference in MPs concentrations between buses and subway wagons was the air conditioning system that operated in the subway network, especially during the COVID-19 pandemic. This system continuously exchanged air between the inside and outside of the wagons, renewing the whole indoor atmosphere every 2.5 min. The MPs concentrations were relatively consistent except for summer when they were higher due to the adjustment of ventilation (Torres-Agullo et al., 2022) . In Edinburg, UK, Catarino et al. (2018) studied household fibers fallout during a meal (Table 2). Fiber sizes observed in their study were generally < 500 μm and the fibers were composed of PET and polyurethane (PUR). The observed deposition rate and concentrations were 1666.8 – 1671.84 particles/day/m^2 and 5 ± 3.3 to 10 ± 4.2 particle/m^3, respectively (Table 2). They concluded that large quantities of MPs were consumed through meals during evening period when cooking was mostly done.

There has been increasing interest in indoor fibers. The production of synthetic fibers continues to increase annually at an approximate rate of 6.6% (Gasperi et al., 2018). In 2016, more than 90 million metric tons of textile fibers were produced (Gasperi et al., 2018), of which approximately 10 million metric tons were synthetic plastic fibers. However, with the increase in the manufacture and use of synthetic fibers, there is no clear trend in the compositions of fibers (whether natural or synthetic) in indoor and outdoor compartments. The compositions might be influenced by the human activities in those compartments. For example, Dris et al. (2017) observed that 67% of fibers detected in indoor environments (Paris, France) were of natural materials while synthetic ones only made up 33%. In contrast, Vianello et al. (2019) observed that synthetic fibers constituted 50% of the total fibers collected in their study conducted in Edinburg, UK, in indoor compartments. Further study is therefore required to better understand this variation. The variability could be partly contributed by a lack of standard operation protocols (SOPs) in the sampling and analysis of indoor airborne MPs. As this review places an emphasis on indoor MPs which is currently understudied compared to outdoor MPs, a review of the methodology for assessing indoor MPs is included.

There are currently no SOPs for MPs analysis in the environment. While SOPs for sampling and analysis of MPs in the marine environment (sand, beach) have been extensively reviewed and documented (Besley et al., 2017; Löder and Gerdts, 2015; Wagner et al., 2017), none were reported on the analysis of airborne MPs. This is mainly due to the lack of studies regarding indoor airborne MPs and only few studies have been published to date. Therefore, we also included a short review of the available methods reported in literature for assessing airborne MPs in indoor atmosphere. The possible procedures for sampling and pre-treating airborne MPs are presented in Figure 1.

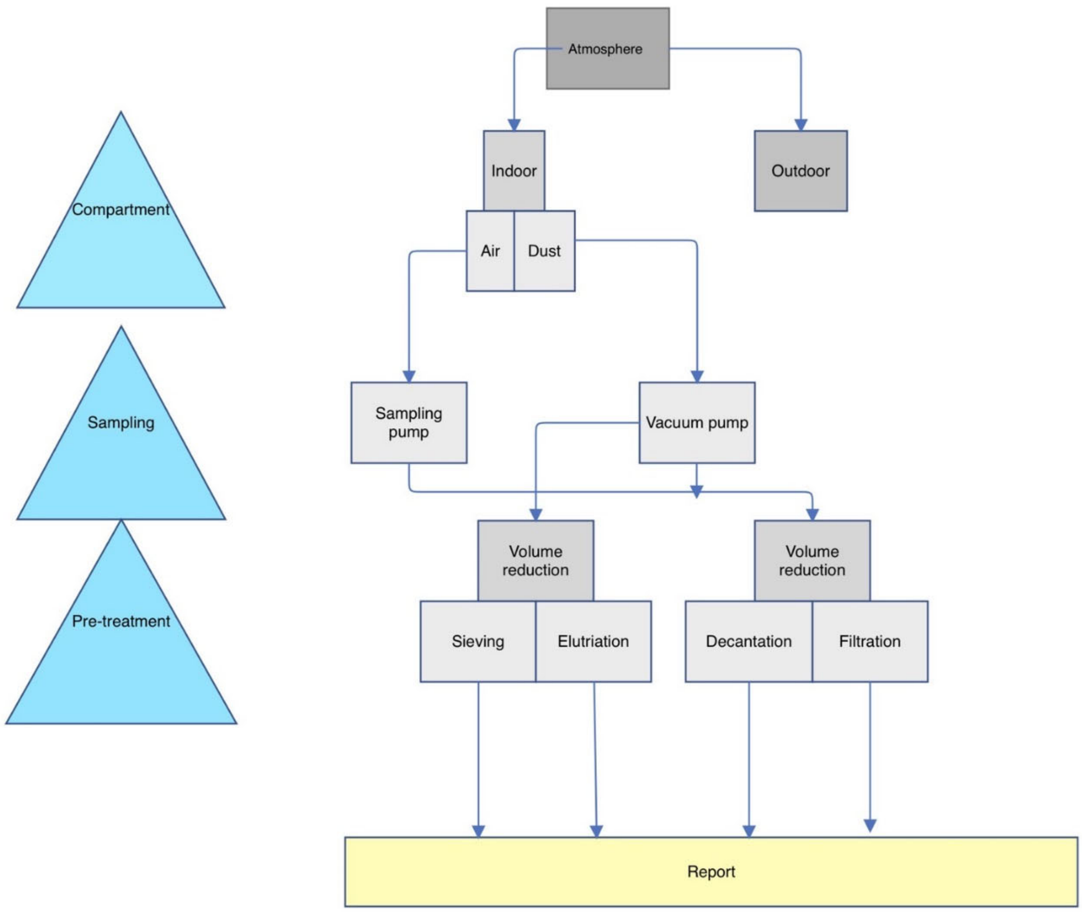

Figure 1. Methods for sampling and pre-treatment of airborne MPs

The sample collection materials/ instruments and methods are different based on the location of air sampled, whether indoor or outdoor. For indoor air, a sampling pump can be used for sample collection. An example of such pump is the stand-alone sampling pump used by Dris et al. (2016). Meanwhile, for deposited indoor MPs, dust can be sampled by a vacuum pump or vacuum cleaner normally used in homes and dust particles are collected in filter bags (Enyoh et al., 2019)(Figure 1).

MPs in settled indoor dust have the tendency of adhering onto dust particles, so they are separated based on their density. Density separation is achievable by the use of $ZnCl_2$ solution. This will cause the MPs particles to either float or sink in the solution depending on plastic type, thus enabling separation. Once separated, they are then further treated (post-treatment) for removing natural debris or unwanted materials on MPs surfaces using fairly aggressive chemicals such as KOH, H_2O_2, $HClO_4$, and HNO_3 or enzymatic digestion (Erni-Cassola et al., 2017; Wagner et al., 2017).

The final analysis before reporting of results includes the use of different spectroscopic or spectrometric techniques. The common techniques for distribution determination and quantification include the use of microscope or naked eye for visual identification, as well as pyrolysis gas chromatography-mass spectroscopy (Pyr-GCMS), thermal desorption system gas chromatography-mass spectroscopy (TDS-GCMS), Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, and scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS) for compositional profile. The experimental principles and their usefulness for MPs analysis have been extensively reviewed (Klein et al., 2018; Wagner et al., 2017). The analytical techniques are often used in tandem, i.e. separating followed by quantifying or observing followed by confirming. For example, identification of MPs of size < 500 µm by visual identification alone is not recommended and, therefore, requires a follow-up technique for confirmation such as micro-FTIR and micro-Raman (Hidalgo-Ruz et al. 2012).

3. Source of Airborne MPs

MPs enter the atmospheric environment via multiple pathways depending on their sources. One of the main sources is synthetic fibers in textiles. Dris et al. (2016) studied atmospheric fallout in the urban and suburban areas of Paris and surprisingly found a large number of fiber components in the fallout where those of petrochemical origin took up 29% of the total. To be exact, 12% of them were mixtures of multiple materials while the remaining 17% consisted of pure synthetics including PET and PA, two polymers widely used in textiles. Some research conducted in China showed similar findings, indicating that geographical factor does not seem to largely influence the result (Cai et al., 2017b; Huang et al., 2021b). Since these fibers have the function of extending the lifespan of clothes and beddings (like bed sheets, pillows, and blankets) by improving their resilience and resistance to abrasion, manufacturers add these materials to their products (Liu et al., 2019b). Fragments of synthetic fibers possibly come off from these household supplies through multiple pathways consisting of physical breakdown due to the friction when wearing, washing as well as doing activities on daily basis, mechanical damage which occurs during grinding and chopping of textiles as parts of their manufacturing process, as well as photo-oxidative degradation. Thermal effects and wind shear on clothes and bedsheets left to dry under the sun also contribute to fragmentation of synthetic textiles (Chen et al., 2020b; Gasperi et al., 2018; Liu et al., 2019b). In addition, Dris et al. (2016) estimated the annual generation of microfibers in a 2500 km^2 agglomeration in Paris was about three to ten tons, thus bringing attention to the prevalence of airborne MPs.

Previous studies have shown that tire and brake particles from vehicles are another source of MPs in the air. Wear and tear of tires leads to 3 to 7% of $PM_{2.5}$ and 0.1 to 10% of PM_{10} released into the air. It is the main MPs source related to traffic and transportation followed by brake wear, road markings, and airplane tires (Jan Kole et al., 2017). Plastic particles derived from tires, including those due to brake abrasion, contain both rubber core and metal additives such as titanium, zinc, and lead, which are potentially hazardous (Sommer et al., 2018). Brake pads contain other components which help cars to stop, especially a kind of binder named phenol-formaldehyde resin. While braking, the brakes in vehicles experience wear, causing fine particles of MPs containing a mix of synthetic rubber and metals to be emitted into the atmosphere with the assistance of wind and warm airflow. Unlike larger plastic fragments which settle onto the ground and enter the aquatic environment through rainwater runoff, these fine tire and brake wear particles can be suspended in the atmosphere and transported through air movement over a long distance, with some ending up in remote areas (e.g. Arctic region). It is estimated that 34% and 30% of wear particles from tires and brakes respectively finally enter the ocean by deposition (Evangeliou et al., 2020).

Moreover, industrial activities and waste incineration could contribute to the generation of fine ambient MPs. According to a study conducted in Iran, domestic industries were deduced to be the sources of airborne MPs of various colors, materials, shapes, and sizes, given that the average abundance of MPs particles in fallout collected in industrial areas is more than three times higher those in the samples of the urban areas (Abbasi et al., 2019). Also, it seems that the atmospheric environment of densely populated regions possibly contains relatively more MPs particles (Mbachu et al., 2020). In addition, garbage treatment facilities such as incineration plants and landfills are believed to be potential sources of airborne MPs (Prata, 2018b). Yang et al. (2021) reported the presence of MPs in the bottom ash of an incinerator and identified it as a potential source of MPs. This indicated that burning process leads to degradation of large plastic waste to form finer pieces. The study also suggested that the abundance of plastic particles tends to increase under incomplete combustion. Suspended MPs can be transported to the atmosphere through chimneys (Liu et al., 2019a).

Some authors have also suggested that wear and tear of walls and ceilings, interior decoration, and special woods or metal products are potential sources of airborne MPs especially in the indoor environment (Huang et al., 2020; Kacprzak and Tijing, 2022; Liu et al., 2019d). Alkyd resins and epoxy are two common coating materials used for waterproofing and insect prevention, which are usually applied to wooden and metal furniture. Their wear and tear could form airborne MPs. Daily use and cleaning of the surfaces of wall and floor finishes are likely to enhance peeling and release unwanted tiny plastic pieces (Kacprzak and Tijing, 2022). Through long-term physical abrasion and exposure to UV radiations in the outdoor environment, synthetic covering materials would gradually fragment and break down, leaving small plastic particles floating in the air (Liu et al., 2019d). Rios Mendoza et al. (2021) highlighted the increased use of masks, protective clothing, and gloves as well as the overuse of plastic packaging for deliveries certainly contributed to plastic debris generation during the COVID-19 pandemic. Similarly, a large number of MPs could be found in the burned ashes of personal protection equipment after incineration (Tang, 2022).

There are other possible sources of MPs with complex material exchange mechanisms that lead to the release of MPs not only into the air but also water bodies or the soil environment. It is well established that construction activities (e.g. building materials), agricultural practices (e.g. plastic mulch and synthetic fertilizers), sewage sludge, and landfill leachate are some of the sources (Prata, 2018b). In addition, it is of great importance to understand the dynamic cycle of MPs particles exchange in various environments including aquatic, terrestrial, and air environments, which has a significant effect on the concentrations of MPs in the atmosphere (Wang et al., 2021b). It is noteworthy that airborne MPs can be transferred to remote areas and the deposition of suspended MPs particles is a source of water and soil pollution. Based on Boucher & Friot (2017), 7% of terrestrial plastics are transferred by wind and ultimately enter the ocean. What should be taken into consideration is the regeneration and remobilization of MPs particles both on the sea surface and roadside by adverse weather conditions, resulting in long-distance transport (Evangeliou et al., 2020).

4. Fate of Airborne Microplastics

The fate of atmospheric MPs is often linked to terrestrial and marine MPs because freshwater, marine, terrestrial and atmospheric environments are interconnected and have different source-path-sink connectivity networks. These MPs, which remain in nature for a long time, continue to have an impact on humans and the ecosystem. For MPs in the outdoor atmosphere, they will mostly be transported by the action of air because of the high mobility of the air (Figure 2). They will then enter the soil and the ocean through dry deposition, wet deposition, or atmospheric deposition (Li et al., 2022b).

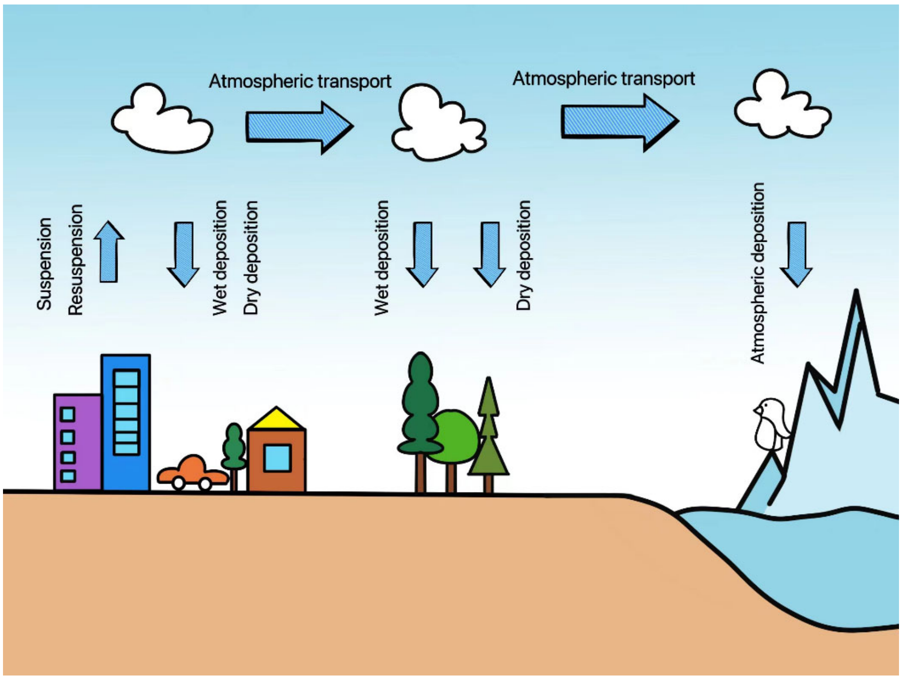

Figure 2: Transport of airborne MPs

Researchers have found that MPs particles can stay in the air from 1 hour to 6.5 days (Brahney et al., 2021), a duration that is sufficient for transcontinental transport to occur. Researchers have discovered MPs and artificial fibers in the glaciers of the Tibetan Plateau, the third pole of the world (Zhang et al., 2021). MPs have also been found in streams in the Antarctic Specially Protected Area, which has strict environmental protection measures (González-Pleiter et al., 2020). This could prove that MPs are carried by the wind and spread in the natural environment. MPs can disperse in the atmosphere over considerable distances before they are affected by natural factors and settle (Figure 2). The dispersion and movement of MPs in the atmosphere can be influenced by urban topography, local meteorology, and changes in wind direction due to thermal cycling (Li et al., 2022b). In 2019, Allen et al. (2019) applied the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) for the first time to study atmospheric MPs transport and pollution source tracking. Combined with field investigations, the study hypothesized that MPs can be transported in the air up to 95 km. Subsequently, Wang et al. (2020) conducted a transoceanic investigation of atmospheric MPs and hypothesized that ambient air MPs underwent a long-range transport of more than 1000 km. Also, laboratory studies have shown that wind erosion plays a key role in the transport of MPs in the terrestrial environment, especially for particles with lower densities. The density and shape of MPs particles play a significant role in their transport (Horton and Dixon, 2018). (2019). Rezaei et al. (2019) showed that the density of MPs of smaller particle sizes is lower than that of mineralogical dust (2.65 g/cm^3) and that wind can transport this kind of MPs on the ground easily away from the sources of MPs contamination. Through wind tunnel experiments, Bullard et al. (2021) found that fiber-shaped MPs are more easily transported by wind than spherical MPs.

In addition to spreading elsewhere by wind, MPs also settle under the influence of natural conditions and human activities. Studies have shown that about 140,000 tons of MPs from road traffic are deposited into the ocean through the atmosphere every year, causing a huge impact on the marine ecosystem (Su et al., 2020; Liu et al., 2019d). Over recent years, atmospheric transport of MPs has been recognized as an influential vector that may lead to the pollution of MPs in terrestrial or aquatic environments (Allen et al., 2019; Bergmann et al., 2019). Although no uniform conclusion has been reached, studies have pointed out that meteorological factors such as wind, snow, rain, and human activities can influence the deposition of MPs in the air. Factors such as pollution concentration gradient, wind speed, wind direction, temperature, and humidity affect the dispersion and deposition of MPs in the air (Figure 2). Su et al. (2020) showed in their study that atmospheric concentrations of MPs are higher near areas of dense urban land use and high regional population. It has also been shown in the study that MPs in the urban atmosphere settle and accumulate on roads and road edges during dry weather, and are washed away and transferred during heavy rainfall. In a study by Dris et al. (2015) on the relationship between atmospheric MPs deposition fluxes and precipitation in Paris, it was found that fluxes were much greater during periods of high precipitation than during periods of low precipitation. An investigation of MPs adhering to common plants in Shanghai found that the sources of MPs adhering to plants in different areas were similar, and atmospheric MPs were temporarily deposited on plant leaves in large quantities during transport before being blown away by the wind (Liu et al., 2020a). In addition, the study also found that atmospheric MPs were less diverse at night than during the day, presumably related to their physicochemical properties and environmental factors. The physicochemical properties include density and water absorption of MPs. The environmental factors include pollution sources and humidity.

Guo et al. (2012) studied the adsorption of MPs and found that the oxygen-containing functional groups in polyphenylene ethers act as hydrogen bond acceptors and interact with other molecules, making the MPs more susceptible to adsorbing pollutants and microorganisms. It has also been shown that there are significant oxidation and local cracking on the surface of the aged MPs (Liu et al., 2019b). The main mechanisms are electrostatic interactions and intermolecular hydrogen bonding, leading to the higher adsorption capacity of aged MPs than the original MPs. The size distribution of atmospheric MPs in different environments is related to their density and floatability in air, with larger particles tending to be deposited more quickly. These MPs that have adsorbed other substances are larger in size and more likely to settle under gravity. Furthermore, there may be interactions between MPs and other atmospheric particulate matter. There are no clear studies on whether atmospheric MPs react with other particulate matter and thus influence the time of MPs agglomeration and suspension. The resolution of these complex issues relies on more in-depth studies in the future.

There are several differences between the fate of indoor atmospheric MPs and outdoor atmospheric MPs. Due to the poor mobility of indoor air, indoor atmospheric MPs do not diffuse easily (Vianello et al., 2019). This is one of the reasons for the high concentrations of indoor atmospheric MPs. Smaller MPs are more concentrated in the indoor atmosphere and are less likely to settle, thus, can be easily inhaled by humans and animals (Vianello et al., 2019). Similar to outdoor atmospheric MPs, the larger the MPs, the more likely they are to settle and collect on the ground. It is worth noticing that the main types of indoor airborne MPs in different locations still need to be further investigated. Extrapolating from the behaviors of particulate matter, the fate of indoor airborne MPs may be related to room compartmentation, ventilation, and airflow. Thus, downwind rooms have higher levels of MPs (Alzona et al., 1979). The study by Dris et al. (2017) also noted that different flooring materials in the room may have different adsorption effects on MPs. For example, indoor carpets may retain MPs through adsorption. In contrast, bare floors have little adsorption of MPs, and MPs that settle on the floor can easily reenter the atmosphere. Apart from this, other indoor equipment and facilities may also have different degrees of adsorption to MPs. In some existing studies, it was mentioned that air conditioning filters can trap MPs in the indoor atmosphere. Simultaneously, when the air conditioner is in operation, it increases the circulation of air in the room, causing dust and MPs to move and resuspend into the air (Kacprzak and Tijing, 2022).

Whether deposited on the soil surface or entering rivers to migrate with water flow, MPs are subject to external environmental factors and are broken down into smaller particle sizes, even of nanoscale, or are eventually degraded and converted into CO_2, H_2O, and methane (Moore, 2008). Photodegradation is considered as one of the most effective abiotic degradation methods. MPs suspended in the atmosphere, floating on the surface of water bodies, and gathering on the surface of land are exposed to sunlight for a long time and gradually decompose under the action of the ultraviolet light and oxygen in the air (Wang, 2018). MPs deposited in the ocean and in the soil are also accidentally eaten by marine organisms and terrestrial animals and thus enter the marine and the terrestrial food chains. Studies on the biological effects of MPs in marine organisms have shown that these particles can be swallowed or ingested by a variety of marine organisms and accumulated in the organisms, thus affecting their systemic balance and normal metabolism, causing their death (Shah et al., 2008). MPs in the soil can also be transferred and enriched through the food chain, posing health risks. Although studies have reported the effects of MPs on crops, their potential impact on terrestrial ecosystems remains largely unknown and requires further research.

5. Risks of Airborne MPs

Permeation of MPs through the atmospheric environment has serious implications on ecosystems and the organisms living therein. Most of the existing studies center on the impacts of airborne MPs on human health due to the public health concern associated with human exposure to airborne MPs through inhalation and ingestion. In view of the complexity of ecosystem and the potential transfer of MPs from other organisms contaminated by airborne MPs to human, this section aims to provide a balanced review on the risks of airborne MPs on various components of the ecosystem, particularly the terrestrial animals, plants and human, in contrast to emphasizing their risks on human only.

5.1. Risks of Airborne MPs to Plants

Currently, the direct effects of airborne MPs on plants are insufficiently studied. It is still unclear whether the sources of MPs and the modes of accumulation of MPs contribute differently to the risks of MPs on plant, making it challenging to characterize such risks. Since there is a dynamic cycle of MPs transport in the natural environment (Wang et al., 2021b) which carries them to remote areas (Trainic et al., 2020), researchers often analyze the potential risks based on their transport and migrations. MPs in the atmosphere can enter water bodies and land environment through rainfall or natural deposition (Ding et al., 2021; Liu et al., 2019e). Through atmospheric diffusion and deposition, airborne MPs can affect the structures and functions of other ecosystems, thus, posing further risks to plants via migration, enrichment, as well as accumulation in terrestrial (soil) and aquatic environments (Xu et al., 2022). However, studies on the direct risks posed by the air-deposited MPs on plants are extremely limited.

Plants in terrestrial and aquatic ecosystems are exposed to airborne MPs through wind or directly through precipitation falling on their surfaces (De Silva et al., 2021). Due to the structure of airborne MPs, it is possible for a new niche of atmospheric microbes on form on the MPs, making them carriers of microbes which pose risks to plants indirectly (Pickett et al., 2019). It is also supported by studies showing the formation of biofilms on MPs, which contain some dominant bacterial phyla (Tu et al., 2022).

In addition to being intercepted and accumulated by plants, airborne MPs could absorb or scatter radiation from the sun and the ground, thereby, affecting the Earth's climate and photosynthesis of plants. Evangeliou et al. (2020) reported that pigmented MPs may absorb more radiation in the visible spectrum than they scatter, which produces a net positive effective radiative forcing and contributes to atmospheric warming. In urban areas with relatively greater concentrations of airborne MPs, these particles are likely to influence atmospheric temperature, which could pose significant impacts on plant growth, photosynthesis, and biochemical reactions (Revell et al., 2021; Sridharan et al., 2021).

5.1.1. Aquatic Plants

Different from the MPs directly emitted from sewage treatment plants (or other sources) to the natural aquatic ecosystems, the process of airborne MPs entering, depositing, and subsequent adsorbing and accumulating in aquatic ecosystems is relatively slow and their toxic effects on algae (microalgae) are most commonly studied, since they may enter the aquatic food web through microalgae (Prata et al., 2019). Aquatic microplastic concentrations can be attributed in part to atmospheric sources (Dris et al., 2015; Liu et al., 2019e), which explains why airborne MPs could pose threats to aquatic plants. Additionally, upon entering aquatic environment, biofilm formation on the surface of MPs would be different and this changes their adsorption capacity on plant surface (Li et al., 2022a). It has been observed that aged airborne MPs may capture more pollutants or heavy metals upon depositing in water and subsequently pose risks to aquatic plants. With biofilms formed on the surfaces of MPs, MPs are more capable of aggregating, sinking and depositing (Michels et al., 2018). Cumulative hetero-aggregation would also cause direct physical damage to aquatic plants and affect their growth (Mao et al., 2018).

Before further studies on the direct effects of airborne MPs on aquatic plants are available, it could be most plausibly implied that their current risks on aquatic plants are contributed mainly by their deposition and accumulation in water bodies. While accumulation of airborne MPs in water bodies could pose potential long-term risks to aquatic plants and the aquatic ecosystem as a whole, no significant effect was observed from the adsorption of MPs on root surfaces (Dovidat et al., 2020). This suggests that most of these particles only cause physical blockage and are not small enough to be taken up by plants to cause toxic effects.

5.1.2. Terrestrial Plants

Generally, the adsorption of airborne MPs on leaves can affect the physiological activities of plants such as photosynthesis, which subsequently affects the carbon and nitrogen cycles, and community structure of the forest canopy ecosystem (Xu et al., 2022). Also, Liu et al. (2020a) claimed that the leaves of terrestrial plants could retain airborne MPs, thus serving as a temporary sink (Figure 3). The authors examined the MPs captured from the atmosphere and aquatic environment by non-submerged and submerged mangrove leaves. They concluded that MPs on the leaves came from the atmospheric environment. Deposited MPs may be uplifted by wind, migrate and deposit again. This could expose the plants in the surrounding to MPs. Airborne MPs are more likely to suspend in the air due to their small sizes. There was a greater abundance of smaller-sized MPs on non-submerged leaves which were less disturbed by water flow (Ma, 2021).

The leaves of terrestrial plants could retain airborne MPs, thus serving as a temporary sink (Figure 3). Airborne MPs deposited on leaves or soil would have both direct and indirect impacts on plants. The direct adverse effect is the inhibition of plant growth and seed germination physically. If MPs fall on soil, they may alter the physical and chemical properties of soil while exerting ecotoxicological effects on soil organisms due to particle effects as well as the leaching of plastic additives, and other pollutants adsorbed

(Li and Tang, 2022; Deng et al., 2023). Airborne MPs accumulated near the roots of plants and vegetables could be transported to other parts of the plants (Li et al., 2021), and re-accumulated by the roots (Rillig et al., 2019b; Li et al., 2020). Carbon and nitrogen released by decomposed MPs particles may fertilize soil while exerting selective stress on soil (Rillig et al., 2019a). In the long run, they may disturb the equilibrium of the soil ecosystem. Airborne MPs carried by fallen leaves are transported by earthworms and accumulated near the roots (Figure 3), during which contaminants might combine with the MPs particles and cause adverse effects on the plants and other benthic flora (Zhao et al., 2022; De Silva et al., 2021; Tunali et al., 2020; Tang, 2020).

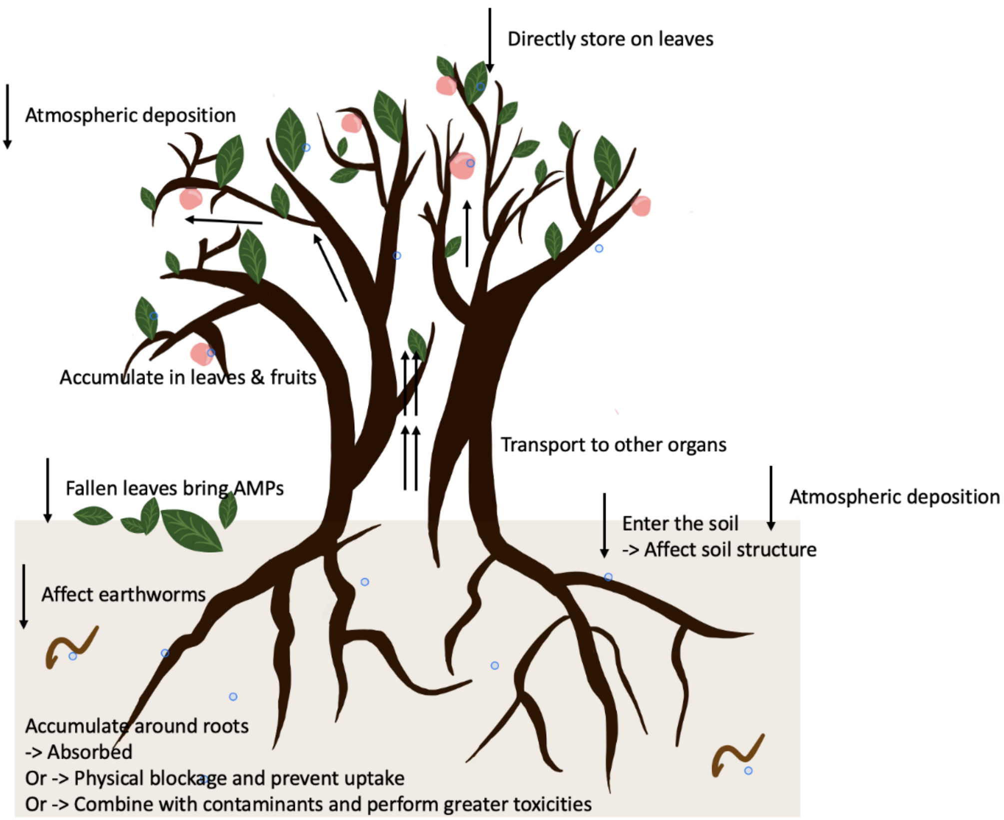

Figure 3. The transport of airborne MPs on the exterior and the interior of a plant

Table 3: Risks of airborne MPs on plants

Type of Ecosystem	**Mechanism of Exposure**	**Effect or Risk on Plants**	**Example of Plant with Risk Reported**	**Reference**
Terrestrial & aquatic	Atmospheric dispersion	Enter ecosystems; may adsorb other pollutants and cause ecotoxicity before subsequent transfer to plants	Not specified; the health of ecosystems generally	Xu et al., 2022
Terrestrial	Atmospheric deposition in ecosystems	Captured by plants; accumulate on leaves; or fall and accumulate on soil	Vascular plants	Bosker et al., 2019
Aquatic	Atmospheric deposition in ecosystems	Expose to marine microbes with biofilms formed on surfaces; captured by plants; accumulate on and absorb by plants, giving rise to ecotoxicity (complicated by biofilms); adsorb by plants, forming physical blockage	*Chlorella; Scenedesmus*; *Lemna minor*	Bhattacharya et al., 2010; Besseling et al., 2014; Mao et al., 2018; Kalčíková et al., 2017; Pickett et al., 2019
Terrestrial	Indirect transfer through fallen leaves with airborne MPs; MPs accumulate in the soil	Affect soil properties, hence plant health; accumulate around roots, causing blockage; absorbed and transported in plants, causing toxic effects	*Triticum aestivum*; *Lactuca sativa*; cucumber;	Bosker et al., 2019; Li et al., 2020; Li et al., 2021

5.2. Risks of Airborne MPs to Animals and Human

As has been previously reported in the literature, exposure to MPs poses a wide range of toxic damage to the biota, for example, it may impair or disturb ingestion, reproduction, energy metabolism, and liver physiology, and it may even interact with other pollutants from low to high trophic zones (Anbumani and Kakkar, 2018). There is growing concern about the risk of airborne MPs to animals and humans. Many studies have suggested that MPs suspended in the air may enter the respiratory system through inhalation, but there is no direct evidence to draw a conclusion (Enyoh et al., 2019).

As for animals, a recent study by Deng et al. (2017) concluded the adverse consequences of MPs using mice as experimental subjects. They found that MPs can accumulate in the liver, kidney, and intestine of mice (Table 4). The results also showed that MPs exposure caused disturbances in energy metabolism, lipid metabolism, and oxidative stress. Gu et al. (2020) conducted an experiment that used adult zebrafish as subjects in which polystyrene MPs were found to notably impact phagosomes and cause dysfunction of intestinal immune cells (Table 4). They could potentially increase the abundance of pathogenic bacteria. Another study carried out by Cui et al. (2022) on earthworms found that MPs in higher concentrations and of smaller sizes were more harmful to earthworms. MPs led to a higher accumulation of heavy metals and organic pollutants in earthworms, causing more serious harm (Cui et al., 2022). Humans are exposed to airborne MPs through inhalation since MPs are ubiquitous in the air (Figure 4). Vianello et al. (2019) stated that one person can inhale 272 airborne MPs in a 24 h period in an indoor environment. After inhalation, MPs in the body can then be transported through the blood to other parts of the body, where they can cause diseases in the immune system, nervous system, and reproductive system (Table 4) (Xu et al., 2022). The current concentration of MPs in the atmosphere is 2-355 fibers/m^2/d through actual measurements and simulations (Dris et al., 2016). MPs may result in mucus reduction, bacterial imbalance, oxidative stress, inflammatory cell activation, inflammatory cytokines secretion, changes in cellular activities, morphology and cell cycle, lipid and energy metabolism disorders, as well as a decline in sperm counts and energy (Table 4) (Huang et al., 2021a). MPs accumulation in humans may pose health risks such as hereditary lesions, cancer, and other acute and chronic diseases in severe cases, while less severe effects include sensory organ stimulation, endocrine disorders, respiratory difficulties, etc. (Table 4) (Zhang et al., 2019).

According to Pauly et al. (1998), plastic fibers have been found in lung tissue (Figure 4). MPs are bio-persistent and they pose the risk of causing lung cancer (Table 4) (Pauly et al., 1998). The likelihood of inhaling airborne MPs depends on their sizes, which also determines whether they will reach the respiratory system (Enyoh et al., 2019). Early toxicological evidence suggests that MPs as small as 5 mm can be engulfed by cells and translocated to accumulate in various organs (Ageel et al., 2022). Furthermore, Prata (2018b) pointed out that depending on the mechanism of deposition and clearance rate, the potential risks of MPs on different organs differ. If the deposition rate is higher than the clearance rate, humans may be at risk of particle, chemical toxicity, and microbial toxins, even at low particle concentrations. It was said that individuals with impaired clearance mechanisms may have a higher risk of particle toxicity compared to individuals with normal clearance mechanisms. When humans inhale particles in the air, there will be different reactions and the manifestation of effects depending on individual metabolisms and susceptibility (Enyoh et al., 2019). The effects of inhaling fibrous MPs on human health are little understood. The majority of fibers are thought to be cleared from the respiratory system, but some will cause inflammatory responses and even respiratory lesions (Prata, 2018a). Based on the study of Pauly et al. (1998), 87% of lung specimens from 114 patients who had pneumonectomy for tumor resection contained cellulosic or plastic fibers, indicating that these small fibers are respirable and accumulate in lung tissue (Pauly et al., 1998). Other pathways may occur through the skin and through atmospheric deposition on meals left uncovered (Enyoh et al., 2019).

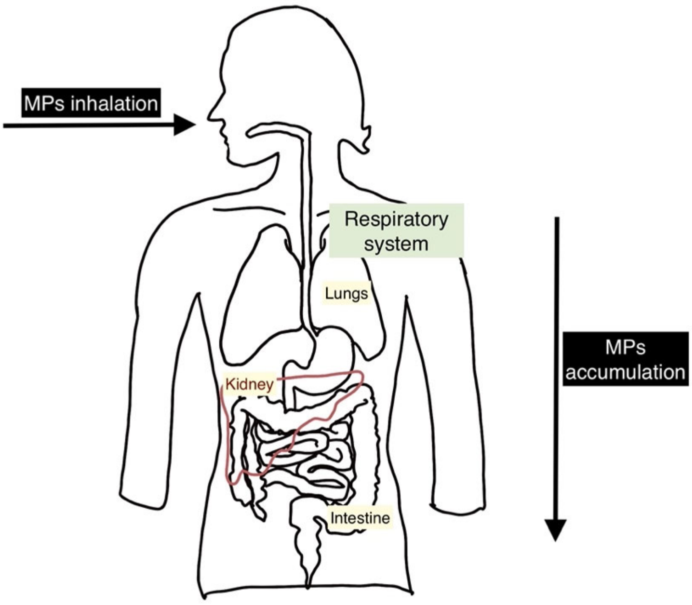

Figure 4: Pathway of airborne MPs through inhalation

Synthetic textiles are believed to be the primary source of airborne MPs, particularly indoors where concentrations are higher (Dris et al., 2017). Airborne MPs can be inhaled directly, posing health risks to humans, particularly industry workers (Chen et al., 2020a). It was found that an increased risk of lung cancer is associated with PVC dust exposure in the vinyl chloride monomer/PVC industry (Mastrangelo et al., 2003). Also, a previous study claimed that the inhalation of fibers during factory work can cause some cancers. Although the magnitude of the effect was small, increasing exposure to synthetic fiber dust increased the risk of stomach cancer (Gallagher et al., 2015). Hwang et al. (2019) discovered that direct contact of microscale PP with cells has the potential to cause health problems by inducing the production of cytokines from immune cells rather than causing direct toxicity to cells (Hwang et al., 2019).

Besides, urban aerosols contain a variety of bacteria with an abundance close to that of some soil bacterial communities (Brodie et al., 2007), and some of the microorganisms may be transported to the human lungs through airborne MPs via formed biofilms and may lead to infection (Prata, 2018b). Also, airborne MPs have the same tendency to adsorb heavy metals and hydrophobic organic contaminants (HOCs) such as persistent organic pollutants (POPs) and carry those toxic chemicals to human lungs which may trigger health problems (Wirnkor Verla et al., 2019).

Table 4: Risks of airborne MPs on human and animals

Animal	**Risk/ Toxicity of MPs**	**Reference**
Mice	Disturb energy metabolism and lipid metabolism, oxidative stress	Deng et al., 2017
Zebrafish	Impact phagosomes, intestinal immune cells	Gu et al., 2020
Earthworm	Accumulate heavy metals and organic pollutants, causing more serious harm.	Cui et al., 2022
Human	Cause diseases in the immune system, nervous system, reproductive system	Jia et al., 2022
Human	Mucus reduction, bacterial imbalance, dysfunction, inflammation, oxidative stress, inflammatory cell activation, and inflammatory cytokines secretion.	Huang et al., 2021a
Human	Hereditary lesions, cancer, and other acute and chronic diseases in severe cases, while less severe effects include sensory organ stimulation, endocrine disorders, respiratory difficulties, etc.	Prata, 2018b
Human	Lung cancer	Pauly et al., 1998, Chen et al., 2020a, Mastrangelo et al., 2003
Human	Increase the risk of stomach cancer.	Gallagher et al., 2015
Human	Induce the production of cytokines from immune cells.	Hwang et al., 2019

6. Mitigations of Airborne MPs

Currently, there are two approaches to reduce the presence of MPs in the environment: indirect and direct. Indirect methods include installing appropriate filters in new and existing ventilation or air conditioning systems as well as using air purifiers in private homes not equipped with or not frequently using air-conditioning systems (Kacprzak and Tijing, 2022). A direct approach is to reduce the sources of MPs (Patil et al., 2021). Both methods are complex and often difficult to combine.

In the indirect method, the existing ventilation and air conditioning system may not have sufficient space to house a suitable filter. Existing fans may not be able to generate enough static pressure to overcome the resistance of the new filter. The higher maintenance and operating costs of a system with a new filter can be prohibitive. The direct approach is harder to follow. This is a long-term solution that requires public education and awareness of the MPs problem and a willingness to work together to reduce plastics at their sources or avoid plastics altogether. It drives the quest to look for new materials as plastics substitutes and ideally nullify the demand for all kinds of plastics. There are pros and cons to both approaches, and they are not needed if readily biodegradable plastics substitutes are available and there is an environmental-friendly way to degrade plastics (Kacprzak and Tijing, 2022).

6.1. Indirect Approaches

Considering that certain filter systems are capable of removing particles as small as 0.3 µm, MPs particles in the air can also be removed from indoor spaces. Filters are a very important part of any mechanical ventilation system. Not only do they remove harmful substances from the air, they also protect heating, ventilation, and air conditioning (HVAC) equipment. There are many different types of filters in the market that remove a certain percentage of dust particles according to their ratings (Patil et al., 2021). However, factors such as the quality of the installation or the concentration of contaminants may affect the performance of the filter.

There are four major categories based on their average removal efficiencies, namely coarse dust filters, fine dust filters, highly efficient particulate air filters (HEPA) filters, and ultra-low penetration air filters (ULPA) (Purchas and Sutherland, 2002). Coarse dust filters usually have limited efficiency in air purification though they are inexpensive. Disposable course dust filters such as glass fiber air filters are not recommended as they aggravate waste generation issue in addition to their limited MPs removal efficiency. Washable air filters with comparable efficiency may be a potential substitute since they are reusable but are also constrained by their ability to remove MPs less than 10 µm (Kacprzak and Tijing, 2022).

Fine dust filters, such as folded filters and bag filters are relatively more effective in trapping MPs (> 3 µm) due to their large surface areas but are more costly and create greater airflow resistance. Their use has been confined to prefilters (Kacprzak and Tijing, 2022). HEPA filters have been widely used in multiple sectors due to their ability to capture small particles (0.3 µm) and remove up to 99.97% air pollutants to meet more stringent indoor air quality requirements. However, they often require pre-filters and powerful fans to overcome high resistance, hence, necessitating professional servicing. In relation to the sizes of MPs which are less than 5 µm, most HVAC systems may require HEPA filters to reduce or remove MPs (Zia et al., 2021). The use of HEPA air purifier has been reported in multiple studies investigating MPs prevalence in water treatment plants to minimize contamination caused by airborne MPs. It is stated in those studies that the air purifier could remove airborne particles larger than 0.3 µm with 99.97% efficiency (Cherniak et al., 2022; Pivokonský et al., 2020). Vishwakarma et al. (2022) synthesized a filter system consisting of a compressed HEPA filter layer and a multiwalled carbon nanotube membrane, which can remove $PM_{0.3}$ and MPs as small as 0.3 µm with more than 90% efficiency. Generally, particles larger than 10 µm are trapped on filters. Particles between 0.3 and 1 µm can fit the gaps on the filters but the heavier fractions do not move fast enough and are often trapped by the filters. Besides, the Brownian motion of the smaller particles also facilitates their entrapment by the filters (Kacprzak and Tijing, 2022).

ULPA filters can trap airborne particles with sizes between 0.12 and 0.4 µm, but have the drawback significantly higher resistance than HEPA filters. They also require pre-filters as well as frequent servicing and replacement, making them capital-intensive and operationally expensive (Patil et al., 2021). The emergence of air purifiers in the market has provided a feasible avenue for removal of indoor MPs and these air purifiers frequently employ the HyperHEPA filtration system, which is claimed to be able to remove particles as small as 0.003 µm and is deemed to be effective in removing all airborne MPs. In addition to conventional HEPA air purifiers, new technologies such as HEPASilent combining electrostatic and HEPA filters are also available to remove particles as small as 0.1 µm (Zia et al., 2021).

Considering the above, portable air purifiers using a HEPA filter (pre-filter to capture the larger particles and protect the filter) seem to provide the best immediate solution to remove airborne MPs especially in an indoor environment, and powerful fans are needed to ensure air circulation throughout the space. Reducing MPs in indoor environment helps to clean indoor air, but the filters need to be replaced or cleaned, so that MPs are effectively captured by the filters. Air filtration helps to protect human health, especially as we spend 90% of our time indoors (Enyoh et al., 2019). However, this method only transfers pollutants from one medium to another. Filtration helps, but it does not solve the problem of MPs in the air. Most filters have media made of plastics which could contribute to the plastics problem. Studies assessing the contribution of plastic filter media to the increase in MPs in indoor air should also be considered.

6.2. Direct Approaches

The versatile use of plastics has resulted in more than 9 billion tonnes of plastics being manufactured globally as of 2019, and a large proportion of the waste generated from the plastics has been mismanaged leading to the leakage of plastics into the environment and their subsequent degradation into MPs (PlasticsEurope, 2018). Considering the magnitude of the problem, it is essential to start controlling MPs pollution. Source reduction and government interventions are crucial to the reduction and removal of MPs from the environment. Non-biodegradable plastics which are readily subject to wear and tear, particularly plastic bags and packaging, should be avoided and natural or biodegradable materials such as reusable bags made of natural fabrics should be used instead. Other ways MPs could be avoided are personal hygiene products, such as soap or toothpaste and cosmetics, and general cleaning products containing microbeads.

Plastics in the form of microbeads and fragments find their way into the environment. Even though there have been a series of measures taken by the global community to tackle plastic pollution and its environmental effects in recent years, there are currently limited regulations on the production and utilization of plastics (Xanthos and Walker, 2017). To reduce the contamination of MPs in the environment, some countries and regions have implemented regulations that control the production of primary MPs, including microbeads, as well as limit the use of single-use MPs (for example drinks bottles, carrier bags). For instance, legislation has been passed in Ontario, Canada and the United States to ban the production of microbeads (Xanthos and Walker, 2017).

MPs control at source has been advocated as one of the most sustainable and effective means to prevent and contain plastic pollution. For instance, the ban on plastic bags can effectively reduce the overuse of plastics and ultimately contribute to the mitigation plastic and MPs pollution (Schnurr et al., 2018). Besides, plastic manufacturers must ensure that their products are standardized and labeled properly to facilitate recycling. Furthermore, increasing awareness through universities, schools, organizations, and networks about MPs issues through campaigns and educating the personal responsibility of individuals for mitigating plastic and MPs pollution by choosing to reject, reduce, reuse and recycle plastics are important. Educational interventions (e.g. marine litter education) for children will boost their awareness, perceptions of the consequences, and self-reported action (Hartley et al., 2015).

The management of MPs problems in the long term should involve scientific research to come up with ways of dealing with plastic waste so that all plastic waste can be recycled, regardless of its chemical composition. This concept would involve new methods of breaking down plastic materials into their major constituents or other chemicals suitable for reuse as components of new materials (Tang et al., 2022). Studies have shown that microorganisms have yielded good results in the degradation of MPs (Tang and Hadibarata, 2022). Biodegradation is one major means by which MPs can be controlled. Microorganisms such as bacteria, fungi, and mealworms are used to degrade plastics. It has been identified as a reliable and environmentally safe action that helps to tackle plastic pollution by degrading plastics without posing negative effects. A recent study by Bombelli et al. (2017) revealed that larvae of the wax moth *Galleria mellonella* can degrade PE at an average degradation rate of 0.23 mg cm^{-2} per hour, producing ethylene glycol. Similarly, low-density polyethylene (LDPE) MPs particles can be degraded with bacteria isolated from the gut of earthworms (*Lumbricus Terrestris*) (Huerta Lwanga et al., 2018). The bacteria *Bacillus gottheilii* has also been proven to degrade MPs. Auta et al. (2017) used *Bacillus cereus* and *Bacillus gottheilii* to remove MPs of PE, PS, PET, and PP, and the results were encouraging. The fastest reduction in mass (0.0019/day) and shortest degradation half-life (363.16 days) were found using *B. cereus* isolate to degrade PS MPs. Meanwhile, the use of *B. gottheilii* on PE gave a degradation rate and degradation half-life of 0.0016/day and 431.25 days respectively making *B. gottheilii* a potential bacterium for MPs degradation (Auta et al., 2017).

These plastic-eating organisms provide an environmentally friendly means of managing plastic waste, hence controlling MPs. It is, therefore, crucial for governments to fund additional research to find organisms that will break down plastics more efficiently. Alternatively, and preferably, future research should continue to improve the properties and biodegradability of bioplastics suitable to replace the current bio-resistant plastics (Akanyange et al., 2021).

7. Conclusion

Airborne MPs have been detected in various regions of the world and pose significant risks to human health and the ecosystem as a whole. However, in comparison to MPs in the marine, freshwater and terrestrial environments, studies on airborne MPs are significantly less. This review aims to contribute to the advancement in the research of airborne MPs through systematically presenting the current knowledge concerning airborne MPs particularly their prevalence, sources, fate and risks in addition to proposing mitigation measures to reduce their abundance. Airborne MPs have been found to permeate the indoor and outdoor atmosphere with indoor atmosphere often containing more airborne MPs than outdoor air. In the outdoors, airborne MPs have been detected in many remote areas. Indoor airborne MPs are commonly generated from synthetic textiles, wear and tear of walls and ceilings as well as furniture finishings. These MPs could be suspended through indoor air movements, entrapped and deposited, settle under gravity and get resuspended. Outdoor MPs are produced from numerous sources, particularly the wear and tear of tires, brake pads, waste incineration and industrial activities. They undergo more complex transport and fate involving the spread by wind, wet and dry depositions, suspension and resuspension. They are also transformed through interactions with UV radiations and microorganisms, and their transport is governed by their own physical characteristics as well as environmental factors.

Airborne MPs pose multiple risks to plants, animals and humans. Atmospheric MPs deposited on the surface of leaves could find their ways to the soil and roots when the leaves fall and they are known to retard plant growth and seed germination. Airborne MPs entering animals through ingestion and inhalation could potentially disturb metabolisms, disrupt immune system and induce oxidative stress. In human, they could trigger inflammatory responses and oxidative stress, while increasing the risks of certain cancers. Airborne MPs could be removed indirectly using filters attached to indoor air-conditioning system, particularly the HEPA filters, and directly through regulation, source reduction, educational intervention, substitution with biodegradable materials and bioremediation. This review highlights the need to further examine the complex interactions of airborne MPs with other environmental compartments and other particulate in the atmosphere to better understand their fate and transport. It provides practical suggestions for developing indoor air-conditioning system that could improve the removal of airborne MPs. It points to the knowledge gap in their impacts on plants and to some extent the aquatic plants through their exchanges between different environmental compartments. Besides, it clearly points out the significant lack of understanding on their direct impacts on plant, human and animal health. It therefore, plays a significant role in bridging the existing research in airborne MPs to the future directions of research in this domain.

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