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Airborne microplastics: A review of current perspectives and environmental implications

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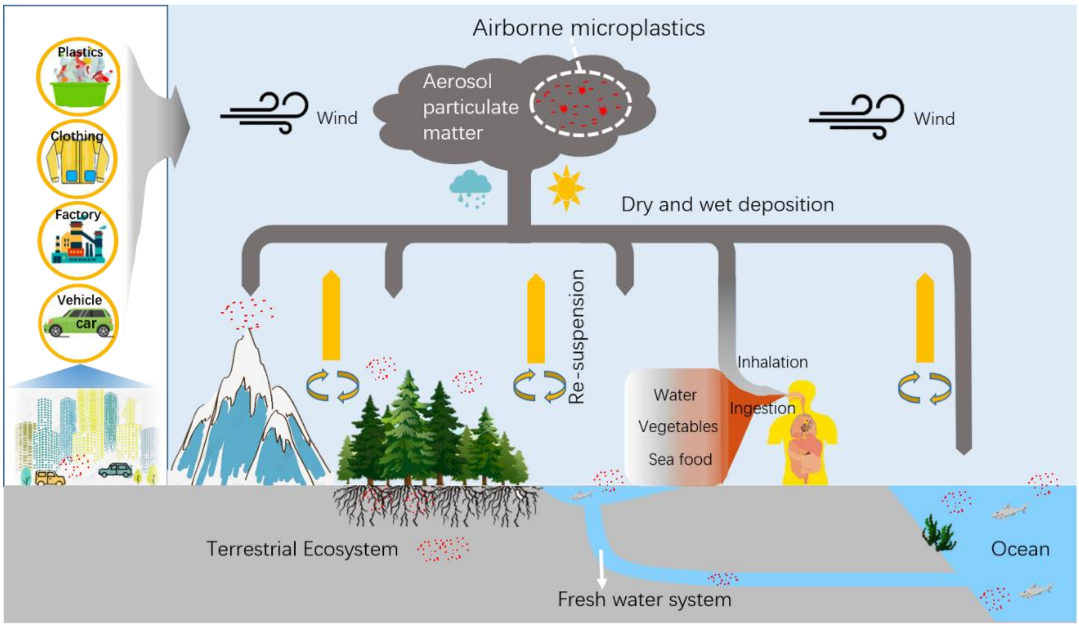
Highlights

- Atmospheric pollution by airborne microplastics is of increasing concern.
- Research methods require meaningful comparisons between different studies.
- Airborne microplastics can lead to the ‘fiber paradigm’ and bioreactivity.
- The atmosphere is one of the main pathways for microplastic transport.
- There is a need for a comprehensive inventory of airborne microplastics.

Graphical abstract



Abstract

Microplastics (MPs), as an entirely anthropogenic type of pollution, are considered to be stratigraphic markers of the Anthropocene Epoch, and have become of increasing public concern over the past decade. Recent studies have revealed that the atmosphere is an efficient medium to disseminate MPs from their sources to remote mountains and marine areas. However, current research on atmospheric MPs (i.e. airborne MPs) is generally less highlighted than MP water and soil pollution studies due to the lack of standard methods for the identification and quantification of atmospheric MPs. This paper reviews the published literature on airborne MPs, gives an overview of the advantages and disadvantages of current airborne MPs collection techniques, extraction methods and identification (i.e., 'passive' and 'active' sampling, density separation and visual identification), and lays a foundation for future studies. The physical and chemical characteristics, classification, spatial and temporal scale distributions, sources, transport, and environmental impacts of airborne MPs are summarized. There are substantial research gaps in the quantification of airborne MPs and the exploration of toxicity mechanisms of inhalable MPs. The establishment of accredited methods is an urgent challenge for a better understanding on airborne MPs and their environmental and health effects. As one of the constituents in many aerosols, airborne MPs should be treated as a recognized pollutant for long-term monitoring, and the factors that specifically affect airborne MPs could be better addressed by means of the characterization of individual MPs. In the future, the effects and interaction of MPs in the atmosphere, lithosphere and hydrosphere are also of critical importance.

Keywords: Airborne microplastics, analytical methods, Anthropocene, human health, physicochemical characteristics, source and transport.

1. Introduction

The global concerns about environmental pollution caused by microplastics (MPs) has significantly increased in both the popular media and scientific community over the last decade (Beaurepaire et al., 2021; Ramkumar et al., 2021). The term "plastic" includes materials composed of various elements, such as, carbon, hydrogen, oxygen, nitrogen, chlorine, and sulphur (Li et al., 2020). Plastics are made from natural materials such as cellulose, coal, natural gas, salt and crude oil through a polymerization or polycondensation process (Brydson, 1999). The distribution of Microplastics (MP) in the marine environment was first described in 2004 (Thompson et al., 2004), and were defined at the first international research workshop on the occurrence, effects, and fate of MP marine debris in 2008 (Arthur et al. 2009). MPs are plastic particles with a particle size of < 5mm (Andrady, 2011), and this definition is recognized by the American National Oceanic and Atmospheric Administration. MPs in different environments can be broadly classified into two categories. Primary MPs are released in their original plastic state from products containing MPs such as personal products (e.g., clothing, toothpaste, cosmetics, etc.) usually in the form of microfibers, beads and pellets (Conkle et al., 2018). Secondary MPs result from large scale plastic disintegration or degradation, such as natural weathering, mechanical decomposition, oxidation, and degradation of manufactured plastic products during use and recycling (Rezania et al., 2018).

MPs first gained global attention due to their presence in the oceans (Arthur et al. 2009). Subsequently, MPs have been found in soils, human populated areas and numerous places around the globe, and of particular concern in the Antarctic and Arctic regions (Bergmann et al., 2019; Petersen and Hubbart, 2021). Since MPs are found in the polar regions and high Himalayas, some studies suggest that atmospheric transport must be an important factor in the spread of MPs (Sridharan et al., 2021). Carbon in plastic particles in the atmospheric, marine and soil environments can directly affect natural carbon sequestration and climate change (Shen et al., 2020). Most of the MPs found in the atmosphere are in the micron or nano-size range and are difficult or impossible to observe with the naked eye (Gasperi et al., 2018). However, they still have a large pollution impact through transport and atmospheric deposition on all types of environments and ecologies, as well as on human health (Fig. 1) (Huang et al., 2021;

Ramkumar et al., 2021). Previous research results have indicated that MPs have entered different terrestrial environments including the hydrosphere and atmosphere on a global scale resulting in soil, water, and atmospheric pollution (Petersen and Hubbart, 2021; Wang et al., 2021b). MPs are directly or indirectly ingested and introduced into the food chain by microorganisms and macro-organisms (Bi et al., 2020; Foekema et al., 2013; Khalid et al., 2020; Syafei et al., 2019). As a result of MPs passing through the food chain, this transportation pathway can result in a very significant proportion of the biosphere becoming polluted (Toussaint et al., 2019). This is currently of special concern in the global oceans. Significant quantities of MPs can enter the bodies of marine organisms via their respiratory systems, resulting in their death (Gong and Xie, 2020). Recently, MPs have been found in the Antarctic and Arctic regions (Bergmann et al., 2019； Bessa et al., 2019), indicating that atmospheric transport is an important mechanism for the global transport of MPs (Brahney et al., 2021; Can-Güven, 2021; Qian et al., 2021; Szewc et al., 2021). Between 2015 and 2060, global plastic waste is expected to triple to 265 million tons annually, which will increase the volume of MPs released into the environment (Lebreton and Andrady, 2019). Some studies have defined the global pollution from MPs as 'plastisphere' (Ramkumar et al., 2021; Zettler et al., 2013). This happens because larger plastic fragments or waste are degraded into MPs (1 mm - 5 mm) or smaller nano-plastics (<1000 nm) (Jahnke et al., 2017). MPs have resilient physical and chemical characteristics, and are not easy to degrade physically or chemically, albeit they can remain buoyant in soil and water for long periods of time (Gong and Xie, 2020). As a result, MPs, which have been dispersed around the globe, have considerable ability to resist degradation. This feature suggests that plastic is an ideal marker of the Anthropocene in the future deposition record (Corcoran et al., 2018; Ramkumar et al., 2021).

Numerous studies have investigated MP pollution and potential toxicity in the oceans and soil, although there are only a few systematic studies on MPs in the atmosphere. MPs can be suspended in the air and transported over long distances (i.e., 95 kilometers) (Allen et al., 2019). Eventually they will contaminate terrestrial surfaces and the hydrosphere through dry and wet deposition (Li et al., 2020). MPs release their own chemical components such as plasticizers, flame retardants, antimicrobial agents, bisphenol A (BPA) (Khalid et al., 2020). Some chemicals, such as polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), and dichlorodiphenyltrichloro-ethane (DDTs), are adsorbed onto the surface of MPs (Akhbarizadeh et al., 2021; Jiménez-Skrzypek et al., 2021). In addition, they can release heavy metals that have been adsorbed during the degradation process (Santana-Viera et al., 2021; Wright and Kelly, 2017). Some MPs have hydrophobicity and large specific surface areas to absorb more harmful substances, which will affect their polluting potential (Akhbarizadeh et al., 2021). Concerns about the pollution characteristics of atmospheric MPs and their potential harmful effects on human health (e.g., oxidative stress, inflammatory lesions, metabolic disturbances, neurotoxicity, and increased cancer risk) demands that more vigorous scientific research should be undertaken (Wang et al., 2020b). The transport and toxicity of MPs in the atmosphere are important aspects that need further study (Huang et al., 2021).

In comprehensive databases such as ISI Web of Science and Science Direct, we searched keywords like "microplastics", "atmosphere" and “airborne” as valid data records. The 145 papers published between 2015 and 2021 are summarized in this review (Table S1). Although the initial retrieval dates were set for 2000-2021, the first finding in the literature on atmospheric MPs was in 2015 (Dris et al., 2015). As shown in Fig. S1, there has been a gradual increase in the number of studies on MPs in the atmospheric environment from 2015 to 2019, and then a rapid increase since 2020. The study of atmospheric MPs pollution has become the focus since 2020. In recent years, some review articles on atmospheric MPs have been published.

A small number of reviews have focused mostly on techniques for the collection and identification of atmospheric MPs (Auta et al., 2017; Crawford and Quinn, 2017). More recently, researchers have expanded the scope of MPs research to include toxicology and health effects (Bejgarn et al., 2015; Kutralam-Muniasamy et al., 2021; Wright et al., 2017). In addition, MPs transport and interactions in the atmospheric environment are discussed (Huang et al., 2021; Petersen and Hubbart, 2021). Currently, research on the fate and role of MPs in the atmosphere and terrestrial environments is now a significant topic (Wang et al., 2021b). However, most of these reviews or studies focus on a single research aspect, e.g., either the morphological characteristics or the chemical types, or a single process or sampling methods, and therefore they do not provide a comprehensive and systematic overview on airborne MPs. There is an urgent need for integration and critical analysis of various research units, and for new research directions or perspectives. This review provides readers with a comprehensive and systematic understanding and overview on airborne MPs.

In this paper, we present a detailed assessment of the global literature on MPs in the atmospheric environment, and evaluate the collection, extraction and identification methods (i.e., 'passive' and 'active' sampling, density separation and visual identification) currently used to investigate atmospheric MPs. The physical and chemical characteristics of atmospheric MPs, as well as their possible sources, and the spatial and temporal scale distributions, are summarized. We address the impact of MPs on the environment, particularly the impact of airborne MPs when deposited in soil and the hydrosphere. Our study provides a reference for research on the prevention and control of MP pollution and has identified further research priorities.

2. Sampling and analysis of airborne microplastics

2.1 Microplastics sampling

2.1.1 Passive sampling

The different sampling methods can collect different types of MPs in the air, due to factors such as particle morphology and density, and these diverse methods can also affect empirical values such as MPs concentration levels (Table 1). The currently used MPs sampling methods include 'passive' and 'active' sampling (Fig. 2). Passive sampling methods (Fig. 2a) can be ideal sampling methods for atmospheric MPs deposition due to simplicity, ease of use, low cost, and use of standard laboratory equipment. In addition, passive sampling methods do not require electricity or other power supplies, and are suitable for outdoor or long-term sampling, lasting for weeks or months (Chen et al., 2020). Passive sampling can collect a large particle size range of MPs. Therefore, passive sampling methods are commonly used when it is necessary to know detailed information of the whole MPs deposition range over a certain period of time. However, adverse weather conditions may significantly affect the sampling quality and outputs. Therefore, it is necessary to systematically record the weather conditions for any subsequent assessment of weather impacts on MP deposition (Dris et al., 2016). The most common passive sampling method is to collect dry or wet atmospheric deposition in a glass container through a funnel. The funnel is made of stainless steel or glass which has a smooth surface (Akhbarizadeh et al., 2021; Dris et al., 2016; Klein and Fischer, 2019). The atmospheric deposition will either slide down the slope of the funnel in a dry state into the bottle or will be washed into the bottle by precipitation. If collecting dry samples, the equipment needs to be physically covered to protect it from precipitation (e.g., rain or snow). This 'dry' deposition sampling method is widely used to collect and study outdoor MPs; however, it has drawbacks that include contamination by vegetation or insects and is vulnerable to vandalism.

Wet deposition collection methods can be problematic for water-soluble pollution (i.e., whole soluble particles or water-soluble components within non-soluble particles). Roblin et al. (2020) investigated MPs deposition and its influencing factors by vacuum filtration of wet deposition and rainfall samples onto glass fiber filters. Another passive sampling method is to collect a certain area of dustfall or collect a certain weight of dustfall; this is applicable to both indoor and outdoor dust collection. This method can use a vacuum cleaner or brush as a collection tool, then transferring the dust into sample bags for further analysis. Dris et al. (2017) collected dust samples from apartments in Paris, France, using a vacuum cleaner. Abbasi et al. (2017) studied MPs deposition in the dust by collecting road dust with metal pans and brushes. A clear advantage of these methods is the possibility of obtaining large masses for chemical analysis, where the reproducibility of the analyses is improved via bulk sampling. A good example of this is the study of platinum group metals in road dust, with the samples analyzed by ICP-MS (Mitra et al., 2021).

Another passive sampling method is to collect atmospheric particles in a petri dish with adhesive or a glass slide with adhesive using a sampler with a wind-sheltered and low turbulence air volume; typically, a simply constructed container. Sommer et al. (2018) and Tian et al. (2017) used this passive sampling method to investigate tire wear particles, a major source of MPs in the environment. Compared with other methods, passive sampling amasses fewer particles and is generally utilized for measuring the morphology and volume of individual particles as well as the sedimentation rate. Passive samplers can be employed for continuous sampling of atmospheric deposition, where these dust particles, including MPs, fall on the surface due to gravity and weather conditions (i.e., wind or rain). MPs with smaller particle size and lighter weights can be suspended in the air for a long time (e.g., days to weeks), and a recognized outcome of this is passive sampling tending to preferentially collect the coarser fractions of airborne particles. Another important disadvantage of passive sampling using an adhesive tape substrate is that the adhesive chemically contaminates the sample, and obscures the particles embedded in the adhesive if they are needed to be viewed under high magnification, such as electron microscopy. Moreover, the volatile nature of the adhesive can be problematic in the electron microscopy chamber, whereby the electron gun, specifically the 'filament', may be obscured by the volatiles, reducing the imaging quality.

2.1.2 Active sampling

Active sampling methods are based on pumping sampler systems. These methods involve pumping a controlled amount of air over a certain period of time. As the air passes through the sampler (Fig. 2b), the particulate matter is collected on a filter or substrate. Filters allow the air to pass through them while collecting the particles on the surface or in the body of the filter. Substrates are impacted by the airflow which bounces off leaving the particles behind. Some systems effectively work as hybrid filters/substrates such as Tapered Element Oscillating Microbalances (TEOMs), which are widely used Worldwide in air pollution monitoring networks (Jones et al., 2006).

Therefore, the sampling time and volume, and mass of particulate matter collected with this sampling method are known; as a result, the quantity or mass concentration of particulate matter in each volume of air can be calculated. This method has been routinely used for the study of PM_{10}, $PM_{2.5}$ and PM_1 in the air, but now has also been used for the study of MPs in the air. An advantage of active sampling methods is that they can rapidly and accurately collect atmospheric MPs from outdoor or indoor air over a range of different locations. An active pumped sampler system typically consists of a pumping or vacuum unit, multi-stage particulate matter size-sorter (TSP-PM_{10}-$PM_{2.5}$-PM_1) and filter or substrate. Air pumping rates can usually be adjusted, and the particulate matter size ranges can be selected, and appropriate filter or substrate characteristics and material can be chosen. Typical filter pore sizes are 2 μm, 1.6 μm, 0.8 μm, and collection materials could include glass or quartz fiber, cellulose, Teflon and polycarbonate, to meet the requirements of different studies (Chen et al., 2020). For example, a study involving electron microscopy would choose to avoid fibrous media to optimize imaging, whereas an analytical study might prefer a fibrous medium with more efficient collecting capacity. The sampling time, sampling volume and efficiency of active collection methods can be controlled. Thus, the number or mass concentration of particulate matter per volume of air can be calculated. This method has also been routinely used for the study of individual particle size, morphology, type, color, etc. It is noteworthy that pollution by MPs in the atmosphere is exclusively related to human activity, population density, and levels and sophistication of industrialization (Can-Güven, 2020). Dris et al. (2017) studying MPs in indoor and outdoor air showed that the MPs concentration in outdoor air was significantly less than that seen indoors. Li et al. (2020) recorded that the concentration of microfibers at 1.5 m above the land surface is higher than that at 18 m above the surface, which has important implications as the lower 1.5 m level corresponds to a typical human breathing height. It is necessary to choose passive or active collection methods according to the research objectives, and to consider the sampling sites and periods, and the effect of weather conditions.

It should be noted that each sampling method has its own limitations. Especially the collection process can be influenced by different background conditions and natural environments, such as meteorology, the precision of the collection instruments and human activities. There are currently no standardized methods for sampling MPs, which means that results cannot be effectively compared with each other. Therefore, it is imperative that standardized methods are developed for future research on MPs.

2.2 Sample preparation

The particles, collected using both passive and active sampling methods, will not consist of only MPs, but also other natural and anthropogenic particles. With the complex and variable compositions, the bulk atmospheric particles need to be processed to separate and concentrate MPs. Currently, there is no recognized standard for sample preparation. However, previous studies have suggested that the best methods are density separation, and chemical digestion that can be used in the removal of non-MP organic matter.

2.2.1 Density separation

Density separation to isolate the MPs from the non-MPs in the bulk sample is a critical and challenging step (Table 2). Studies have used sodium chloride (NaCl) (Kunz et al., 2016), calcium chloride ($CaCl_2$) (Stolte et al., 2015), sodium iodide (NaI) (Abbasi et al., 2017) and zinc chloride ($ZnCl_2$) (Liu et al., 2019b). The different densities of the separation solutions have a direct effect on the flotation of different MPs and the densities of the different plastics. Density separation using NaCl can be undertaken on the less dense MPs by flotation; this depends on the molarity of the solution, but as a guideline seawater typically ranges between 1.02 and 1.03 g/cm^3, with the denser MPs sinking to the base of the column. $ZnCl_2$ solution with a density of 1.6-1.7 g/cm^3 or higher has been widely used for MPs density separation (Imhof et al., 2012; Uddin et al., 2020). Table 2 shows the densities of a range of plastics, and the suggested solutions used for density separation. During the separation process, the solution is kept moving at a constant speed, avoiding turbulence, to prevent physical damage to the MPs. In addition, to improve extraction efficiency, it is recommended that repeated extractions are undertaken. After separation, the particles are washed and dried, and are then available for analysis.

2.2.2 Digestion and removal of non-MP organic matter

Removing non-MP organic matter by digestion in oxidizing or reducing agents is an important first step, and this includes removing any organic matter adsorbed on the surface of MPs. Hydrogen peroxide (H_2O_2) (Abbasi et al., 2019), Sodium hypochlorite (NaClO) (Klein and Fischer, 2019), Hydrogen nitrate (HNO_3) (Van et al., 2015), Hydrogen chloride (HCl) (Desforges et al., 2015), Potassium hydroxide (KOH) (Prata et al., 2020; Zhang et al., 2017; Zhang et al., 2019), Sodium hydroxide (NaOH) and enzymes (Cole et al., 2014) have been used to remove non-plastic organics from the bulk sample (Table S2). H_2O_2 solution or NaClO have typically been used to remove organic matter from MPs in atmospheric particulate matter samples. In the work of Allen et al., (2019), the non-MP organic matter in the sample was removed by 30% H_2O_2 solution. Other studies have used NaClO to remove non-MP organic matter (Dris et al., 2016; Klein and Fischer, 2019). Notably, some studies suggest that the use of 30% H_2O_2 has affected the MPs as well, with changes such as decolorization and making the MPs harder to positively identify. Reducing the concentration of H_2O_2 (20 - 25%) could improve this situation, however further study is required on the removal efficiencies of various digesting agents and their impact on the MPs themselves. Some researchers have suggested that Fenton chemistry might be more efficient at removing unwanted organic matter than H_2O_2; a suggestion that requires further research and verification (Chen et al., 2020).

The preparation of MPs samples, including density separation and removal of organic matter, has some significant effects on the analysis and identification of MPs. On the one hand the composition of the reagents or filters may seriously interfere with the identification of plastics, e.g., H_2O_2, a fluorescent indicator and colorant, on the other hand the quantity or mass concentration of MPs may be underestimated (Chen et al., 2020; Stanton et al., 2019). In addition, other substances, such as biofilms in the solution, can be mixed in the preparation process, leading to incorrect estimates of compositions of MPs (Santos Galva et al., 2022). Therefore, MPs samples should be pre-treated depending on the collection environment. For example, the samples obtained from dry and wet deposition and dustfall should follow the steps of density separation, digestion, sieving and then filtration to ensure the validity of the sample (Zhou et al., 2017). Without pre-treatment, non-MP components in the samples can be misidentified as MPs during analysis by some analytical techniques that are sensitive to carbon, silica, biofilm and other organic components, resulting in misidentification (Santos Galva et al., 2022)."

2.3 Instrumental analysis of microplastics

Among the various methods for the analysis of atmospheric MPs, appropriate ones can be selected for different research purposes (Fig. 3). In many studies included in this review， the analyses of MPs mainly focused on morphological and chemical composition analysis (Table 3). To determine the MPs morphology, the most used method is microscopy. Stereoscopic microscopy has been employed in many studies to identify MPs (Dris et al., 2017; Liu et al., 2019a). The shape, size, color and opacity of MPs can be identified by stereoscopic microscopy (Al-Salem et al., 2020). Furthermore, image analysis automated processing software can radically increase the numbers of particles measured per analysis session. However, stereoscopic microscopy cannot identify MPs with smaller particle sizes (< 500 μm), which are within the accepted detection limit of optical instruments (Silva et al., 2018). To detect and characterize MPs with smaller particle sizes (< 500 μm), some researchers have used scanning electron microscopy (SEM) (Abbasi et al., 2019; Li et al., 2020). SEM can provide a high-resolution image of the particle by emitting a high-intensity electron beam onto the surface of the sample. As a result, the surface of MPs can be clearly observed, and the microstructure can be determined. A problem that can occur with this analysis is that some plastic materials are not stable under the electron beam and will visibly move and distort when under that beam, which makes imaging or elemental analysis impossible; however, this characteristic can be used to identify the least robust plastic particles (Abbasi et al., 2019; Gniadek and Dąbrowska, 2019). Li et al., (2020) have used the combined application of SEM and Energy-dispersive X-ray spectroscopy (SEM-EDX) to analyze microfibers in the atmosphere. It is worth noting that SEM-EDX, as a powerful means of individual particle analysis (Li et al., 2016; Shao et al., 2021, 2022), can provide detailed quantitative information of the elements that make up the MPs. It can also observe the surface morphology of MPs, such as grooves, pits, cracks, and flakes (Fries et al., 2013; Wang et al., 2021c). Using these individual particle analysis techniques, the pattern of mechanical degradation of microfibers can be determined based on their surface characteristics (Cai et al., 2017; Chen et al., 2020). In addition, SEM-EDX can help to distinguish between non-MP natural materials and MPs, thus establishing the ratios of these two particle types in the bulk samples. Therefore, although time-consuming, optical microscopy and scanning electron microscopy can often effectively detect atmospheric MPs, especially for the characterization of individual particles. Visual identification and SEM-EDX have been widely used to analyze the physical characteristics and semi-quantitative elemental composition of MPs.

With advancements in the research in this field, often a more detailed understanding of the chemical composition of MPs becomes more important. Studies have therefore combined an initial microscopy identification with Fourier Transform Infrared Spectroscopy (FTIR), Raman Spectroscopy, High Performance Liquid Chromatography-Tandem Mass Spectrometry (HPLC-MS-MS), Pyrolysis-Gas Chromatography-Mass Spectrometry (PYR-GC-MS), Thermal Desorption (TD), Thermogravimetric Analysis (TGA) and hyperspectral cameras being widely used techniques (Chen et al., 2020; Kitahashi et al., 2021; Maghsodian et al., 2021).

FTIR is one of the most common techniques used for the chemical characterization of MPs. FTIR provides unique infrared spectra for specific chemical bonds. Infrared spectroscopy can not only accurately identify the polymer types of MPs, but also understand the physical and chemical weathering of MPs by analyzing their oxidation state (Corcoran et al., 2009). Micro-FTIR can detect MP particles (> 10 μm) (Suaria et al., 2020); Focal-plane-array Fourier transform infrared (FPA-FTIR) can detect MP particles (> 20 μm) and has a high lateral separation rate (Sven and Knepper, 2018); Attenuated total reflectance Fourier transform infrared (ATR-FTIR) was more suitable for identifying irregular MP particles (> 500 μm) (Vianello et al., 2019). Although FTIR can provide accurate MPs identification, this technology is not suited to high throughput (HTP) MPs analysis. It is also an expensive method, and is economically prohibitive to apply HTP analysis to regular airborne MPs monitoring programs.

Raman spectroscopy is another technique commonly used to identify MPs. A monochrome laser beam is projected onto the target sample, and because different chemistries scatter, reflect and absorb the beam to produce different backscattered light frequencies, it can identify different plastics in MPs (Crawford and Quinn, 2017; Li et al., 2017). In particular, the combination of Raman spectroscopy and microscopy (i.e., micro-Raman) has made it possible to chemically identify MPs with diameters less than 1 μm (Lder and Gerdts, 2015). Therefore, this technique is widely used in the identification and classification of MPs (Kumar et al., 2020; Maghsodian et al., 2021). Compared with FTIR, Raman spectroscopy has a wider spectral range, higher spatial resolution, narrower spectral bonds and lower sensitivity to water interference (Araujo et al., 2018). Raman spectroscopy not only enables the non-destructive chemical characterization of MPs, but it also has a high reliability with a small number of samples (Araujo et al., 2018; Shim et al., 2016). However, Raman spectroscopy is susceptible to interference from sample surface attachments or additives contained in the sample itself, which can reduce the determination of the particle plastic type but yields an improved overview of the actual particle chemistry. It is still a powerful and high-resolution analysis technology.

HPLC-MS-MS can be used to detect polyethylene terephthalate (PET) and polycarbonate (PC) based MPs in atmospheric dust (Wang et al., 2017b). The MPs containing PET and PC are depolymerized in pentanol or butanol, then a determination is made of the concentrations of the depolymerized building block compounds (Zhang et al., 2019). Pyrolysis-gas chromatography-mass spectrometry (PYR-GC-MS), Thermal desorption–gas chromatography–mass spectrometry (TD-GC-MS) and

Thermal extraction desorption–gas chromatography–mass spectrometry (TED-GC-MS) with Thermogravimetric analysis (TGA) can be used to identify MPs particles by thermal degradation (Chen et al., 2020; Kaeppler et al., 2018). The different types of MPs were determined by the chemical composition of the thermal degradation products (Kaeppler et al., 2018). The advantages of these techniques are that they are not affected by the physical characteristics of the MPs (e.g., shape, color, size), or by the additives in the MPs (Kaeppler et al., 2018). However, these methods can only analyze a small number of samples, only one sample each time, which limits their wider use (Duemichen et al., 2017). However, more recently, a hyperspectral camera enables high-speed characterization of MPs. This analytical method can quickly and efficiently measure hyperspectral data (chemical composition) of MPs and build classification models capable of classifying MPs types regardless of particle size or filtration conditions (wet and dry) (Kitahashi et al., 2021).

3. Physicochemical characteristics of airborne microplastics

3.1 Types and individual particle characteristics of microplastics

The morphology, size, color, thickness, and surface mechanical wear of individual MP particles collected by passive or active methods can be characterized by visual observation (Chen et al., 2020). Meanwhile, these physical characteristics constitute the basis for the classification of MPs.

The identification and classification of MPs, specifically microfibers (fibrous MPs), can be based on their length into five categories: very long (1 000 μm ≤ L), long (500 μm ≤ L < 1 mm), middle (250 μm ≤ L < 500 μm), short (100 μm ≤ L < 250 μm), and very short (L ≤ 100 μm) (Dehghani et al., 2017; Abbasi et al., 2017) (Table 4). Fibers are normally defined as having an aspect ratio equal to or greater than 3:1. It is worth noting that in atmospheric particles, fibrous particles have been subdivided into two groups; organic fiber particles and inorganic particles (Li et al., 2020). Fibrous MPs belong to the organic fiber particles which differ significantly from inorganic fiber particles (e.g., asbestos fibers and man-made mineral fibers) in terms of their microscopic morphology and chemical composition. SEM-EDX can be used to identify the main elemental composition of fiber particles. The main elements of organic fiber particles are C and O as well as small or trace amounts of other elements (Li et al., 2020), while the inorganic fiber particles are characterized by an elemental composition of S, Ca, Al, Si, Fe, Ca, Mg, Ti, Mg and Na (Li et al., 2020). In addition, Fourier Transform Infrared Spectroscopy (FTIR) and Raman Spectroscopy can be used to efficiently identify organic particles (Maghsodian et al., 2021; Suaria et al., 2020).

The length and quantity of fibrous microplastics varies from different countries or regions. For example, the MPs in the atmosphere of Paris, France, were mainly fibrous, ranging in length from 200 - 600 μm (Dris et al., 2016). MPs in the Pyrenees Mountains were predominantly smaller than 300 μm in length, and 60% of MPs in the atmosphere of Hamburg, German were less than 63 μm in length (Klein and Fischer, 2019). Eighty seven percent of MPs in the atmosphere of Shanghai in China, were found to be 23-1000 μm in length (Liu et al., 2019b). Most MPs in the atmosphere of London, UK, were 400 - 500 μm in length (Wright et al., 2020). Some of the recent studies showed that MPs collected by the active collection method can also be fibrous with a length of 5 - 200 μm (Li et al., 2020)(Table 5). It is worth noting that MPs may act as condensation nuclei for rain or snow. Among the MPs detected in snowfall samples, 98% were less than 100 μm in length, and 80% were less than 25 μm in length (Bergmann et al., 2019).

Another scheme of MPs classification places them into five groups according to their shape; fibers, sphere/pellets, fragments, film and foam (Dehghani et al., 2017; Cai et al., 2017) (Table 4). Studies have shown that most MPs in the air are fibrous, followed by fragments and then pellets. In Paris, France, more than 90% of MPs in the air were fibers, and 0 - 10% were fragments (Dris et al., 2015). In Shanghai, China, fibers (67%), fragments (30%), granules (i.e., sphere/pellets) (3%) were found in the atmosphere (Liu et al., 2019a). In addition, films and foams MPs have been detected in atmospheric samples (Cai et al., 2017) (Table 5). It is probable that there are collection and analysis bias in some datasets due to the difficulty of researching the smaller MPs (< 50 μm);

particularly, with optical microscopy (Dehghani et al., 2017), a problem not encountered when using SEM to accurately image different sizes and shapes such as fibers, spheres, hexagons, irregular polyhedrons and surface wear (Cai et al., 2017; Li et al., 2020). So far, a variety of morphological types of MPs have been identified based on SEM observation, including fragments, film, fiber and spherical. (Fig. 4) (Abbasi et al. 2017, 2019; Li. et al., 2020).

The MPs can have different colors (Fig. 5), and so far, the reported colors of the identified MPs include white, red, yellow, blue, green, black, grey, brown, pink, orange, as well as transparent (Abbasi et al., 2017; Cai et al., 2017; Dris et al., 2015; Dobaradaran et al., 2018; Liu et al., 2019a)(Table 5). Blue and red MPs were commonly found in the air in Paris, France (Dris et al., 2015), and transparent, blue, red and grey MPs were identified in a study in Dongguan, China (Cai et al., 2017; Liu et al., 2019a). Black, yellow, blue, red, and green are the most abundant colors. There were also small numbers of brown, pink and orange MPs observed in Tehran, Iran (Dehghani et al., 2017). In order to meet the needs of use, different colors are added to the plastic during the manufacturing process, thus resulting in the different colors of MPs (Kwon et al., 2017; Khalid et al., 2020).

Finally, MPs can be classified according to their source, i.e., primary and secondary MPs. Plastics that were manufactured into particles (0.5 - 5 mm) are defined as primary MPs (Cole et al., 2011). For example, plastics such as polyethylene are commonly used in cosmetics, either in products designed to rinse-off, such as skin cleansers, or developed to stay on the skin, like eye make-up or face powders. Secondary MPs are formed by the physical, chemical and/or biological breakdown of larger plastic fragments (Auta et al., 2017).

3.2 Chemical compositions of airborne microplastics

After morphological identification, the focus is often on determining the chemical composition of atmospheric MPs. SEM-EDX, ICP-MS, FTIR, Raman, PYR-GC-MS and HPLC-MS-MS are commonly used to characterize the chemical composition of

MPs.

The elemental composition of individual MP particles can be detected using SEM-EDX (Abbasi et al. 2017; Li et al. 2020). Bulk analysis by ICP-MS has revealed that, in addition to major elements C and O, minor Ca, S, Mg, Al, Si Zn, Pb, Mn, Cu, Ni, Co, Cd, and Cr are also detected in MPs (Bolea-Fernandez et al. 2020; Wang et al. 2017c). However, these methods were limited to determining just that elemental composition, and cannot identify the organic chemical structure of MPs (Kutralam-Muniasamy et al. 2021).

FTIR, Raman spectroscopy and hyperspectral camera spectroscopy have been used to identify the types of MP polymers (Kitahashi et al., 2021; Wang et al., 2017b). Numerous studies have reported that PET, PC, polypropylene (PP), Polyphenylene ether (PPE), , polyvinyl chloride (PVC), polystyrene (PS), polyethylene (PE), polymethyl methacrylate (PMMA), Nylon, acrylonitrile–butadiene–styrene (ABS) and Polyformaldehyde (POM) were identified and classified (Table S3) (Cai et al., 2017; Kitahashi et al., 2021; Szewc et al., 2021; Zhang et al., 2020a).

Studies from China have reported PET, PP, PVC and PS (Cai et al., 2017; Liu et al., 2019a; Zhou et al., 2017). PET, PP, PE, PVC, and PMMA were found in the Baltic coastal air (Szewc et al., 2021), while polycarbonate PC, PVC, Nylon, PE, PP and PS, dominated the samples in the other areas of northern Europe and the Arctic (Allen et al., 2019; Bergmann et al., 2019). In addition, FTIR spectroscopy may be utilized to identify the chemical weathering of MPs, which results from the oxidation of MPs by photochemical reactions (Cai et al., 2017). Some studies on PET- and PC-based MPs have suggested that PET and PC were prevalent in indoor dust in 12 countries (Wang et al., 2017b; Zhang et al., 2020a), further confirming that MPs are globally common indoor pollutants.

More recently, a hyperspectral camera enables high-speed characterization of MPs. PE, PP, PS, PVC, PET, PC, ABS, nylon, and POM can be quickly identified and characterized (Kitahashi et al., 2021). However, sometimes these chemical composition data of MPs can be interfered with by other substances. This is due to the fact that in the process of degradation and weathering, the surface of MPs undergoes different degrees of wear, which makes the MPs more vulnerable to chemical reactions and influences the adsorption capacity for other chemicals (Abbasi et al., 2017). It has been shown that MPs can adsorb organic matter, pharmaceuticals and some heavy metals. PPE and PE have a strong ability to adsorb polycyclic aromatic hydrocarbons (PAHs) (Peng et al., 2017; Santana-Viera et al., 2021), and hence, increasing the toxic capacity of the MPs (Fig. 6).

3.3 Concentration and distribution of microplastics

The concentration and distribution of MPs are affected by numerous environmental factors, resulting in the types, concentrations and distribution of airborne MPs being highly variable in different geographical locations and at different times of the day or year/season. MPs have been recorded in different concentrations and types in indoor and outdoor settings, at different sampling heights, and in urban, suburban, and rural conurbations (Dris et al., 2017; Liu et al., 2019a). The possible factors affecting MPs pollution levels include population density, degree of industrialization, level of afforestation, infrastructure, and meteorological conditions (Klein and Fischer, 2019). In a pioneering study, Dris et al. (2015) found that there were 29 - 280 MP particles /m^2/ day in the atmospheric dustfall in Paris, France. This was followed by further studies reporting that concentrations of MPs in urban air were higher than in suburban areas (Dris et al. 2016), while indoor concentrations of plastic fibers (Dris et al. 2017) and MPs (Zhang et al. 2020a) were higher than outdoor. Studies have shown the concentrations of MPs in the indoor (1586 - 11,130 particles/ m^2/ day) (Dris et al., 2017) is significantly higher than the outdoor MPs concentrations (29 - 280 particles/ m^2/ day) (Dris et al. 2015) in Paris and that most of these MPs are fibers. However, Gaston et al. (2020) reported that the concentration of MP fragments outdoor was higher than indoor. The high detected concentrations of indoor MPs may be related to the source release flux of indoor MPs and their dispersion mechanisms (Wang et al. 2021a). Li et al. (2020) reported that the airborne fiber concentrations at 1.5 m above the ground were higher than at 18 m above the ground in Beijing, China. This probably resulted from the fact that the MPs were either generated or resuspended nearer the surface, and any higher samples would have an overall movement downwards driven by gravity, unless carried upwards by wind currents (i.e., fugitive dusts) (Szewc et al., 2021). In Dongguan city of Guangdong in China, MPs and fiber content in dustfall ranged from 175 - 602 particles/ m^2/ day (Cai et al., 2017; Zhou et al., 2017). In the UK, the concentrations of MPs in Nottingham and central London were 3-128 fibers/ m^2/ day and 550-874 particles/ m^2/ day, respectively (Stanton et al., 2019; Wright et al., 2020). Further studies on the factors affecting the MPs pollution showed that the wet deposition by rain or snow of MPs (including fibers, fragment and films) was higher than dry deposition, and most of MPs were fibers (62 ± 24%) (Szewc et al., 2021). At present, the majority of studies suggest that concentrations of fibers in the atmosphere are higher than those of fragments, and also indicated that the dry and wet deposition rates of MPs might vary regionally depending on different climatic factors (e.g., wind and solar radiation) and on the quantity and mass of MPs in the atmosphere (Tan et al., 2020). Roblin et al. (2020) showed that meteorological variables, i.e. relative humidity, rainfall, wind speed and direction, were significantly correlated with MPs abundance. Rainfall and air masses are important influencing factors for MPs deposition.

4. Sources and transport of airborne microplastics

4.1 Sources of airborne microplastics

Understanding the sources and transport of atmospheric MPs are essential steps towards implementing legislation and guidance to minimize this anthropogenic pollution. Some studies have shown that atmospheric MPs were predominantly fibers, and most of these fibers were synthetic (Dris et al., 2017; Liu et al., 2019a; Moreno et al., 2014). Therefore, textile fibers shed from clothing are a major source of natural or synthetic fibers in the atmosphere (Wright et al., 2020). Vianello et al., (2019) found that polyesters were the most abundant synthetic polymers in MPs from indoor environments, and that polyesters could come from clothing, furniture and carpets. The global production of textile fibers exceeded 90 million tons in 2016, two-thirds of which were synthetic and plastic fibers (Barceló and Franzellitti, 2020); production and consumption should continue to increase in the future as demand increases. This supports the view that anthropogenic activity was an important factor affecting fiber abundance in the air (Liu et al., 2019a). From the analysis of these particle physicochemical characteristics, many researchers now believe that the sources of these MPs could be construction materials, industrial emissions, furniture plastic debris, particle resuspension, landfills, traffic particles and waste incineration (Abbasi et al., 2019; Dris et al., 2017; Li et al., 2020; Sun et al., 2021). However, some studies have found that the majority of MPs in the atmosphere were secondary MPs, which suggests that the MPs of different shapes, colors and lengths were degraded from larger plastic debris in a variety of different environments (Auta et al., 2017; Horton et al., 2017; Wang et al., 2021a). A study estimated global mismanaged plastic waste production in 2015 to be between 60 and 99 million metric tons. Under normal circumstances, global mismanaged plastic waste is expected to triple from 2015 - 2060 to 265 million metric tons (Lebreton and Andrady, 2019). This discarded plastic waste is gradually degraded in the environment; especially in atmospheric environments, photochemistry (Auta et al., 2017), chemical weathering (Yan et al., 2018; Zhang et al., 2020b) and mechanical physical weathering damage (Allen et al., 2020; Cai et al., 2017), such as abrasion in turbulent airflow (Barnes et al., 2009). In addition, the physical and chemical characteristics of the plastics themselves also determine their presence and ageing in the environment (Table S3). The brittleness (glass transition temperature) and extremely low degradation rate of these plastics lead to the formation of MPs from plastic waste in the environment (Huerta Lwanga et al., 2016).

All these factors have led to an increasing number of MPs in the atmosphere (Dris et al., 2015; Li et al., 2019). All the above studies on the sources of MPs were based on the analysis of the physical and chemical characteristics of MPs. Recently, stable carbon isotope ratio mass spectrometry (IRMS) has been applied to the tracing of atmospheric MPs sources (Berto et al., 2017; Birch et al., 2021). IRMS is based on each polymer having a distinct $\delta^{13}C$ value to determine whether the MPs in the atmosphere were plant-derived or fossil fuel-based materials (Jackson, 2009). In addition, IRMS can detect differences in the raw materials of the same type of polymer to determine the manufacturing sources (Birch et al., 2021). Birch et al. (2021) showed a trend towards higher $\delta^{13}C$ values for PS and PP exposed to ultraviolet (UV) light, which correlated with the UV sensitivity of these polymers. This result was consistent with previous studies on the ageing of plastics. IRMS has a high sensitivity, rapid and automated analysis and is relatively low cost (Birch et al., 2021). In addition, this technique is not affected by additives in the plastic, as is the case with Raman and FTIR spectroscopy (Berto et al., 2017). Therefore, a combination of different techniques such as IRMS can be used in conjunction with Raman and FTIR spectroscopy to trace the sources of MPs in the atmosphere.

4.2 Transport of airborne microplastics

Atmosphere is one of the main pathways for the transport of MPs. Dris et al. (2015) first reported MPs transport in the atmosphere in Paris, France, and suggested that fibers found in freshwater mainly originate from atmospheric deposition. The transport and deposition of MPs are related to both meteorological factors such as rain, snow, temperature, humidity, air pressure and wind speed (Hitchcock, 2020; Wang et al., 2020a), and also to the shape and size of the MPs (Zhang et al., 2020a). Several studies have found that the particle size of MPs suspended in air (i.e. < 0.5 mm, Wright et al., 2020) and in dustfall (i.e. < 5 mm, Syafei et al., 2019) is generally small compared to that of MPs in water (i.e. < 4.975 mm, Deng et al., 2020) and soil (i.e. < 2 mm, Yang et al., 2021). Airborne MPs need to be transported by suspension therefore their particle size is generally small (Abbasi et al., 2019). The majority of airborne MP morphology types are fibrous, which is probably due to the fact that fibrous MPs are more easily suspended in the air (Li et al., 2020; Materic et al., 2020). Generally, PC, nylon, PVC and PET, which have a higher density, sink more easily, while PE, PP and PS are prone to floating or suspension, but biofouling of organic matter and adsorption of inorganic matter can alter their original behaviour (Kaiser et al., 2017). The distribution characteristics of MPs in different environments are different (Wang et al., 2021b). Smaller MPs are more easily transported by the atmosphere (Allen et al., 2019). The wind is the main factor and driver of transport of MPs to remote areas (Evangeliou et al., 2020; Liu et al., 2019a). Allen et al. (2019) found that the number of MPs in the atmosphere was positively correlated with wind strength and suggested that wind was very effective for the transport and keeping MPs in atmospheric suspension. However, it is noted that for this correlation to work the MPs collection site needs to be downwind from the major sources. Therefore, local meteorological factors are an important mechanism for MPs suspension and transport (Abbasi et al., 2019). Mahrooz et al. (2019) reported higher concentrations of light-density MPs (LDMP) in recent wind-eroded surface deposits in Fars Province, Iran, than found in local stable soil surfaces; suggesting that the wind was the transport mechanism for synthetic polymer particles resulting in the enrichment of MPs in recent wind-eroded superficial sediments. Researchers have used long-term wind direction and intensity data to predict and model the movement of MPs. Allen et al. (2019) have used post-air mass trajectory analysis to show that the transport distance of MPs in the atmosphere can be up to 95 km/s. González-Pleiter et al. (2021) noted the existence of MPs in the planetary boundary layer (PBL) for the first time and based on air mass trajectory analyses, they showed that MPs can be transported over 1000 km/s in the atmosphere. MPs have been found in the snow cover of glaciers in Europe, the Arctic and Antarctica, and the Tibetan Plateau of China, proving that MPs can be transported over long distances, as these remote areas are rarely affected by human activities (Bergmann et al., 2019; Zhang et al., 2021). In cities, wind direction, rainfall and high humidity have significant effects on MPs deposition (Liu et al., 2019a). It has also been reported that there is a correlation between urban population density and MPs deposition (Wright et al., 2020), but this result is still controversial (Can-Güven, 2021; Liu et al., 2019a). The shape and size of the MPs determines the efficiency of atmospheric transport. MPs with smaller sizes and lower densities are more likely to be suspended in the air for longer. Flat film MPs are more easily transported in the atmosphere than similar mass fragment MPs (Allen et al., 2019). Fibrous MPs are easily suspended in the air, and large amounts of fibrous MPs are detected in many locations, including indoors and outdoors (Klein and Fischer, 2019; Materic et al., 2020). Bergmann et al., (2019) reported that 98% of MPs found in the Antarctic and Arctic regions were less than 100 μm. Currently, many researchers consider that MPs contribute to the aquatic and terrestrial environments via atmospheric transport, and that MPs are already extensively distributed in the atmosphere, hydrosphere, and lithosphere (Fig. 1) (Brahney et al., 2020; Gasperi et al., 2018; Zhang et al., 2020b). The transmission and interaction of MPs between these three units will be an important focus of future research because these three spheres interact with each other to make our planet livable (Brahney et al., 2021; Huang et al., 2021).

5. Implication for the environment and human health

5.1 Implication for the environment

MPs in the atmosphere are an important transport mechanism for the global deposition of MPs in the hydrosphere and lithosphere (Huang et al., 2021; IMO, 2015; Zhang et al., 2020a). The impact of these MPs on those environments often causes significant damage to ecosystems, both by the plastics themselves and their strong adsorption capacity for hydrophobic chemical pollutants, heavy metals and bacteria (Uddin et al., 2020). Moreover, in the process of MPs degradation, a variety of pollutants are released, such as flame retardants, plasticizers, antibacterial agents and bisphenol A (BPA) (Madeleine et al., 2018). Earlier research on the environmental impact of MPs has focused on soil, freshwaters, wetlands, and oceans, however in recent years MPs in the atmosphere have become of increasing concern (Chen et al., 2019; Novotna et al., 2019; Qian et al., 2021; Rillig, 2012; Suaria et al., 2020). Studies have shown that a variety of MPs (e.g., PE, PP, PVC, PET, PS) can be found in soil ecosystems, as films, fragments, pellets and fibers, the same morphologies seen in the atmosphere (Sarah et al., 2018; Zhou et al., 2019). Therefore, a component of MPs in the soil were considered to originate from atmospheric transport (Can-Güven, 2020). MPs are not only found in the surface soils as a result of dust fall, but also in deep subsoils (Liu et al., 2018). This is due to different processes such as agricultural tillage, soil fracturing or soil biological disturbances that transport MPs down to deeper soil horizons (He et al., 2018; Van et al., 2015). MPs can also be transported to the groundwater through earthworm bioturbation and downwards leaching of contaminated near-surface water (Rillig, 2012). The falling MPs contamination of groundwater can subsequently result in the contamination of surface water bodies where the water is in hydraulic connectivity; these affecting freshwaters and their sediments in different lakes and rivers globally (Wang et al., 2021a). Where high concentrations of MPs are found in freshwater sediments, these MPs are typically polypropylene pellets, polystyrene fragments, and acrylic fibers (Hoellein et al., 2019; Wang et al., 2017a). The smaller and lighter MPs can be carried further from the sources or deposition sites by currents (Huang et al., 2021). MPs are also found in wetlands, coastal, near offshore and the open ocean; where they have either been carried into these environments by water transport or directly deposited on the water surfaces by atmospheric transport (Qian et al., 2021; Suaria et al., 2020). If there are sufficient MPs in the soil this can change the soil characteristics (e.g., bacterial community composition and structure, pH and C:N ratio), which in turn impacts on the biological and microbial activities in the soil (Qi et al., 2020). In addition, MPs not only affect biological and soil characteristics and microbial communities, but can also lead to an increase in anaerobic communities, which cause an increase in CO_2 and methane emissions. Therefore, MPs pollution has a direct impact on global climate change (Ng et al., 2020).

Smaller MPs (5 - 100 nm) in size can be absorbed by the plant's roots, accumulate in the plant's body, and can obstruct vessels to slow or completely inhibit water absorption in the plant (Khalid et al., 2020). MPs can be ingested by herbivores, whether the MPs were adsorbed on the surface or inside plants (Khalid et al., 2020). In addition, MPs in the atmosphere can enter plants directly through their leaves and completely inhibit water circulation (Huang et al., 2021). MPs thus have the potential to enter the food chain and cause harm to higher organisms (Bejgarn et al., 2015). In freshwater and marine ecosystems, the research on biological impacts is more established. It has been shown that MPs are eventually degraded in the ocean, where the plastic surface is covered by microorganisms (Jan et al., 2018). This microbial covering changes the buoyancy of the MPs, potentially causing them to sink to deeper waters (Wang et al., 2021a). MPs have a serious impact on marine life, with studies finding MPs in fish, shellfish and microorganisms in the ocean (Al-Salem et al., 2020; Liu et al., 2021; Van et al., 2015; Xu et al., 2021). MPs can affect the reproductive capacity of fish (Clara et al., 2018), and can be deposited continuously in fish through gill filtration (passive ingestion) or feeding (active ingestion) leading to slow growth and even death (Al-Salem et al., 2020). Therefore, MPs in the aquatic, terrestrial and atmospheric environments could eventually have a negative impact on humans since they are adversely affecting important human food resources.

The reduction and elimination of environmental pollution from MPs is a focus of future research. Some results have been achieved in recent years for the recovery and elimination of MPs from wastewater. Jiang et al (2021) proposed a novel aluminum coating modification method for the flotation separation of PVC and PC in the environment, which effectively removed MPs from wastewater. In addition, the separated and collected MPs should not only be treated harmlessly, but also be converted into Fenton-like catalysts for wastewater treatment by a “waste treating waste” approach (Wang et al., 2021c). More effective treatments could be developed which can be used to block the transport of MPs in air, water and soil and reduce their impact on the environment..

5.2 Implication for human health

Recent studies have found significant amounts of MPs in the ambient air, hydrosphere, and lithosphere (Dehghani et al., 2017; Dris et al., 2016; Du and Wang, 2021; Huang et al., 2020;Wang et al., 2020a). Many of the MPs in the air have a fibrous morphology and range in size from 20 - 5000 μm (Cai et al., 2017; Li et al., 2020). Akhbarizadeh et al., (2021) found that MPs were present in $PM_{2.5}$ and that most of those MPs were less than 1 μm in size, and as a result were respirable and a possible threat to human health. The average human breathes 10 - 20 times per minute (Russo et al., 2017), therefore MPs can easily enter the body via the respiratory system (Akhbarizadeh et al., 2021). MPs can have the same aerodynamic characteristics as $PM_{2.5}$ particles in the air, and they can reach the deep lung or alveoli by respiration (Enyoh et al., 2019). Airborne MPs vary in concentration, size, and shape, all of which are important considerations when determining possible adverse effects in humans (Rainieri and Barranco, 2019). It has been reported that humans inhale up to 272 MPs per day from indoor air (Vianello et al., 2019). It has been shown that MPs over the size range of 0.1-10 μm were able to translocate from the lungs into organs, the placenta, cross cell membranes and the blood-brain barrier (Alexander et al., 2016). Specifically, MPs of < 1 μm were able to cross lung epithelial cells (Goodman et al., 2021). In addition, airborne MPs can also enter the body through eating contaminated foods (Toussaint et al., 2019) or foods containing MPs (e.g., seafood, sea salt, sugar, etc.) (Khalid et al., 2020; Madeleine et al., 2018), and through dermal contact (Abbasi et al., 2017). At present, research is finding that MPs ingested into the human body are removed through the body's excretory system (Madeleine et al., 2018), however, information about the longer-term fate of MPs in the human body has yet to be determined (Akhbarizadeh et al., 2021). It is possible that MPs entering the human body could cause physical damage as MPs can be absorbed into human tissues through phagocytosis and cellular adsorption in the respiratory system and gastrointestinal tract, which results in inflammation, cellular necrosis and tissue tearing (Enyoh et al., 2019). In addition, MPs can cause chemical damage in the human body by the production of Reactive Oxygen Species (ROS). Several studies have shown that MPs have potential cytotoxic effects, especially MPs < 10 μm in diameter, which can generate oxidative stress on human cells (Schirinzi et al., 2017). MPs in human cell models can also generate ROS, increase glutathione s-transferase activity and activate antioxidant-related enzymes and mitogen-activated protein kinase signaling pathways (Alomar et al., 2017; Yu et al., 2018). Moreover, the surface of MPs can be hydrophobic, which then potentially adsorb and concentrate hydrophobic organic pollutants, such as polychlorinated biphenyls and organochlorine pesticides (Jiménez-Skrzypek et al., 2021) and polycyclic aromatic hydrocarbons (PAHs) (Akhbarizadeh et al., 2021), and can also adsorb heavy metals such as Cd, Zn, Ni and Pb (Brennecke et al., 2016; Wang et al., 2020b). The water-soluble heavy metals absorbed on the airborne particles have been suggested to be toxic components which is potentially harmful to human health (Feng et al., 2020; Shao et al., 2017). MPs can adsorb chemicals, heavy metals, bacteria and additives that can cause indirect harm to the human body (Akhbarizadeh et al., 2021). The risks to children from MPs may be even more serious. In urban areas of China, the number of days children are exposed to PET through indoor dust is estimated to be 17,300 ng/kg body weight (Liu et al., 2019a). Abbasi et al. 2022 showed that children aged 6 - 14 years may be exposed to approximately 5 and 440 MP per day through inadvertent ingestion in Shiraz, Iran. The concentration of MPs quantities near the ground (1.6 m) was significantly higher than at high altitude (Li et al., 2020).

However, the actual health risks presented by MPs requires more investigation to elucidate the relationship of airborne MPs and their impact on human health to be able to determine clinical/therapeutic interventions, create risk assessments and to establish public health guidelines. The techniques for assessing the toxicity of inhalable particles, such as single-cell gel electrophoresis (Yang et al., 2003; Zhang et al., 2003), Ames fluctuation test (Brito et al., 2013; Du et al., 2019), micronucleus test (Brito et al., 2013), lung cell apoptosis (Zhou et al., 2010; Zhou et al., 2014), the plasmid scission assay (Feng et al., 2022; Moreno et al., 2004; Shao et al., 2017;) and hemolysis assay (Mesdaghinia et al., 2019; Zhang et al., 2022), could be used for the airborne PMs.

6. Conclusions and perspectives

The study of MPs in the atmosphere is attaining increased importance in environmental science, and clear progress has been achieved in this subject. The methods and techniques of MPs sample collection, extraction and identification are constantly being improved and optimized. A preliminary understanding of the physical and chemical characteristics and pollution sources of MPs has been achieved. However, standardized methods for the identification and classification of airborne MPs are needed to allow meaningful comparisons of global data between different research groups. Currently, the analysis of airborne MPs is a complex process involving multiple factors. MPs cannot be satisfactorily identified by direct analysis with almost any single analytical technique on its own. Specifically, the methods of collection and preparation of MPs have significant impacts on the results, such as the concentration of MPs in the atmosphere. In addition, by necessity, researchers include a decontamination phase, also known as the pre-treatment step, before analysis. Sample pre-treatment can significantly change the interpretation of MPs in the atmosphere, making the study of their interaction with other particles or pollutants in the air very difficult. The use of microscopy or SEM linked to FTIR and Raman spectroscopy offers advantages not available with other analytical methods, allowing information on the original morphology of the fragments to be obtained.

There are still many unknowns or poorly elucidated factors, such as the sources, degradation, chemistry and transport of MPs in the air. Our overall knowledge of atmospheric MPs still lacks sufficient data to undertake comparative studies, especially in different regions of the World. In addition, the potential toxicity of MPs in the atmosphere is not well understood. Important considerations for future work include the following aspects.

(1) The physicochemical characteristics of MPs in the atmosphere needs more sophisticated research. A combination of active and passive collection methods should be used to study MPs in the air, along with optimizing existing and developing new analytical techniques. The focus on standardizing methods of collection and identification of atmospheric MPs, including chemical composition, shape, length, color and units of measurement will facilitate more comparative studies of MPs.

(2) Airborne MPs are constituents of many aerosols, especially in urban settings, and should be a recognized pollutant for long-term monitoring. The percentage number of MPs per unit volume of aerosol particulate matter, and the percentage mass of MPs per unit mass of aerosol particulate matter should be monitored. Information on respirable MPs is imperative to produce meaningful human

health impact assessments.

(3) The toxicity of additives or adsorbed pollutants on MPs should be further investigated. Toxic organic pollutants and heavy metals carried by MPs may affect and alter the physiology of organisms, microorganisms and ecosystems. Therefore, it is important to focus on the original occurrence of MPs in the atmosphere and their effects on human health, as well as their mechanisms of action in the overall ecosystem.

(4) It is necessary to pay attention to the factors that specifically affect airborne MPs and the mechanisms by which these factors act on MPs. It is recommended to focus on the characterization of individual MPs. The method allows the influence of different factors on the fate of MPs to be taken into account, with the result that fingerprint features acting on MPs factors may be identified.

(5) The degradation and transport mechanisms of MPs in the air needs to be better understood. The contribution of atmospheric MPs to MPs in the lithosphere and hydrosphere, and the effects and interaction of MPs in the atmosphere, lithosphere and hydrosphere are also critically important.

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Figure captions

Fig. 1. Schematic illustration showing the sources, transport paths and fate of airborne microplastics and the interaction with pedosphere, hydrosphere and human community.

Fig. 2. Two methods for microplastic sampling in the atmosphere. (A) Passive atmospheric deposition. (B) Active pumping sampler.

Fig. 3. Principles of collection, preparation and identification of airborne microplastics.

Fig. 4. SEM images of MPs. (a) Fragments MPs, (b) film MPs, (c), fibrous MPs and (d) Spherical MPs, (e) fibrous MPs and (f) film MPs. (a), (b) and (d) were collected in Beijing, China; (c) was collected in Beijing, China by Li et al. (2020), with permission from Elsevier (License number: 5223390347409);(e) and (f) were collected in Hangzhou, China.

Fig. 5. Optical microscope images of different types of MPs. (a) fibrous MPs, (b) film MPs, (c) film MPs, (d) spherical MPs, (e) fragmented MPs. Modified after Abbasi et al. (2019), with permission from Elsevier (License number: 5223490330353).

Fig. 6. Degradation process of microplastics and its impact on humans.
Partly derived by Abbasi et al. (2019), with permission from Elsevier (License number: 5223490330353).

Fig. S1. Publication trend of related literature on microplastic contamination in atmosphere.

Table captions

Table 1. Different sampling techniques for collection of microplastics.

Table 2. The density of microplastics in aerosol and suitable solutions used for separation.

Table 3. Different methods and techniques used for laboratory identification of microplastics in atmospheric samples.

Table 4. Morphological types of individual MP particles

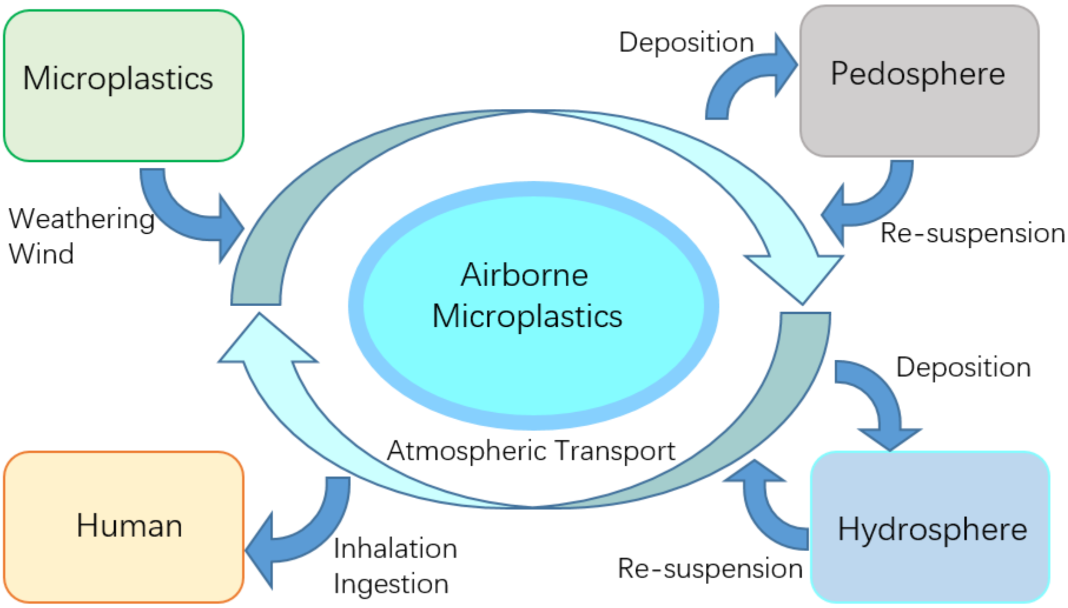
Table 5. Physical and chemical characteristics of airborne microplastics in some megacities.

Table S1. Published papers on atmospheric microplastics between 2015 and 2020.

Table S2. Sample collection, processing, and identification of microplastics from atmospheric samples

Table S3. Physical and chemical characteristics of airborne MPs.

Figures



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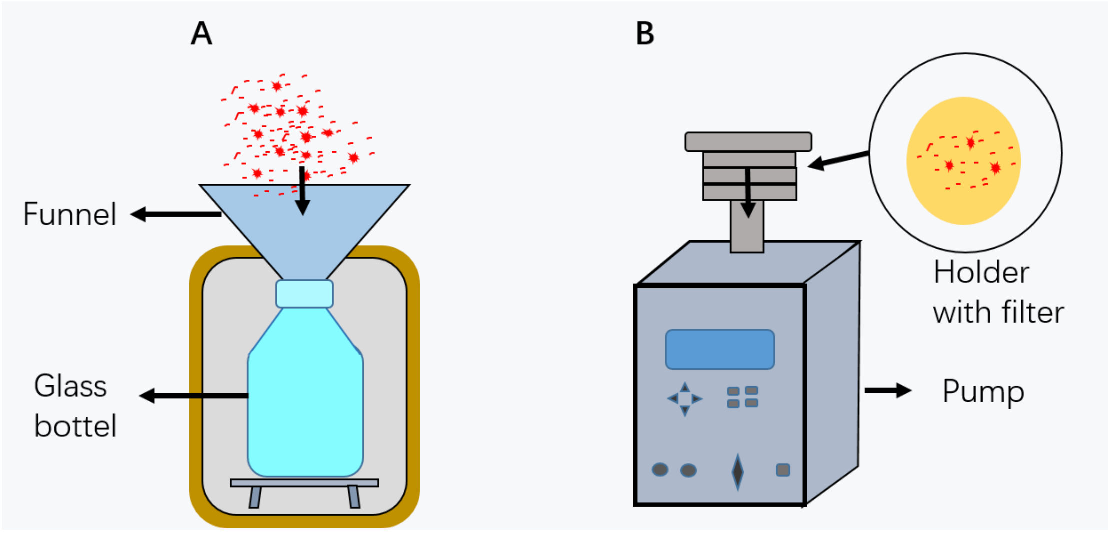

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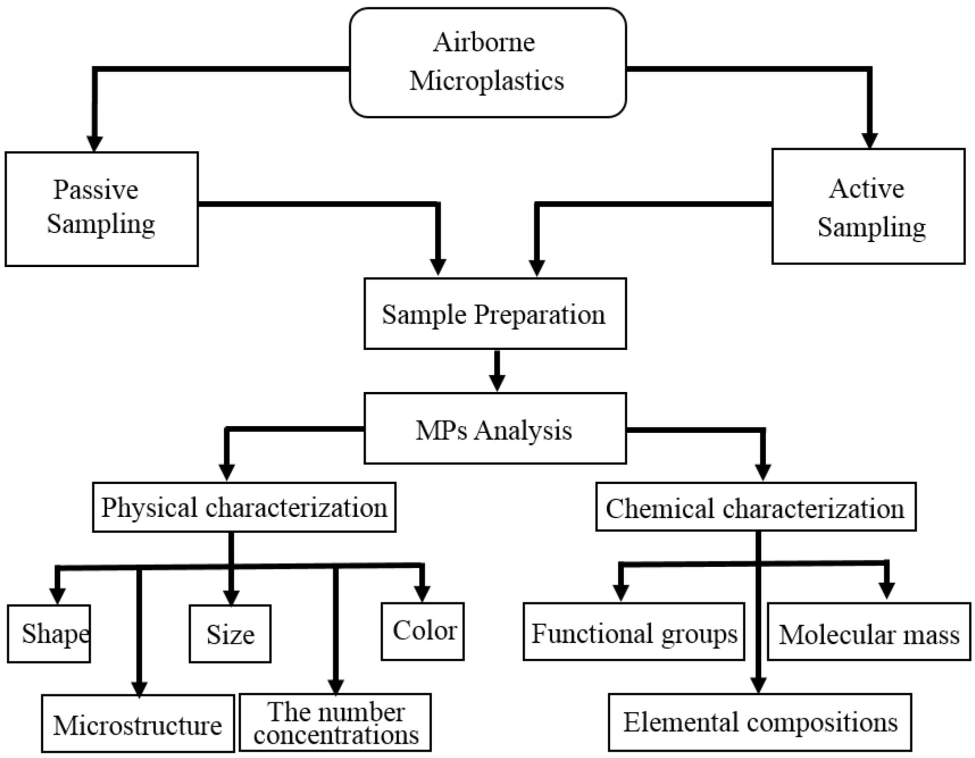

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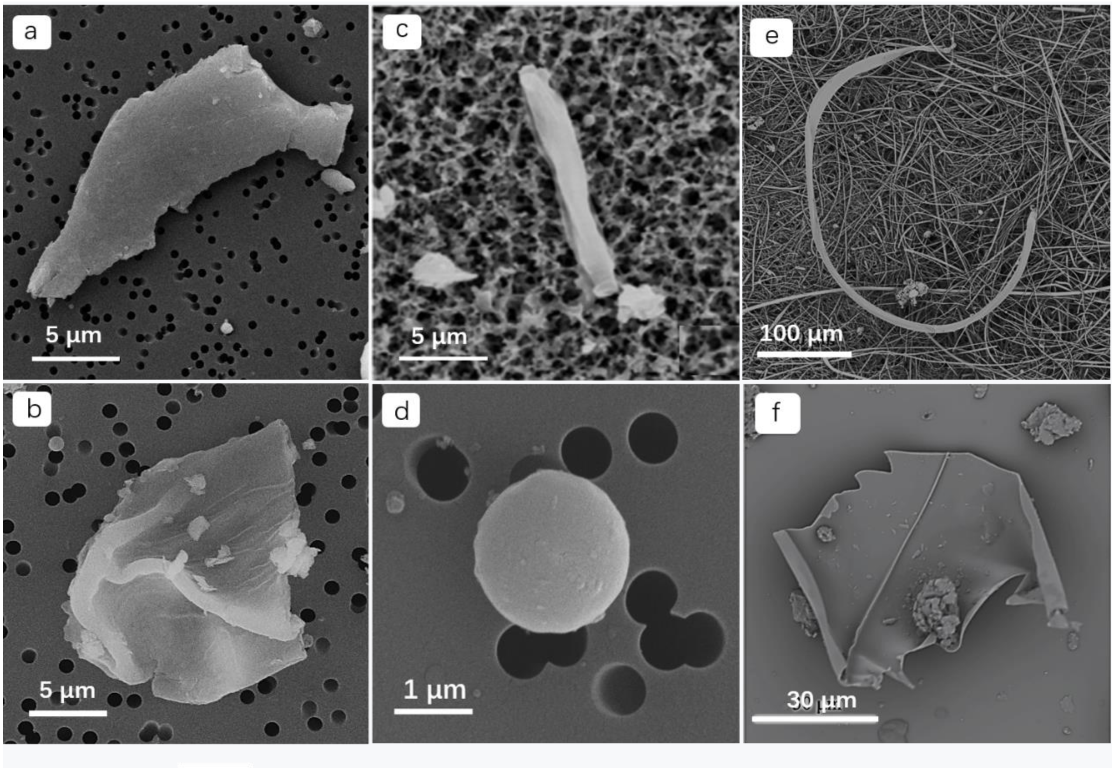

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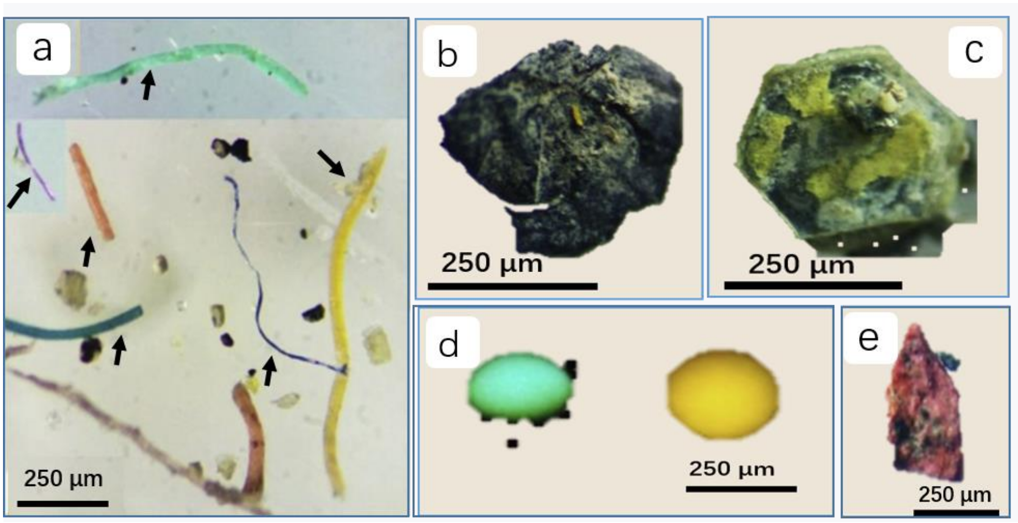

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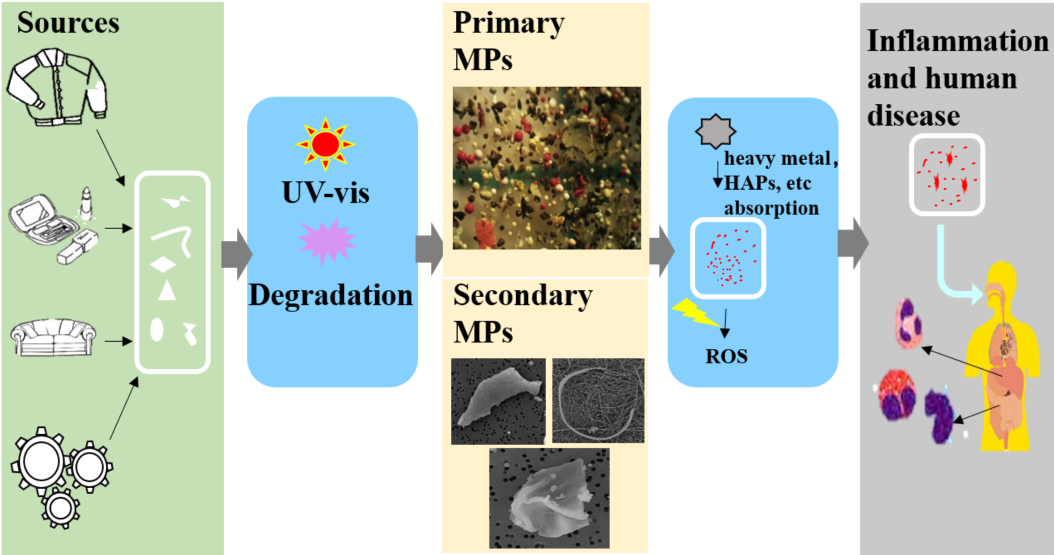

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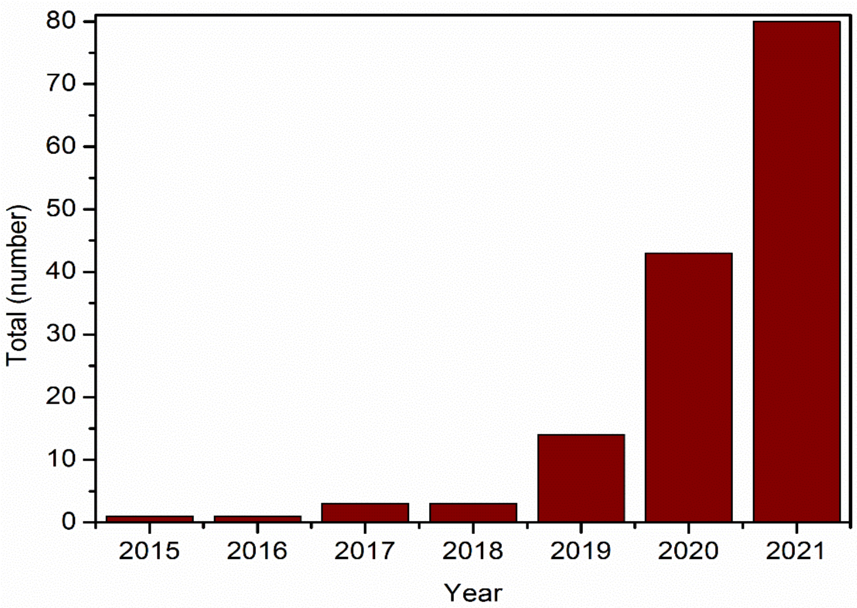

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Tables

Table 1. Different sampling techniques for collection of microplastics.

Sampling methods	Mode	Sample Matrix	City/ Country	Location	Sampling Technique	Reference
Passive	The funnel collects the fallout in the container.	Dry atmospheric deposition	Paris, France	Outdoor	Samples are collected through a stainless steel funnel, with a 20 L glass bottle placed at the bottom to collect water in an opaque box.	Dris et al., 2015,2016
		Dry atmospheric deposition	Dongguan, China	Outdoor	a glass bottle (30 cm × 15 cm)	Cai et al., 2017
		Dry/wet atmospheric deposition	Central London, UK	Outdoor	Aluminum rain gauge with a 200 mm diameter (0.03 m^2); samples collected 50 m above ground	Wright et al., 2020
		Dry/wet atmospheric deposition	Gdynia, Poland	Outdoor	steel funnel (Ø 65 cm,0.33 m^2), and 20 L glass jar with an aluminium cap	Szewc et al., 2021
	Collect a certain area (weight) of dustfall; Antistatic brush	Dustfall	Bushehr, Iran	Outdoor	Brush and pan; About 500 g of dustfall were collected within a 5 meter radius of the sampling site	Abbasi et al. 2017
		Dustfall	39 major cities in China	Outdoor	Pre-Cleaned Aluminium-Lined paper bags, dust samples collected from balconies and Window sill	Liu et al., 2019
		Snow	Bremen, Germany	Outdoor	Spoon to collect freshly surface snow deposits into glass jar	Bergmann et al., 2019

		Dustfall	Beijing, China	Outdoor	Pre-Cleaned Aluminium-Lined paper bags, dust samples collected from the surface of public facilities.	Li et al., 2020
	Atmospheric particles are collected in a petri dish with adhesive or on a glass slide with adhesive using a sampler with a wind-sheltered and a low turbulent air volume.	Total suspended particulate	Freiburg, Germany	Outdoor	a petri dish with adhesive or on a glass slide with adhesive.1.5 m height and at a horizontal distance of 4.6 m from the roadway	Sommer et al. 2018
Active	Suction pump; aerosol sample collected at filters	Aerosol	Paris, France	Indoor	A pump for drawing air (8 L/ min) and quartz fiber GF/A Whatman filters (1.6 mm, 47 mm) for Sample collection (2 - 5 m^3) from two sites and an office	(Dris et al., 2017)
		Aerosol	Asaluyeh, Iran	Outdoor	Volume air sampler (16.67 L/ min); size-fractionated samples ($PM_{2.5}$, PM_{10}, and TSP) were collected.	Abbasi et al., 2019
		Aerosol	Beijing, China	Outdoor	Fliter: MCE; pore size 0.8 µm; diameter 47 mm The flow rate: 5 L/ min (particles:TSP)	Li et al., 2020
		Aerosol	The southeastern coast of china	Outdoor	GF/A glass microfiber filters (1.6 µm pore size, 90 mm diameter) at a sampling flow rate of 100 ± 0.1 L/ min	Wang et al., 2021b

Table 2. The density of microplastics in aerosol and suitable solutions used for separation.

Polymer type of MPs	Density ($g\ cm^{-3}$)	Solutions ($g\ cm^{-3}$)			
		NaCl (1.2)	NaI (1.60)	KI (1.67)	$ZnCl_2$ (3.02)
Polyethylene (PE)	0.910 – 0.925	√	√	√	√
Ethylene vinyl acetate (EVA)	0.93 – 0.95	√	√	√	√
Polyethylene (HDPE)	0.959 – 0.965	√	√	√	√
Polypropylene (PP)	0.90 – 0.91	√	√	√	√
Polyamide (Nylon)	1.02 – 1.05	√	√	√	√
Polystyrene (PS)	1.04 – 1.10	√	√	√	√
Acrylonitrile butadiene styrene (ABS)	1.05 – 1.18	√	√	√	√
Acrylic	1.09 – 1.20	√	√	√	√
Polypheylene ether (PPE/PPO)	1.10 – 1.13	√	√	√	√
Polyamide (Nylon 6 / Nylon 66)	1.13 – 1.15	√	√	√	√
Polyvinylchloride (PVC)	1.16 – 1.58	√	√	√	√
Poly methyl methacrylate (PMMA)	1.16 – 1.20	√	√	√	√
Polycarbonate (PC)	1.20 – 1.22		√	√	√
Polyurethane (PU)	1.20 – 1.26		√	√	√
Alkyd	1.24 – 2.10		√	√	√
Polyster	1.24 – 2.30		√	√	√
Polyethylene terephthalate (PET)	1.29 – 1.40		√	√	√
Polyformaldehyde (POM)	1.39 – 1.43		√	√	√
Polyoximethylene	1.41 – 1.61		√	√	√
Polyvinylidene difluoride (PVDF)	1.70 – 1.80			√	√
Polyvinyl alcohol (PVA)	1.91 – 2.31			√	√
Polytetrafluoroethylene (PTFE)	2.10 – 2.30			√	√

Table 3. Different methods and techniques used for laboratory identification of microplastics in atmospheric samples.

Identification methods / techniques	Limit of detection	Features of the outcome	Analysis and identification results	Reference
Stereoscopic microscopy	particle sizes (> 500 µm)	Shapes, Colors, opacity, size, and the number concentrations	Fibers (> 90%), Fragments (~ 10%); Blue, Red Size 100 - 5000 µm (50% fibres > 1000 µm) 29 - 280 particle/ m^2/ day	Dris et al., 2015
SEM- EDX	0.2 nm	Shapes, microstructure, size, and the number Concentrations, elemental compositions	Fibers (Beijing, China); Spherules, Films (Asaluyeh, Iran) Size 5 - 600 µm (Beijing, China); 100 - > 1000 µm (Asaluyeh, Iran) Concentration 5.7×10^{-3} f/ ml (Beijing, China); 0.3 - 1.1 n/ m^3(Asaluyeh, Iran)	Li et al., 2020 Abbasi et al., 2019
FTIR	particle sizes (> 10 µm)	Tyeps of organic compounds (functional groups)	Polyester, Polyacrylonitrile, Nylon, Polyethylene, Polypropylene, Poly(ethylene: propylene), Acrylic, Polyurethane, Polyethylenimine	Liu et al.,2019a Suaria et al., 2020
Raman spectroscopy	particle sizes (> 1 µm)	Tyeps of organic compounds (functional groups)	Polystyrene, Polyethylene, Polypropylene, Polyethylene terephthalate; polystyrene polycarbonate	Allen et al., 2019 Maghsodian et al., 2021
HPLC-MS-MS	-	Tyeps of organic compounds (molecular mass)	Polyethylene terephthalate, Polycarbonate	Wang et al., 2017b
PYR-GC-MS	-	Tyeps of organic compounds (molecular mass)	Polyvinyl chloride, polymer, polypropylene and polyethylene.	Hendrickson et al., 2018
TD-GC-MS	-	Tyeps of organic compounds	polypropylene , polyethylene and polystyrene	Chen et al.,

		(molecular mass)		2020
TED-GC-MS	-	Tyeps of organic compounds (molecular mass)	Polyethylene, Polystyrene, Polypropylene, Polyethylene terephthalate	Funck et al., 2021
TGA	-	Chemical compositions (thermal stability)	polypropylene , polyethylene and polystyrene	Chen et al., 2020
ICP-MS		Elemental compositions	Metal elements in MPs (Ni, Cd, Pb, Cu, Zn and Ti)	Wang et al., 2017c
Hyperspectral camera	particle sizes (> 100 μm)	Tyeps of organic compounds (functional groups）	polystyrene	Kitahashi et al., 2021
IRMS	20 μg	Sources of microplastics ($\delta^{13}C$ values)	Higher values are expected for plant derived materials and lower values are expected for petroleum-based plastics. (polyethylene terephthalate, high- and low-density polyethylene, polypropylene, polystyrene, polyvinyl chloride, polylactic acid, acrylonitrile butadiene styrene and polyester)	Birch et al., 2021)

Table 4. Morphological types of individual MP particles

Morphological types	**Major characteristics**	**References**
Fiber	Aspect ratio equal to or greater than 3:1, including fowling sub-types according to length (L): very long (1000 µm ≤ L) long (500 µm ≤ L < 1 000 µm) middle (250 µm ≤ L < 500 µm) short (100 µm ≤ L < 250 µm), and very short (L < 100 µm)	Dris et al., 2016 Abbasi et al., 2017; Cai et al., 2017; Dehghani et al., 2017 Li et al., 2020; Wright et al., 2020
Sphere/Pellet	Spherical or subspherical	
Fragments	Irregular shape, hexagon, or polygon	
Film	Irregular shape	
Foam	Irregular shape	

Table 5. Physical and chemical characteristics of airborne microplastics in some megacities.

Collection location	Sample Matrix	MPs Concentra tion	Shape Classification	Size range	Fiber category	Polymer	Color	Surface mechanical wear	Reference
Paris, France	Atmospheri c fallout (passive)	Urban: 2 - 355 particles/ m^2/ day avg. 110 ± 96 particle/ m^2 / day Suburban: Avg.: 53 ± 38 particles/ m^2	Fibers Fragment	50 - 200 µm: 3% 200 - 600 µm: 42% 600 - 1400 µm: 40% 1400 - 4850 µm: 15%	Long very long	PET; PA; PET–PU; cotton–PA	N/A	N/A	Dris et al., 2016
Hamburg,Ger many	Atmospheri c deposition wet and dry (passive)	Avg. 275 n/ m^2/ day (Median range: 136 - 512 particles/ m^2/ day)	Fragment Fibers	Fragments : < 63 µm: 60%, 63 - 300 µm: 30% > 300 µm: 20% Fibres:	Long very long	PE, EVAC, PTFE, PVA, PET	bright yellow to white	N/A	(Klein and Fischer, 2019)

				300 - 5000 μm: 68% 63 - 300 μm: 25% < 63 μm: 7%					
Shanghai, China	Aerosol (passive)	0 - 4.18 n/ m^3 (average 1.42 ± 1.42 n/ m^3)	Fibers fragment, sphere/pellets	Fibres: 23 - 1000 μm: 87%	Long	PET, PE, PES, PAN, PAA, EVA, RY, EP, ALK	blue, black, red, transparent, brown, green, yellow, grey	N/A	(Liu et al, 2019b)
London, UK	Atmospheric fallout (passive)	Fibrous: 510 - 925 MP/ m^2/ day (average 712 ± 162MP/ m^2/ day). Non-fibrous: 12 - 99 MP/ m^2/ day, (average of 59 ± 32 MP/	Fibers fragment, films	Fibers: Most abundant 400 - 500 μm	Middle	Polyacrylonitrile, Polyester, Polyamaide	N/A	N/A	(Wright et al., 2020)

		m^2/ day). Total MPs Deposition rate from 575 - 1008 MP/ m^2/ day.							
Beijing, China	Aerosol (active)	A	Fibers	Fibres: 5 - 200 µm	Short	N/A	N/A	YES	(Li et al., 2020)
Dongguan, China	Atmospheric fallout (dry & wet deposition) (passive)	36 ± 7 particles/ m^2/ day (average of three sites), Deposition rate175 - 313 particles/ m^2/ day	Fibers (80%), fragments , Films, Foam	200 – 4200 µm (majority of fibres to be 200 - 700 µm in length)	Short Middle	PE, PP, PS	Blue, Red, Transparent, Grey	YES	(Cai et al.,2017)
Surabaya, Indonesia	Aerosol (passive)	55.93 - 174.97 particles/ m^3	Fibers, fragments, films	< 500 - 5000 µm	Long very long	Polyethene terephthalate, polyester, cellophane	N/A	N/A	(Syafei et al., 2019)

Table S1. Published papers on atmospheric microplastics between 2015 and 2020

No.	Authors	Article Title	Source Title	DOI	Volume	Page	Article Number	Publication Year
1	Ding, Yongcheng et al	The abundance and characteristics of atmospheric microplastic deposition in the northwestern South China Sea in the fall	Atmospheric Environment	10.1016/j.atmosenv.2021.118389	253		118389	2021
2	Huang, Yumei et al	Atmospheric transport and deposition of microplastics in a subtropical urban environment	Journal Of Hazardous Materials	10.1016/j.jhazmat.2021.126168	416		126168	2021
3	Dong, Huike et al	Microplastics in a Remote Lake Basin of the Tibetan Plateau: Impacts of Atmospheric Transport and Glacial Melting	Environmental Science & Technology	10.1021/acs.est.1c03227	55	12951-12960		2021

4	Bain, Alison; Preston, Thomas C.	Hygroscopicity of Microplastic and Mixed Microplastic Aqueous Ammonium Sulfate Systems	Environmental Science & Technology	10.1021/acs.est.1c04272	55	11775-11783		2021
5	Zhang, Yulan et al	Microplastics in glaciers of the Tibetan Plateau: Evidence for the long-range transport of microplastics	Science Of The Total Environment	10.1016/j.scitotenv.2020.143634	758		143634	2021
6	Can-Güven, Emine	Microplastics as emerging atmospheric pollutants: a review and bibliometric analysis	Air Quality Atmosphere And Health	10.1007/s11869-020-00926-3	14	203-215		2021
7	Allen, S. et al	Evidence of free tropospheric and long-range transport of microplastic at Pic du Midi Observatory	Nature Communications	10.1038/s41467-021-27454-7	12		7242	2021
8	Agathokleous, Evgenios et al	Ecological risks in a 'plastic' world: A threat to biological diversity?	Journal Of Hazardous Materials	10.1016/j.jhazmat.2021.126035	417		126035	2021

9	Brahney, Janice et al	Constraining the atmospheric limb of the plastic cycle	Proceedings Of The National Academy Of Sciences Of The United States Of America	10.1073/pnas.2020719118	118		e2020719118	2021
10	Huang, Danlian et al	Microplastics and nanoplastics in the environment: Macroscopic transport and effects on creatures	Journal Of Hazardous Materials	10.1016/j.jhazmat.2020.124399	407		124399	2021
11	Sridharan, Srinidhi et al	Microplastics as an emerging source of particulate air pollution: A critical review	Journal Of Hazardous Materials	10.1016/j.jhazmat.2021.126245	418		126245	2021
12	Wang, Yi et al	Airborne Microplastics: A Review on the Occurrence, Migration and Risks to Humans	Bulletin Of Environmental Contamination And Toxicology	10.1007/s00128-021-03180-0	107	657-664		2021
13	Yang, Huirong et al	Characteristics, Toxic Effects, and Analytical Methods	Nanomaterials	10.3390/nano11102747	11		2747	2021

		of Microplastics in the Atmosphere						
14	Revell, Laura E et al	Direct radiative effects of airborne microplastics	Nature	10.1038/s41586-021-03864-x	598	462-467		2021
15	Wang, Xiaohui et al	Efficient transport of atmospheric microplastics onto the continent via the East Asian summer monsoon	Journal Of Hazardous Materials	10.1016/j.jhazmat.2021.125477	414		125477	2021
16	Smyth, Kelsey et al	Bioretention cells remove microplastics from urban stormwater	Water Research	10.1016/j.watres.2020.116785	191		116785	2021
17	Hamilton, Bonnie M et al	Microplastics around an Arctic seabird colony: Particle community composition varies across environmental matrices	Science Of The Total Environment	10.1016/j.scitotenv.2021.145536	773		145536	2021
18	Beaurepaire, Max et al	Microplastics in the atmospheric compartment: a comprehensive	Current Opinion In Food Science	10.1016/j.cofs.2021.04.010	41	159-168		2021

		review on methods, results on their occurrence and determining factors						
19	Akanyange, Stephen Nyabire et al	Does microplastic really represent a threat? A review of the atmospheric contamination sources and potential impacts	Science Of The Total Environment	10.1016/j.scitotenv.2021.146020	777		146020	2021
20	Gonzalez-Pleiter, Miguel et al	Occurrence and transport of microplastics sampled within and above the planetary boundary layer	Science Of The Total Environment	10.1016/j.scitotenv.2020.143213	761		143213	2021
21	Tran-Nguyen-Sang Truong et al	Microplastic in atmospheric fallouts of a developing Southeast Asian megacity under tropical climate	Chemosphere	10.1016/j.chemosphere.2021.129874	272		129874	2021
22	Bullard, Joanna E et al	Preferential transport of microplastics by wind	Atmospheric Environment	10.1016/j.atmosenv.2020.118038	245		118038	2021

23	Parker-Jurd, Florence N. F et al	Quantifying the release of tyre wear particles to the marine environment via multiple pathways	Marine Pollution Bulletin	10.1016/j.marpolbul.2021.112897	172		112897	2021
24	Chen, Jiaxin et al	A review on the occurrence, distribution, characteristics, and analysis methods of microplastic pollution in ecosystem s	Environmental Pollutants And Bioavailability	10.1080/26395940.2021.1960198	33	227-246		2021
25	Yao, Ying et al	Characterization of microplastics in indoor and ambient air in northern New Jersey.	Environmental Research	10.1016/j.envres.2021.112142			112142	2021
26	Pires, Ana; Sobral, Paula	Application of failure mode and effects analysis to reduce microplastic emissions	Waste Management & Research	10.1177/0734242X211003133	39	744-753		2021

27	Patil, Sakshi et al	Environmental prevalence, fate, impacts, and mitigation of microplastics-a critical review on present understanding and future research scope	Environmental Science And Pollution Research	10.1007/s11356-020-11700-4	28	4951-4974		2021
28	Senathirajah, Kala et al	Estimation of the mass of microplastics ingested - A pivotal first step towards human health risk assessment	Journal Of Hazardous Materials	10.1016/j.jhazmat.2020.124004	404		124004	2021
29	Chaudhry, Akshay Kumar; Sachdeva, Payal	Microplastics' origin, distribution, and rising hazard to aquatic organisms and human health: Socio-economic insinuations and management solutions	Regional Studies In Marine Science	10.1016/j.rsma.2021.102018	48		102018	2021
30	Choi, Yu Ri et al	Plastic contamination of forest, urban, and	Journal Of Soils And Sediments	10.1007/s11368-020-02759-0	21		1962-1973	2021

		agricultural soils: a case study of Yeoju City in the Republic of Korea						
31	Hu, Wei et al	Photochemical Degradation of Organic Matter in the Atmosphere	Advanced Sustainable Systems	10.1002/adsu.202100027	5		2100027	2021
32	O'Brien, Stacey et al	Quantification of selected microplastics in Australian urban road dust	Journal Of Hazardous Materials	10.1016/j.jhazmat.2021.125811	416		125811	2021
33	Ali, Muhammad Ubaid et al	Environmental emission, fate and transformation of microplastics in biotic and abiotic compartments: Global status, recent advances and future perspectives	Science Of The Total Environment	10.1016/j.scitotenv.2021.148422	791		148422	2021
34	Hollerova, Aneta et al	Microplastics as a potential risk for aquatic environment organisms - a review	Acta Veterinaria Brno	10.2754/avb202190010099	90	99-107		2021

35	Liao, Zhonglu et al	Airborne microplastics in indoor and outdoor environments of a coastal city in Eastern China	Journal Of Hazardous Materials	10.1016/j.jhazmat.2021.126007	417		126007	2021
36	Kernchen, Sarmite et al	Airborne microplastic concentrations and deposition across the Weser River catchment.	The Science Of The Total Environment	10.1016/j.scitotenv.2021.151812			151812	2021
37	Penalver, Rosa et al	Assessing the level of airborne polystyrene microplastics using thermogravimetry-mass spectrometry: Results for an agricultural area	Science Of The Total Environment	10.1016/j.scitotenv.2021.147656	787		147656	2021
38	Alfonso, Maria B et al	Continental microplastics: Presence, features, and environmental transport pathways	Science Of The Total Environment	10.1016/j.scitotenv.2021.149447	799		149447	2021

39	Padha, Shaveta et al	Microplastic pollution in mountain terrains and foothills: A review on source, extraction, and distribution of microplastics in remote areas.	Environmental Research	10.1016/j.envres.2021.112232			112232	2021
40	Huang, Daofen et al	Effect of cadmium on the sorption of tylosin by polystyrene microplastics	Ecotoxicology And Environmental Safety	10.1016/j.ecoenv.2020.111255	207		111255	2021
41	Wang, Yuan et al	Effects of exposure of polyethylene microplastics to air, water and soil on their adsorption behaviors for copper and tetracycline	Chemical Engineering Journal	10.1016/j.cej.2020.126412	404		126412	2021
42	Vaid, Mansi et al	Microplastics as contaminants in Indian environment: a review	Environmental Science And Pollution Research	10.1007/s11356-021-16827-6	28	68025-68052		2021
43	Rosal, Roberto	Morphological description of	Marine Pollution Bulletin	10.1016/j.marpolbul.2021.112716	171		112716	2021

		microplastic particles for environmental fate studies						
44	Facciola, Alessio; Visalli, Giuseppa et al	Newly Emerging Airborne Pollutants: Current Knowledge of Health Impact of Micro and Nanoplastics	International Journal Of Environmental Research And Public Health	10.3390/ijerph18062997	18		2997	2021
45	Ronda, Ana C et al	Plastic Impacts in Argentina: a Critical Research Review Contributing to the Global Knowledge	Current Environmental Health Reports	10.1007/s40572-021-00323-7	55	373-384		2021
46	Jiang, Xuefeng	Future directions of environmental chemistry	Pure And Applied Chemistry	10.1515/pac-2020-0806	93	1403-1409		2021
47	Akhbarizadeh, Razegheh et al	Suspended fine particulate matter (PM2.5), microplastics (MPs), and polycyclic aromatic hydrocarbons (PAHs) in air: Their possible relationships	Environmental Research	10.1016/j.envres.2020.110339	192		110339	2021

		and health implications						
48	Jenner, Lauren C. et al	Household indoor microplastics within the Humber region (United Kingdom): Quantification and chemical characterisation of particles present	Atmospheric Environment	10.1016/j.atmosenv.2021.118512	259		118512	2021
49	Barr, Brian Charles et al	Mitigation of Suspendable Road Dust in a Subpolar, Oceanic Climate	Sustainability	10.3390/su13179607	13		9607	2021
50	Vasiljevic, Tijana; Harner, Tom	Bisphenol A and its analogues in outdoor and indoor air: Properties, sources and global levels	Science Of The Total Environment	10.1016/j.scitotenv.2021.148013	789		148013	2021
51	Wang, Liuwei et al	Modeling the Conditional Fragmentation-Induced Microplastic Distribution	Environmental Science & Technology	10.1021/acs.est.1c01042	55	6012-6021		2021
52	Parolini, Marco et al	Microplastic Contamination in	International Journal Of	10.3390/ijerph18020768	18		768	2021

		Snow from Western Italian Alps	Environmental Research And Public Health					
53	Masry, Maria et al	Experimental evidence of plastic particles transfer at the water-air interface through bubble bursting	Environmental Pollution	10.1016/j.envpol.2021.116949	280		116949	2021
54	Gonzalez-Pleiter, Miguel et al	A pilot study about microplastics and mesoplastics in an Antarctic glacier	Cryosphere	10.5194/tc-15-2531-2021	15	2531-2539		2021
55	Ageel, Hassan Khalid et al	Occurrence, human exposure, and risk of microplastics in the indoor environment	Environmental Science-Processes & Impacts	10.1039/d1em00301a				2021
56	Li, Penghui et al	Characteristics of Plastic Pollution in the Environment: A Review	Bulletin Of Environmental Contamination And Toxicology	10.1007/s00128-020-02820-1	107	577-584		2021
57	Szewc, Karolina; Graca, Bozena; Dolega, Anna	Atmospheric deposition of microplastics in the coastal zone: Characteristics and	Science Of The Total Environment	10.1016/j.scitotenv.2020.143272	761		143272	2021

		relationship with meteorological factors						
58	Rai, Prabhat Kumar et al	Environmental fate, ecotoxicity biomarkers, and potential health effects of micro- and nano-scale plastic contamination	Journal Of Hazardous Materials	10.1016/j.jhazmat.2020.123910	403		123910	2021
59	Song, Zhangyu et al	To what extent are we really free from airborne microplastics?	Science Of The Total Environment	10.1016/j.scitotenv.2020.142118	745		142118	2021
60	Kumar, Manish et al	Current research trends on micro- and nano-plastics as an emerging threat to global environment: A review	Journal Of Hazardous Materials	10.1016/j.jhazmat.2020.124967	409		124967	2021
61	Kannan, Kurunthachalam; Vimalkumar, Krishnamoorthi	A Review of Human Exposure to Microplastics and Insights Into Microplastics as Obesogens	Frontiers In Endocrinology	10.3389/fendo.2021.724989	12		724989	2021

62	Shi, Minghao et al	Influence of atmospheric deposition on surface water quality and DBP formation potential as well as control technology of rainwater DBPs: a review	Environmental Science-Water Research & Technology	10.1039/d1ew00520k	7	2156-2165		2021
63	Sun, Kailun et al	A review of human and animals exposure to polycyclic aromatic hydrocarbons: Health risk and adverse effects, photo-induced toxicity and regulating effect of microplastics	Science Of The Total Environment	10.1016/j.scitotenv.2021.145403	773		145403	2021
64	Abbasi, Sajjad; Turner, Andrew	Dry and wet deposition of microplastics in a semi-arid region (Shiraz, Iran)	Science Of The Total Environment	10.1016/j.scitotenv.2021.147358	786		147358	2021

65	Wlasits, Peter Josef; Stoellner, Andrea et al	Size characterization and detection of aerosolized nanoplastics originating from evaporated thermoplastics	Aerosol Science And Technology	10.1080/02786826.2021.1998339	56	176-185		2021
66	Ji, Yunxia et al	Revisiting the cellular toxicity of benzo[a]pyrene from the view of nanoclusters: size- and nanoplastic adsorption-dependent bioavailability	Nanoscale	10.1039/d0nr06747d	13	1016-1028		2021
67	Athey, Samantha N.; Erdle, Lisa M.	Are We Underestimating Anthropogenic Microfiber Pollution? A Critical Review of Occurrence, Methods, and Reporting	Environmental Toxicology And Chemistry	10.1002/etc.5173	00	1-16		2021
68	Materic, Dusan et al	Nanoplastics transport to the	Environmental Pollution	10.1016/j.envpol.2021.117697	288		117697	2021

		remote, high-altitude Alps						
69	Soltani, Neda Sharifi et al	Quantification and exposure assessment of microplastics in Australian indoor house dust	Environmental Pollution	10.1016/j.envpol.2021.117064	283		117064	2021
70	Stanton, Thomas et al	It's the product not the polymer: Rethinking plastic pollution	Wiley Interdisciplinary Reviews-Water	10.1002/wat2.1490	8		e1490	2021
71	Fang, Guor-Cheng et al	Ambient air particulates and Hg(p) concentrations and dry depositions estimations, distributions for various particles sizes ranges	Journal Of Environmental Science And Health Part A-Toxic/Hazardous Substances & Environmental Engineering	10.1080/10934529.2021.1918976	56	1-8		2021
72	Antwi, Henry Asante et al	Progressing towards Environmental Health Targets in China: An Integrative Review of Achievements in Air and Water Pollution	Sustainability	10.3390/su13073664	13		524118	2021

		under the Ecological Civilisation and the Beautiful China Dream						
73	Robin, R. S et al	COVID-19 restrictions and their influences on ambient air, surface water and plastic waste in a coastal megacity, Chennai, India	Marine Pollution Bulletin	10.1016/j.marpolbul.2021.112739	171		112739	2021
74	Prenner, Stefanie et al	Static modelling of the material flows of micro- and nanoplastic particles caused by the use of vehicle tyres	Environmental Pollution	10.1016/j.envpol.2021.118102	290		118102	2021
75	Yang, Sheng et al	In vitro evaluation of nanoplastics using human lung epithelial cells, microarray analysis and co-culture model	Ecotoxicology And Environmental Safety	10.1016/j.ecoenv.2021.112837	226		112837	2021

76	Condon, Caitlin A et al	Fate and transport of unruptured tri-structural isotropic (TRISO) fuel particles in the event of environmental release for advanced and micro reactor applications	Journal Of Environmental Radioactivity	10.1016/j.jenvrad.2021.106630	234		106630	2021
77	Chae, Eunji; Jung, Uiyeong; Choi, Sung-Seen	Quantification of tire tread wear particles in microparticles produced on the road using oleamide as a novel marker	Environmental Pollution	10.1016/j.envpol.2021.117811	288		117811	2021
78	Petersen, Fritz; Hubbart, Jason A.	The occurrence and transport of microplastics: The state of the science	Science Of The Total Environment	10.1016/j.scitotenv.2020.143936	758		143936	2021
79	Purwiyanto, Anna Ida Sunaryo et al	The deposition of atmospheric microplastics in Jakarta-Indonesia: The coastal urban area.	Marine Pollution Bulletin	10.1016/j.marpolbul.2021.113195	174		113195	2021

80	Tian, Xia et al	Plastic mulch film induced soil microplastic enrichment and its impact on wind-blown sand and dust.	The Science Of The Total Environment	10.1016/j.scitotenv.2021.152490	813		152490	2021
81	Zhang, Yulan et al	Atmospheric microplastics: A review on current status and perspectives	Earth-Science Reviews	10.1016/j.earscirev.2020.103118	203		103118	2020
82	Wright, S. L et al	Atmospheric microplastic deposition in an urban environment and an evaluation of transport	Environment International	10.1016/j.envint.2019.105411	136		105411	2020
83	Malygina, N. S et al	Atmospheric supply of microplastics in the south of Western Siberia according to microscopic analysis of snow cover samples	26th International Symposium On Atmospheric And Ocean Optics, Atmospheric Physics	10.1117/12.2575577	11560		115604L	2020
84	Chen, Guanglong et al	Mini-review of microplastics in the	Science Of The Total Environment	10.1016/j.scitotenv.2019.135504	703		135504	2020

		atmosphere and their risks to humans						
85	Mbachu, Oluchi et al	A New Contaminant Superhighway? A Review of Sources, Measurement Techniques and Fate of Atmospheric Microplastics	Water Air And Soil Pollution	10.1007/s11270-020-4459-4	231		85	2020
86	Chen, Guanglong et al	An overview of analytical methods for detecting microplastics in the atmosphere	Trac-Trends In Analytical Chemistry	10.1016/j.trac.2020.115981	130		115981	2020
87	Gong, Jian; Xie, Pei	Research progress in sources, analytical methods, eco-environmental effects, and control measures of microplastics	Chemosphere	10.1016/j.chemosphere.2020.126790	254		126790	2020
88	Roblin, Brett; Aherne, Julian	Moss as a biomonitor for the atmospheric deposition of anthropogenic microfibres	Science Of The Total Environment	10.1016/j.scitotenv.2020.136973	715		136973	2020

89	Liu, Kai et al	Global inventory of atmospheric fibrous microplastics input into the ocean: An implication from the indoor origin	Journal Of Hazardous Materials	10.1016/j.jhazmat.2020.123223	400		123223	2020
90	Liu, Kai et al	Terrestrial plants as a potential temporary sink of atmospheric microplastics during transport	Science Of The Total Environment	10.1016/j.scitotenv.2020.140523	742		140523	2020
91	Narmadha, Vellora Veetil et al	Assessment of Microplastics in Roadside Suspended Dust from Urban and Rural Environment of Nagpur, India	International Journal Of Environmental Research	10.1007/s41742-020-00283-0	14		629-640	2020
92	Prata, Joana C et al	The importance of contamination control in airborne fibers and microplastic sampling: Experiences from indoor and outdoor	Marine Pollution Bulletin	10.1016/j.marpolbul.2020.111522	159		111522	2020

		air sampling in Aveiro, Portugal						
93	Du, Fangni et al	Microplastics in take-out food containers	Journal Of Hazardous Materials	10.1016/j.jhazmat.2020.122969	399		122969	2020
94	Levermore, Joseph M et al	Detection of Microplastics in Ambient Particulate Matter Using Raman Spectral Imaging and Chemometric Analysis	Analytical Chemistry	10.1021/acs.analchem.9b05445	92	8732-8740		2020
95	Prata, Joana C et al	An easy method for processing and identification of natural and synthetic microfibers and microplastics in indoor and outdoor air.	Methodsx	10.1016/j.mex.2019.11.032	7	1-9		2020
96	Evangeliou, N. et al	Atmospheric transport is a major pathway of microplastics to remote regions	Nature Communications	10.1038/s41467-020-17201-9	11		3381	2020

97	Sun, Yue et al	Effect of microplastics on greenhouse gas and ammonia emissions during aerobic composting	Science Of The Total Environment	10.1016/j.scitotenv.2020.139856	737		139856	2020
98	Hale, Robert C. et al	A Global Perspective on Microplastics	Journal Of Geophysical Research-Oceans	10.1029/2018JC014719	125		e2018JC014719	2020
99	Huang, Yumei et al	Mini-review on current studies of airborne microplastics: Analytical methods, occurrence, sources, fate and potential risk to human beings	Trac-Trends In Analytical Chemistry	10.1016/j.trac.2020.115821	125		115821	2020
100	Bianco, Angelica et al	Degradation of nanoplastics in the environment: Reactivity and impact on atmospheric and surface waters	Science Of The Total Environment	10.1016/j.scitotenv.2020.140413	742		140413	2020
101	Amato-Lourenco, Luis Fernando et al	An emerging class of air pollutants:	Science Of The Total Environment	10.1016/j.scitotenv.2020.141676	749		141676	2020

		Potential effects of microplastics to respiratory human health?						
102	Ding, Ling et al	High temperature depended on the aging mechanism of microplastics under different environmental conditions and its effect on the distribution of organic pollutants	Water Research	10.1016/j.watres.2020.115634	174		115634	2020
103	Xu, Guanjun et al	Surface-Enhanced Raman Spectroscopy Facilitates the Detection of Microplastics < 1 mu m in the Environment	Environmental Science & Technology	10.1021/acs.est.0c02317	54	15594-15603		2020
104	Bianco, Angelica; Passananti, Monica	Atmospheric Micro and Nanoplastics: An Enormous Microscopic Problem	Sustainability	10.3390/su12187327	12		7327	2020

105	Zhang, Qun et al	Microplastic Fallout in Different Indoor Environments	Environmental Science & Technology	10.1021/acs.est.0c00087	54	6530-6539		2020
106	Bancone, Chiara E. P et al	The Paleoecology of Microplastic Contamination	Frontiers In Environmental Science	10.31119/fenvs.2020.574008	8		574008	2020
107	Kelly, Frank J.; Fussell, Julia C.	Toxicity of airborne particles-established evidence, knowledge gaps and emerging areas of importance	Philosophical Transactions Of The Royal Society A-Mathematical Physical And Engineering Sciences	10.1098/rsta.2019.0322	378		20190322	2020
108	Allen, Steve et al	Examination of the ocean as a source for atmospheric microplastics	Plos One	10.1371/journal.pone.0232746	15		e0232746	2020
109	O'Brien, Stacey et al	Airborne emissions of microplastic fibres from domestic laundry dryers	Science Of The Total Environment	10.1016/j.scitotenv.2020.141175	747		141175	2020
110	Xu, Chenye et al	Are we underestimating the sources of microplastic pollution in	Journal Of Hazardous Materials	10.1016/j.jhazmat.2020.123228	400		123228	2020

		terrestrial environment?						
111	Wang, Ting et al	Interactions between microplastics and organic pollutants: Effects on toxicity, bioaccumulation, degradation, and transport	Science Of The Total Environment	10.1016/j.scitotenv.2020.142427	748		142427	2020
112	Zhang, Junjie et al	Microplastics in house dust from 12 countries and associated human exposure	Environment International	10.1016/j.envint.2019.105314	134		105314	2020
113	Hufnagl, Benedikt; Lohninger, Hans	A graph-based clustering method with special focus on hyperspectral imaging	Analytica Chimica Acta	10.1016/j.aca.2019.10.071	1097	34-48		2020
114	Roblin, Brett et al	Ambient Atmospheric Deposition of Anthropogenic Microfibers and Microplastics on the	Environmental Science & Technology	10.1021/acs.est.0c04000	54	11100-11108		2020

		Western Periphery of Europe (Ireland)						
115	Dong, Cheng-Di et al	Polystyrene microplastic particles: In vitro pulmonary toxicity assessment	Journal Of Hazardous Materials	10.1016/j.jhazmat.2019.121575	385		121575	2020
116	Zhu, Kecheng et al	Enhanced cytotoxicity of photoaged phenol-formaldehyde resins microplastics: Combined effects of environmentally persistent free radicals, reactive oxygen species, and conjugated carbonyls	Environment International	10.1016/j.envint.2020.106137	145		106137	2020
117	Brahney, Janice et al	Plastic rain in protected areas of the United States	Science	10.1126/science.aaz5819	368	1257-1260		2020
118	Cheng, Leilei et al	Polyethylene high-pressure pyrolysis: Better product distribution and	Chemical Engineering Journal	10.1016/j.cej.2019.123866	385		123866	2020

		process mechanism analysis						
119	Kawecki, Delphine; Nowack, Bernd	A proxy-based approach to predict spatially resolved emissions of macro- and microplastic to the environment	Science Of The Total Environment	10.1016/j.scitotenv.2020.141137	748		141137	2020
120	Li, Yaowei et al	Airborne fiber particles: Types, size and concentration observed in Beijing	Science Of The Total Environment	10.1016/j.scitotenv.2019.135967	705		135967	2020
121	Hohn, Soenke et al	The long-term legacy of plastic mass production	Science Of The Total Environment	10.1016/j.scitotenv.2020.141115	746		141115	2020
122	Hu, Lingling et al	Chronic microfiber exposure in adult Japanese medaka (Oryzias latipes)	Plos One	10.1371/journal.pone.0229962	15		e0229962	2020
123	Fournier, Sara B. et al	Nanopolystyrene translocation and fetal deposition after acute lung exposure during late-stage pregnancy	Particle And Fibre Toxicology	10.1186/s12989-020-00385-9	17		55	2020

124	Liu, Kai et al	Consistent Transport of Terrestrial Microplastics to the Ocean through Atmosphere	Environmental Science & Technology	10.1021/acs.est.9b03427	53	10612-10619		2019
125	Zhang, Yulan et al	Importance of atmospheric transport for microplastics deposited in remote areas	Environmental Pollution	10.1016/j.envpol.2019.07.121	254		112953	2019
126	Cai, Liqi et al	Characteristic of microplastics in the atmospheric fallout from Dongguan City, China: preliminary research and first evidence	Environmental Science And Pollution Research	10.1007/s11356-019-06979-x	26	36074-36075		2019
127	Allen, Steve et al	Atmospheric transport and deposition of microplastics in a remote mountain catchment	Nature Geoscience	10.1038/s41561-019-0335-5	12	339-344		2019
128	Allen, Steve et al	Atmospheric transport and deposition of	Nature Geoscience	10.1038/s41561-019-0409-4	12	339-344		2019

		microplastics in a remote mountain catchment (vol 12, pg 339, 2019)						
129	Liu, Kai et al	Source and potential risk assessment of suspended atmospheric microplastics in Shanghai	Science Of The Total Environment	10.1016/j.scitotenv.2019.04.110	675	462-471		2019
130	Enyoh, Christian Ebere et al	Airborne microplastics: a review study on method for analysis, occurrence, movement and risks	Environmental Monitoring And Assessment	10.1007/s10661-019-7842-0	191		668	2019
131	Bergmann, Melanie et al	White and wonderful? Microplastics prevail in snow from the Alps to the Arctic	Science Advances	10.1126/sciadv.aax1157	5		eaax1157	2019
132	Liu, Kai et al	Accurate quantification and transport estimation of suspended atmospheric	Environment International	10.1016/j.envint.2019.105127	132		105127	2019

		microplastics in megacities: Implications for human health						
133	Ganguly, Mainak; Ariya, Parisa A.	Ice Nucleation of Model Nanoplastics and Microplastics: A Novel Synthetic Protocol and the Influence of Particle Capping at Diverse Atmospheric Environments	Acs Earth And Space Chemistry	10.1021/acsearthspacechem.9b00132	3	1729-1739		2019
134	Xu, Mingkai et al	Internalization and toxicity: A preliminary study of effects of nanoplastic particles on human lung epithelial cell	Science Of The Total Environment	10.1016/j.scitotenv.2019.133794	694		133794	2019
135	Abbasi, Sajjad et al	Distribution and potential health impacts of microplastics and microrubbers in air and street dusts from	Environmental Pollution	10.1016/j.envpol.2018.10.039	244	153-164		2019

		Asaluyeh County, Iran						
136	Andrady, A. L.; Pandey, K. K.; Heikkila, A. M.	Interactive effects of solar UV radiation and climate change on material damage	Photochemical & Photobiological Sciences	10.1039/c8pp90065e	18	804-825		2019
137	Martyanov, S.D et al	On the assessment of microplastic distribution in the eastern part of the Gulf of Finland	Fundamental'naya I Prikladnaya Gidrofizika		12	32-41		2019
138	Prata, Joana Correia	Airborne microplastics: Consequences to human health?	Environmental Pollution	10.1016/j.envpol.2017.11.043	234	115-126		2018
139	Garaba, Shungudzemwoyo P.; Dierssen, Heidi M.	An airborne remote sensing case study of synthetic hydrocarbon detection using short wave infrared absorption features identified from marine-harvested macro- and microplastics	Remote Sensing Of Environment	10.1016/j.rse.2017.11.023	205	224-235		2018

140	Gundogdu, Sedat	Contamination of table salts from Turkey with microplastics	Food Additives And Contaminants Part A-Chemistry Analysis Control Exposure & Risk Assessment	10.1080/19440049.2018.1447694	35	1006-1014		2018
141	Cai, Liqi et al	Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence	Environmental Science And Pollution Research	10.1007/s11356-017-0116-x	24	24928-24935		2017
142	Peng, Jinping; Wang, Jundong; Cai, Liqi	Current understanding of microplastics in the environment: Occurrence, fate, risks, and what we should do	Integrated Environmental Assessment And Management	10.1002/ieam.1912	13	476-482		2017
143	Dris, Rachid et al	A first overview of textile fibers, including microplastics, in indoor and outdoor environments	Environmental Pollution	10.1016/j.envpol.2016.12.013	221	453-458		2017

144	Dris, Rachid et al	Synthetic fibers in atmospheric fallout: A source of microplastics in the environment?	Marine Pollution Bulletin	10.1016/j.marpolbul.2016.01.006	104	290-293		2016
145	Dris, Rachid et al	Microplastic contamination in an urban area: a case study in Greater Paris	Environmental Chemistry	10.1071/EN14167	12	592-599		2015

Table S2. Sample collection, processing, and identification of microplastics

City/Country	Sample Matrix	Sampling methods	Sampling preparation		Identification	Characterization	Reference
			Treatment	Extraction			
Paris, France	Atmospheric fallout	passive	glass fiber GF/A Whatman filters	NA	Stereomicroscope	NA	(Dris et al., 2016b)
Dongguan, China	Atmospheric fallout	passive	1.0 µm glass filters with a vacuum pump	NA	Digital microscope	Micro-FTIR	(Cai et al., 2017)
Bushehr, Iran	Atmospheric fallout	passive	30% H_2O_2	NaI	Upright fluorescence microscope	SEM/EDX	(Abbasi et al., 2017)
Yantai, China	Atmospheric fallout	passive	stainless steel sieves (5mm&1mm)	NA	Stereomicroscope	FTIR	(Zhou et al., 2017)
Tehran metropolis, Iran	Street dust	passive	30% H_2O_2	$ZnCl_2$	Upright fluorescence microscope	SEM/EDX	(Dehghani et al., 2017)
Hamburg, Germany	Atmospheric fallout	passive	0.15:1 NaClO	Nile Red	Fluorescence microscope	Micro-Raman	(Klein and Fischer, 2019b)
12 Countries	Indoor dust	passive	KOH	pentanol	NA	HPLC MS/MS	(Zhang et al., 2020a)
Paris, France	Aerosol	Active	2.5 mm mesh size sieve	$ZnCl_2$	Stereomicroscope	FTIR	(Dris et al., 2017c)
Sakarya Province, Turkey	Aerosol	Active	35% H_2O_2	$ZnCl_2$	Light microscope	Micro-FTIR	(Tunahan Kaya et al., 2018)
Asaluyeh, Iran	Aerosol	Active	30% H_2O_2	NaI	Light microscope and fluorescence microscope	SEM-EDX	(Abbasi et al., 2019)
Aarhus, Denmark	Aerosol	Active	Ethanol (99.9%, HPLC grade)	ZnSe	Optical microscope	Micro-FTIR	(Vianello et al., 2019)
Beijing, China	Aerosol	Active	Mixed cellulose ester, 0.8 µm	NA	SEM	SEM-EDX	(Li et al., 2020)

Table S3. Physical and chemical characteristics of airborne MPs.

Characteristics \ Types		PET	PP	PPE	PC	PVC	PS	PE	PMMA	Nylon	ABS	POM
Chemical characteristics	Organic chemical structure	$(C_{10}H_8O_4)_n$	$(C_3H_6)_n$	(C_8H_8O)n	$[C_6H_4C(CH_3)2C_6H_4OCO_2$-]n	(C_2H_3Cl)n	(C_8H_8)n	(C_2H_4)n	$C_5H_8O_2$	C_2ClF_3 (unspec.)	$C_{45}H_{51}N_3X_2$	(CH_2O)n
	Inorganic elements	Ca, S, Mg, Al, Si Zn, Pb, Mn, Cu, Ni, Co, Cd, Cr										
Physical characteristics	Degree of crystallinity	Semi-crystalline	Semi-crystalline (isotactic, syndiotactic)	Semi-crystalline	Amorphous	Amorphous	Amorphous	High (Semi)-crystallinity	Amorphous	Semi-crystalline	Amorphous	Crystalline
	Glass transition temperature (Tg) (◦C)	73 ~ 78	-49/ -20	118	150	60 ~ 100	74 ~ 105	-120/ -20	85 ~ 105	125 ~ 155	88 ~ 105	-