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Microplastics and nanoplastics in the air: a review

Bui Van Nang[1, 2], Nghiem Trung Dung[1, *], Nguyen Thi Thu Hien[1]

[1]*School of Chemistry and Life Sciences, Hanoi University of Science and Technology,*
1 Dai Co Viet, Hai Ba Trung, Ha Noi, Viet Nam

[2]*Viet Nam National University of Forestry, Xuan Mai, Chuong My, Ha Noi, Viet Nam*

[*]Emails: *dung.nghiemtrung@hust.edu.vn*

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Abstract. Given the increasing concern about microplastics (MPs) and nanoplastics (NPs) in the atmosphere, numerous studies have been conducted on their presence and impacts. This review explores the occurrence, sources, physicochemical characteristics, and the sampling and analytical methods of MPs and NPs in ambient air. MPs are primarily found in the form of fibers and fragments, with sizes generally exceeding several micrometers, and have been detected in various environments, including urban, industrial, coastal, and remote areas. Currently, there are no standardized methods for sampling and analyzing MPs and NPs in the atmosphere. Existing studies predominantly employ passive sampling methods to collect depositable microplastics and active sampling methods for suspended MPs. In the laboratory, most samples are treated with H_2O_2 and then separated by density before being analyzed using microscopy and spectroscopic techniques such as FT-IR and Raman. However, the current sampling and analytical methods have proven insufficient for detecting the presence of NPs in the air. Therefore, there is a need to develop new sampling and analytical methods to determine them in the atmospheric environment.

Keywords: Microplastics, nanoplastics, occurrence, physicochemical characteristics, monitoring techniques

Classification numbers: 3.2.1, 3.4.5

1. INTRODUCTION

Plastics, first synthesized by Leo Baekeland in 1907 [1], have become integral to modern society. The production and use of plastic materials has surged dramatically, particularly between 1950 and 2017, with projections indicating continued growth until 2050 [1]. This rapid increase in plastic production and consumption has led to a significant accumulation of plastic waste in the environment, with estimates suggesting an additional 276 million tons of plastic waste by 2025 [2]. The Organisation for Economic Co-operation and Development has identified plastic pollution as one of the major environmental challenges of the 21st century, causing widespread damage to ecosystems and posing serious risks to human health [3].

Over time, plastic waste undergoes fragmentation, breaking down into smaller particles known as microplastics (MPs), defined as plastic particles smaller than 5 mm [1]. MPs originate from various sources, including textile products, the abrasion of synthetic rubber tires, and urban dust [4]. Through processes such as mechanical fragmentation, photodegradation, hydrolysis, and biodegradation, both microplastics and nanoplastics (MnPs) are released into the environment, contaminating not only land and water but also the atmosphere. In the air, MnPs can exist as fine particulate matter and are increasingly recognized as an emerging global pollutant [1].

In 2004, MPs were first reported [5]. Over the years, MPs have garnered significant research attention from scientists worldwide. However, for nanoplastics (NPs), according to statistics by Steve Allen *et al* [6] very few studies were conducted between 2011 and 2021. This topic remains both prominent and complex due to the technical difficulties associated with sampling and analyzing NPs in the environment [6]. From January 2016 to January 2022, the number of studies on NPs showed an increasing trend [7, 8], with a sharp rise from 2019 to 2021 [6]. During this period, most global studies on NPs focused on their fate and toxicity in the environment [7]. Additionally, several review studies on MnPs were conducted during this time. From 2022 to 2024, research on MPs in the air has continued to grow, expanding to remote and isolated areas. To date, MnPs remain a relatively new research topic in atmospheric environments, and there is still no standardized method for their sampling and analysis. Therefore, this review aims to update and evaluate the achievements and existing gaps in the research on MnPs in ambient air. This review focuses on key issues, including the occurrence, sources, physicochemical characteristics, sampling methods, sample preparation, and analysis of MnPs in the air.

2. DEFINITIONS OF MICROPLASTICS AND NANOPLASTICS

2.1. Microplastics

The term 'microplastics' was first introduced by Thompson *et al* in 2004 to describe the accumulation of truly microscopic plastic pieces in marine sediments and the water column in European waters [9]. In 2008, the definition of microplastics, as agreed upon by scientists at the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris held in the United States, is plastic particles smaller than 5 mm. At this workshop, scientists did not establish a lower size limit for microplastics [10]. Since then, the upper size limit of microplastics has remained at 5000 µm. However, there is no consensus on the lower size limit of microplastics. Some authors still use the original 2008 definition without specifying a lower size limit [11 - 15]. Meanwhile, other publications clearly define the lower limit of microplastics as 1 µm [16 - 20]. Clearly defining the lower size limit of microplastics is crucial for distinguishing and refer to plastic particles smaller than this threshold, which are referred to as nanoplastics.

2.2. Nanoplastics

Nanomaterials are defined by the U.S. National Nanotechnology Initiative (NNI) and the European Community (EC) as materials with one or more dimensions within the range of 1 to 100 nm [21]. Regarding nanoplastics, two unresolved perspectives on their upper size limit currently exist [6, 22, 23,]. The first perspective defines nanoplastics as plastic particles smaller than 100 nm [1, 7, 24, 25]. The second perspective considers nanoplastics to be plastic particles ranging from 1 nm to 1000 nm [12, 13, 19, 26], and this view has garnered broader consensus within the research community [6, 21].

The concentration of MnPs in the air is expressed in terms of mass concentration or the number concentration of particles/fragments/fibers of MnPs per unit volume of air (µg/m³ or MnPs/m³). Additionally, the deposition of MnPs from the air onto surfaces is measured in terms of mass or the number of particles/fragments/fibers of MnPs per unit surface area over a specific time period (e.g., µg/m²/day or MnPs/m²/day) [18]. For number concentration (particles/fragments/fibers), there is no consensus in the literature regarding the terminology used to denote the quantity of MnPs in the air. Terms such as “particle,” “items,” “MP,” “numbers,” or symbols like “#” and “n” have been used across various publications. Despite these differences, all these terms refer to the independent entities of MnPs in the air.

In this review, microplastics are defined as plastic particles with sizes ranging from 1 to 5000 µm, while nanoplastics are defined as plastic particles smaller than 1000 nm. The term micro(nano)plastics (MnPs) refers collectively to plastic particles smaller than 5 mm.

3. OCCURRENCE AND PHYSICOCHEMICAL CHARACTERISTICS OF MICROPLATICS AND NANOPLASTICS

3.1. Occurrence

Since the initial studies conducted in Paris, airborne microplastics have been detected in both atmospheric deposition samples and suspended air particles [27]. These samples have been collected from various environments, including urban, industrial, rural, coastal, oceanic, and remote areas worldwide. These findings highlight the widespread occurrence and global distribution of microplastics in the atmosphere.

Urban and industrial areas

Airborne microplastic concentration is typically the highest in large urban and industrial areas. For atmospheric deposition of microplastics, concentration in Paris ranges from 29 to 280 particles/m²/day [27]. In Shanghai, China, concentration varies from 0 to 4.18 particles/m³ [28]. In Ho Chi Minh City, Vietnam, microplastic concentration ranges from 71 to 917 particles/m²/day [29]. In Kuala Nerus and Bangi, Malaysia, concentration is reported at 114 to 689 MP/m²/day and 280 to 394 MP/m²/day, respectively [30]. In Pathum Thani, Thailand, the microplastic deposition rate reaches 325 numbers/m²/day [11]. For airborne microplastics, concentration in major cities such as Dongguan, China, ranges from 175 to 313 particles/m²/day [31]. In Seoul, South Korea, airborne microplastic concentration ranges from 0.33 to 1.21 particles/m³ [32]. In major cities in Germany, particularly in riverine areas like Weser, microplastic concentration in the air reaches up to 91 ± 47 particles/m³ [33].

Coastal and oceanic areas

Numerous studies conducted in coastal regions worldwide have reported the presence of airborne microplastics. In Japan, research in both urban and rural coastal areas revealed suspended microplastic concentration ranging from 0.12 to 0.3 particles/m³ [34]. Similarly, in the coastal city of Wenzhou, China, suspended microplastic concentration in urban and suburban areas was recorded at 224 ± 70 n/m³ and 101 ± 47 n/m³, respectively [35]. A study in the port city of Plymouth, UK, demonstrated suspended microplastic concentration ranging from 0.016 to 0.238 items/m³, with an average of 0.082 items/m³ [36]. Notably, suspended microplastics have also been detected in the central South China Sea, with concentration of 0.8 ± 1.3

items/100 m³, as well as in the Indian Ocean, where concentration was measured at 0.4 ± 0.6 items/100 m³ [37]. Regarding atmospheric deposition of microplastics, concentration in the coastal city of Yantai, China, ranged from 130 to 624 particles/m²/day [38]. In Kochi, India, microplastic deposition rate was reported to range from 12 to 37 particles/m²/day [39].

Suburban and rural areas

In suburban and rural areas, the presence of microplastics has been documented in several countries. A study conducted in the rural regions of Wenzhou, China, reported atmospheric microplastics at concentrations of 101 ± 47 particles/m³ [35]. In contrast, the concentration in the rural areas of the Tibetan Plateau was measured at 15.6 ± 4.4 particles/m³ [40]. Additionally, other studies conducted in Japan and France have also identified microplastics in the air, though at significantly lower levels compared to those found in China (Table 1).

Remote and pristine areas

One of the most remarkable findings is that microplastics have been detected even in remote and pristine areas. In Tibet (China), a region renowned for its isolation, microplastics were found in the air across the pristine lands of the Plateau, with concentration of 8.1 ± 3.0 n/m³ [40]. Similarly, microplastics were also found in the air over Geladandong (China), a remote area with no signs of human activity, at a concentration of 0.12 items/m³ [41]. Additionally, other pristine regions, such as Chagar Hutang Beach on Peninsular Malaysia and the remote mountainous region of Tongariro in New Zealand, have also recorded microplastics in atmospheric deposition or suspended particulates samples (Table 1).

This widespread detection of microplastics, from densely populated urban centers to remote and pristine environments, underscores the pervasive nature of microplastic pollution. This evidence indicates that microplastics are not confined to areas of human activity but have emerged as a global environmental issue, dispersing over vast distances and accumulating even in isolated regions with minimal or no human presence.

3.2. Shape, size and color

Shapes

The shape, size, and color of MPs have been identified in most of the studies presented in Table 1. Generally, MPs exhibit a wide range of shapes, including fibers, fragments, films, granules, foams, spheres, and irregular forms. Among these, fibers and fragments are the most frequently identified, corresponding to 27 and 20 studies out of a total of 28 (96% and 71%, respectively). The remaining shapes were identified in fewer studies, each with a prevalence of less than 10%. Notably, most of the suspended particulates samples identified MPs primarily in the form of fibers and fragments. In contrast, many studies on settled particulates samples detected three to four different shapes of MPs.

Size

In terms of size, MPs exhibit a wide range, typically from several micrometers to a few millimeters. Most studies have identified microplastics larger than 10 µm, while 9 out of 28 studies have detected microplastics smaller than 10 µm. Notably, only two studies, by Madhuraj *et al.* [39] and Liu *et al.* [42] reported the smallest size range of microplastics with a lower bound of 1 µm, specifically in the size ranges of 1-100 µm and 1-10 µm. However, identifying microplastics as small as 1 µm remains unclear, as the authors may have merely divided the size ranges without fully confirming the actual presence of microplastics at this scale. Some perspectives suggest that such small plastic particles could be classified as nanoplastics. The focus of studies on microplastics larger than 10 µm does not fully represent the actual size distribution of MnPs in samples, as the size detected is still dependent on the analytical methods used. The smallest MPs found in these studies were typically several micrometers or larger, with no confirmation of particles below 1 µm. Due to their extremely small size, both sampling and analysis of NPs are challenging. Most current devices can only detect polymer particles down to the micrometer range, and studies often focus on MPs because of the lack of standardized methods for NPs and MPs [22]. In a comprehensive review of the fate, transport, and health impacts of MPs in various environmental compartments, Pawan Kumar Rose *et al.* [4] compiled studies from 2015 to 2023. Among these, there were 14 studies on water, 17 on soil and sediment, 8 on aquatic organisms, and 12 on air and road dust. These studies have similarly only detected MPs larger than 1 µm [4]. Therefore, nanoplastics in the atmosphere, as well as in other environmental compartments, represent a significant research gap. Furthermore, the potential health impacts of NPs are considered greater than those of MPs, highlighting the need to prioritize research on the presence of NPs in the air in future studies.

Color

Regarding color, only 10 out of 28 studies identified the color of MPs (Table 1), accounting for 35.7 % of the total studies. This proportion is lower than that for shape and size. The reason is that most studies immerse the samples in H_2O_2 to remove organic matter before isolating and analyzing the MPs, and the effect of this process on the color of MPs has not been fully evaluated. It may cause the color of MPs to fade or be lost. In such cases, the color may not be identified or may be inaccurately determined. According to the data in Table 1, the initial findings suggest a diversity of microplastic colors in the atmosphere, with 10 distinct colors identified: blue, black, red, green, yellow, white, transparent, brown, gray, and orange. In urban or industrial areas, the range of observed microplastic colors is broader. For example, in Shanghai, China, a wide color spectrum was observed, with eight different colors including blue, black, red, transparent, brown, green, yellow, and gray [29]; similarly, in Guangzhou, China, five different colors were identified [43]. In contrast, in remote areas such as the East Sea and Indian Ocean, the color spectrum of microplastics was more limited, with only three different colors identified. The diversity of microplastic colors may reflect the variety of sources in urban and industrial areas, which are more varied than those in remote areas. However, this relationship is not yet fully established, as the number of studies in Table 1 demonstrating this link is still limited. Therefore, more research is needed to clarify this connection between color diversity and the origin of MPs.

Polymer types

Data from the studies in Table 1 show a significant diversity in the types of polymers present in airborne microplastics across different regions. The most common polymers include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). These polymers are found in various environments, ranging from urban and industrial areas to coastal regions and even remote areas. The distribution of these polymers clearly reflects the diverse sources of microplastic emission, including industrial activities, transportation, and everyday consumer use.

However, the data from current studies do not provide extensive information on the presence of polymers associated with tire wear particles (TRWPs), such as styrene-butadiene rubber (SBR) or natural rubber (NR), even though previous research has shown that TRWPs, generated from the friction between tires and road surfaces, are a significant source of airborne microplastics. For example, studies conducted in France, the United States, and Japan indicate that TRWPs account for between 0.14 - 2.8 % of PM_{10} particles and 0.1 - 0.68 % of $PM_{2.5}$ particles [44].

The absence of data on these polymers may be due to inadequate analytical methods. The polymer identification methods used in these studies primarily rely on Fourier-transform infrared spectroscopy (FT-IR) (Table 2), which is focused on detecting traditional plastic polymers such as PE, PP, and PS. However, this method may not be sensitive enough to accurately detect complex polymers like SBR or NR in tire wear particles, especially when these particles contain carbon black, a filler that does not absorb infrared radiation.

The lack of data on specific polymers from tire wear particles, such as SBR and NR, highlights a significant gap in current research. Tire wear particles are an important source of microplastic emissions, particularly in areas with heavy traffic. However, current studies have not adequately focused on the precise analysis of these polymers in the atmosphere. To address this gap, more advanced sampling and analytical methods need to be developed, with the capability to detect polymers from tire wear particles, especially in high-traffic areas.

4. SOURCES, FATE AND TRANSFORMATION

Food packaging, plastic bottles, laboratory equipment, agricultural films, trash and grocery bags, fishing tools and nets, devices and electronics, vehicle parts, toys, garden pots and equipment, packaging films, cable insulation, household goods, and many other products are common applications of plastics. According to statistical data, the packaging industry accounts for the highest percentage of total plastic consumption, at nearly 42% [45], making it a primary source of MPs in the environment.

In the atmosphere, the main sources of microplastics include synthetic fibers from textiles, tire wear from synthetic rubber, and urban dust [4]. Other potential sources may include construction materials, industrial emissions, plastic debris from household interiors, landfills, waste burning, dryer exhaust, etc. [4]. Plastic fragments from these sources undergo mechanical fragmentation and physicochemical transformations in the environment, releasing MPs and NPs particles into the environment, including the air. Based on the formation mechanisms of MnPs in the environment, their origins are classified into two types: primary sources and secondary sources.

4.1. Sources

Primary sources

Primary MPs are released in their original plastic form from products containing MPs, such as personal care products (e.g., clothing, toothpaste, cosmetics, exfoliating scrubs, sunscreen, etc.), often in the form of small fibers, beads, and plastic pellets [19, 46, 22, 47]. These MPs are intentionally produced and typically have a size in the micrometer range [47]. Primary microplastics can also originate from the abrasion of large plastic materials during production, usage, or maintenance, such as the wear of tires during driving or the abrasion of synthetic fibers during washing [14].

Seren Acare [47] compiled data from numerous studies showing that 0.05 g/g (2,450 particles/g) of MPs were found in facial cleansers, and 0.02 g/g (2.15 particles/g) in shower gels. Additionally, between 48.6 and 307.6 mg/kg of microplastic fibers were released from washing various commercial polyester-containing (PEST) garments in washing machines, corresponding to approximately 640,000 to 1,500,000 microplastic fibers being discharged into the environment [47].

Secondary sources

Secondary MnPs result from the degradation of larger plastic fragments, primarily due to natural processes such as ultraviolet (UV) radiation, mechanical abrasion, oxidation, and the wear and tear of plastic products during use and recycling [22, 46]. Among these processes, photodegradation caused by sunlight appears to be the primary driver of secondary MnPs formation. This process occurs when UV radiation breaks down the chemical bonds in polymers. The extent of photodegradation is influenced by several factors, including the type of plastic, its thickness, and the duration of its exposure to sunlight.

Temperature also plays a significant role in the breakdown and distribution of MPs. Higher temperatures can accelerate degradation, increasing the likelihood of MPs becoming airborne and traveling longer distances [45]. Additionally, the release of surface additives during this process can further accelerate plastic breakdown [48].

A notable challenge with secondary MPs is the difficulty in tracing their origins, as degradation often obscures the characteristics of the original macroplastic sources. Moreover, the lack of data complicates efforts to estimate how much macroplastics have already been converted into microplastics [14]. It is estimated that secondary MnPs account for 70–80% of MPs released into the environment, while primary MPs contribute only 15–31%.

To better understand the origins and behavior of secondary microplastics in the environment, their physical properties such as density (light/heavy), flexibility (rigid/soft), and shape (fragments, pellets, fibers, and granules) are commonly used for classification [49]."

4.2. Fate and transport of MnPs in the environment

MnPs can be found in soil, water, air, and living organisms [22]. MnPs are transported over long distances due to their shape, size, buoyancy, and durability, with travel distances up to 95 km [50]. The lifecycle of MnPs is complex, involving interactions with the atmosphere, water, soil, and sediments [22]. MnPs are released from various sources, they enter soil, water, river sediments, and the atmosphere. On land, they eventually reach the ocean via surface runoff, where they accumulate in aquatic ecosystems, settle on the ocean floor, and disperse as aerosols. MnPs in the atmosphere can be transported between the ocean and land, with deposition occurring from the atmosphere to the surface [4, 22]. Studies have detected MnPs in remote areas, including the North Atlantic [51] and isolated mountainous regions like Lanzhou, China [52]. MnPs also bioaccumulate in birds and can be absorbed by humans through respiration [22]. During their environmental journey, MnPs may be broken down into smaller particles or adsorb pollutants, or release additives into the environment.

According to Mansoor Ahmad Bhat *et al.* [22] the lifecycle of MnPs is much more complex and challenging compared to other geochemical cycles such as water, carbon, nitrogen, phosphorus, and sulfur, as it involves interactions between MnPs and the atmosphere, water, soil, and sediments. MnPs are released into the environment from sources such as waste plastics, wastewater treatment plants, factories, industrial areas, traffic activities, and clothing [4, 22]. From these sources, MnPs enter soil, water, river sediments, and the atmosphere. On land, microplastics eventually make their way to the ocean through surface runoff, where they continue to undergo bioaccumulation in aquatic ecosystems, sedimentation on the ocean floor, and dispersion into the atmosphere as aerosols. In the atmosphere, MnPs are transported between the ocean and land and undergo deposition from the atmosphere to the surface [4, 22]. Research has identified MPs in the air in remote offshore areas of the North Atlantic [51], and in isolated mountainous regions such as Lanzhou, China [52]. MnPs can also bioaccumulate in birds through the food chain and may be absorbed into the human body through respiration [22]. During their environmental journey, MnPs undergo processes such as breaking down into smaller particles, adsorbing environmental pollutants, or releasing harmful additives into the environment.

In a study on the fate of MnPs, Quik *et al.* [53] used the SimpleBox4Plastic (SB4P) model with the SimpleBox4Nano (11/3/2021) version to estimate the fate of MnPs in the environment. Results indicated correlations between mass concentration and particle number concentration of "microbeads" with environmental components such as air, natural soil, industrial soil, agricultural soil, river water, seawater, river sediments, and marine sediments. Liqi Cai *et al.* [54] found that after continuous UV exposure for 3 months, the surface of PE, PP, and PS particles developed cracks and fragments, leading to the formation of microplastics and nanoplastics. The degradation process occurred fastest in air, followed by pure water, and slowest in simulated seawater [54].

Table 1. Occurrence and physicochemical characteristics of microplastics and nanoplastics in the atmosphere.

Location	**Location type**	**Country**	**Sampler type**	**Concentration**	**Shape**	**Size**	**Color**	**Polymer type^a**	**Reference**
Paris	Urban	France	Total atmospheric fallout	29-280 particles/m^2/day	Fiber, fragment	100 -5000 µm	-	-	[27]
Paris	Urban Suburban	France	Total atmospheric fallout	110 ± 96 particles/m^2/day 53 ± 38 particles/m^2/day	Fiber	50-3200 µm	-	-	[55]
Paris	Urban	France	Total suspended particulates	0.3-1.5 particles/m^3	Fiber	50-1650 µm	-	-	[56]
Shanghai	Urban	China	Total suspended particulates	0-4.18 particles/m^3	Fiber, fragment, granule	23-9555 µm	Blue, black, red, transparent, brown, green, yellow, grey	-	[29]
Asaluyeh country	- Urban - Industrial	Iran	Total suspended particulates	0.63 particles/m^3 0.76 particles/m^3	Fiber	2-5000 µm	White-transparent, yellow-orange, red-pink, black-grey	-	[57]
Dongguan	Urban	China	Total atmospheric fallout	175-313 particles/m^2/day	Fiber, fragment, film, foam	200-2200 µm	-	PE, PP, PS	[31]

Location	**Location type**	**Country**	**Sampler type**	**Concentration**	**Shape**	**Size**	**Color**	**Polymer type**[a]	**Reference**
Yantai	Coastal city	China	Total atmospheric fallout	130-624 particles/m^2/day	Fiber, fragment, film, foam		Fiber: white, black, red, transparent	PET, PVC, PE, PS	[38]
Northwest and Central Germany	Across the Weser River catchment	Germany	Aerosol samples Total deposition samples	91 ± 47 particles/m^3; 10 - 367 N/m^2/day (99 ± 85 (mean ± SD)	Impactor samples: Irregular shape, spherical Aerosol filter samples: Irregular shape, spherical Total atmospheric deposition: fragments, fiber, spheres	Impactor samples: 4.1-33 µm Aerosol filter samples: 4.4-29 µm Total atmospheric deposition: < 500 µm	Impactor samples: white, blue transparent black, faint blue, brown Aerosol filter samples: white, red Total atmospheric deposition: Gray, transparent and white	Impactor samples: PE Aerosol filter samples: PE, EVAc	[33]
Pyrenees mountains	Remote	France	Total atmospheric fallout	365±69 particles/m^2/day	Fiber, fragment, film	500-700 µm	-	PS, PE, PP, PVC, PET	[58]
The north, south and center of Hamburg	Metropolitan area	Germany	Atmospheric deposition	275 particles/m^2/day	<63 µm (fragment); 5-0.3 µm (fibres)	> 60 µm	-	PE, EVAC, PTFE, PVA	[59]
Pearl River	Estuary	China	Suspended atmospheric particles	4.2±2.5 items/100 m^3	Fibres, fragment	917.4±563.60 µm; median = 807.3 µm	Yellow, white, black, red, brown.	PP, PET, PEP, PA;	[37]
South China Sea (Southeast Asia Sea)	Remote			0.8±1.3 items/100 m^3		953.0±730.10 µm; median = 1117.9	Yellow, red, black;	PP, PEVA, PET;	
East Indian Ocean	Remote			0.4 ±0.6 items/100 m^3		643.1±319.4 µm; median = 739.0 µm	Yellow, blue, black.	PR, PP, PET, PAN-AA,	
Guangzho	Urban	China	Atmospheric deposition	114 ±40 particles/m^2/day	Fibres, fragment, film	50 µm - 5mm	transparent/white, blue, yellow, red, orange, green, and gray	PET, PS, PAN, ALK, EP, PP, PA, ABS	[43]
Ahvaz City:	Industrial Urban	Iran	Atmospheric particles	0.002-0.017 MP/m^3; 35.34 - 98.34 µg/m^3 0.002- 0.015MP/m^3; 39.64 - 94.64 µg/m^3	-	10 µm	Back-grey, yellow-orange	PET, Nylon, PP	[60]
Kuala Nerus and Bangi Chagar Hutang	Urban Pristine beach	Peninsular Malaysia	Total atmospheric deposition samples	114 - 689 MP/m^2/day; 280–394 MP/m^2/day 172–476 MP/m^2/day	Fibres, fragment Fibres, fragment	5-5000 µm 5-5000 µm	-	PA, Nylon, PVC, HDPE, PP, PES, copolymer	[30]
Kochi	Coastal city	India	Atmospheric	37.29-11.57	Fibres, fragment, film	1-5000 µm	Transparent, blue, red, black	PE, PP, PA, PET, PS	[39]

Location	**Location type**	**Country**	**Sampler type**	**Concentration**	**Shape**	**Size**	**Color**	**Polymer type**^{a}	**Reference**
			microplastic fallout	Particles/m^2/d			green,		
Plymouth	Maritime city	England	Material suspended in air Material deposited from the atmosphere	0.016 to 0.238 (mean: 0.082) items/m^3 0.46-3.30 (mean:1.77) items/m^2/h	Fibres, fragment, pellets, foams,	-	Translucent, blue, white,	EP, expanded PU, PA, PES, PEI, PP, PVC, PVA	[36]
Jakarta:	The coastal urban area	Indonesia	Total atmospheric deposition samples	3 - 40 particles/m^2/day,	Foam, fragment, fiber	300-1000 µm		PES, PS, PBD, PE	[61]
Najning	Urban	China	Deposited atmospheric microplastics Suspended tmospheric microplastics	134.18 to 500.94 items/m^2/day, (0.29–4.88 items/m^3	Fragments, fiber Fragment, fiber	20-5000 µm 20-5000 µm	Black, blue, transparent, red, yellow Blue, black, transparent, red, yellow.	PA, PE, PES, PP, EP PA, PE, PES, PP	[62]
Shiraz	The urban metropolis Remote	Iran	Dry atmospheric deposition samples (DADS) and Wet atmospheric deposition samples (WADS)	<47 MP/m^2/h (DADS) <130MP/m^2/h (WADS) <23 MP/m^2/h (DADS) <123 MP/m^2/h (WADS)	Fiber, fragment	-	-	PET, PTFE, PE, PS, PE,PP, nylon, PVC	[63]
Chengdu	Urban	China	Toltal bulk depositions samplers	207.1–364.0 N/m^2/day (14.17–33.75 µg/ m^2/day)	Fiber, fragments, films, and granules	fibers ranged in 22.9–4165.5 µm non-fibers: 20-1105.5 µm	-	PP, PE, PET, PVA, PS, PA, PMMA	[64]
Pathum Thani	Suburban	Thailand	Dry atmospheric deposition samples; Wet atmospheric deposition samples	199 numbers/m^2/day 285 numbers/ m^2/day total deposition flux (dry + wet) of 325 numbers/m^2/day	Fiber , film. fragment fiber	132 - 4541 µm 121 µm to 4990 µm	-	Cellophane, PET, PE, PU, PP PP, PU, PET, PBA, PEA	[11]
Seoul	Urban	Korea	PM$_{10}$ sampler	0.33–1.21 MP/m^3 (average: 0.72 ±0.39 MP/m^3)	Fiber (12.6%) Fragment (87.4%)	24.38-2278.4 µm	-	PP, PET, PE, PA, PEAV, PS, PU, acrylic	[32]
Ho Chi Minh city	Urban	Vietnam	Total atmospheric fallout samples	71-917 Items/ m^2/d	Fiber Fragment	300-5000 µm	-	-	[29]
Geladandong	Remote region of the world	China	Air samplers	0.12 items/m^3	Fiber, film	50-5000 µm		PP, PET, ALK	[41]
Harbin	Urban: cultivated land and unused land	China	Suspended atmospheric microplastic	1.76 n/m^3	Fiber, Fragment, Granular	1- >50 µm	Transparent colour, black, red, white, blue, yellow	PP, PET, PE, PS, PVC	[42]
The coastal areas of the	Rural, Suburban	Japan	Atmospheric particulate samples	0.12-0.3 particles/m^3		> 10 µm	-	PE, PP, PS	[34]

Location	Location type	Country	Sampler type	Concentration	Shape	Size	Color	Polymer type[a]	Reference
Japan Sea									
Auckland city	Urban	New Zealand		0.12 particles/m^3					
Whanganui	Remote				Particles, fibers	> 10 µm		PE, PP, PS, PET	
and in the montane region of Tongariro		New Zealand		0.03 and 0.06 particles/m^3		> 10 µm		PE, PP, PS, PET	
Tibetan Plateau	Urban Rural Wildland	China	Airborne particles	27.6 ± 14.7 n/m^3 15.6 ± 4.4 n/m^3 8.1 ± 3.0 n/m^3	Particles, fibers	> 5.9 µm	-	PET, PE, PA, PS, PP, PVC	[40]
Wenzhou City (coastal city)	Urban Rural	China	Total suspended particulates	224 ± 70 n/m^3 101 ± 47 n/m^3	Particles, fibers	5-5000 µm	-	PES, PA, PP, PE, PS, PVC	[35]

[a] Polypropylene (PP), poly(ethylene-co-vinyl acetate) (PEVA), polyethylene terephthalate (PET), poly(ethylene-co-propylene) (PEP), poly(acrylonitrile-co-acrylic acid) (PAN-AA), phenoxy resin (PR), polyacrylonitrile (PAN), polyamide (PA), polystyrene (PS), alkyd (ALK), epoxy resin (EP), polyvinyl chloride (PVC), poly(styrene – acrylonitrile - butadiene) (ABS), polyester (PES), poly(11-bromoundecyl acrylate) (PBA), polybutadiene (PBD), polyethylene acrylate (PEA), polyetherimide (PEI), PTFE (Polytetrafluoroethylene).

Thus, both theoretical and experimental research have confirmed the presence of MPs in all environmental compartments including soil, water, air, sediments, and aquatic organisms. However, specific data on the fate of NPs in environmental compartments is still lacking. Notably, in 2023, a significant study reported the presence of NPs in human blood using specialized analytical techniques, including fluorescence staining and flow cytometry [65]. Earlier, in 2022, another study also used fluorescence staining and laser scanning confocal microscopy to identify NPs in plant cell tissues [66]. These techniques may be developed further for environmental analysis in the future.

5. SAMPLING METHODS

The physical state of MnPs under normal temperature and pressure is solid. In the air, they behave similarly to dust particles, and in some respects, they are more persistent than many other dust particles, which are primarily composed of biodegradable organic matter. Currently, there are no methods available to immediately separate MPs and NPs from other airborne dust particles during sampling. Therefore, conventional dust sampling techniques are used to collect MPs and NPs from the air. Any collected samples of MPs and NPs (if present) will include other types of dust particles. Air particulate matter sampling techniques are categorized into two main groups: active sampling and passive sampling methods [67].

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5.1. Passive sampling

MnPs in the air deposit onto surfaces due to factors such as gravity, wind, and rainfall. The process of deposition due to wind and gravity is referred to as dry deposition, while deposition due to rainfall is called wet deposition. Most studies on MnPs deposition from the atmosphere involve the simultaneous collection of both dry and wet depositions. Consequently, the design of collection equipment for these samples needs to accommodate both types of deposition. This sampling method for MPs has been employed in the majority of air MPs studies [68]. Out of a total of 64 studies, 39 used this method to collect deposited dust in the air from 2020 to 2022 [67]. For outdoor air, according to the statistics in Table 2, from the initial study in Paris by Dris [27] to recent studies published in 2024, 16 out of 28 (57.1%) studies have utilized this method for sampling atmospheric MnPs deposition.

The sampling equipment for this method essentially consists of two main components: a deposition surface for collecting dust and a container for the collected dust and rainwater. The deposition surface, designed to collect both dust and rainwater, is typically funnel-shaped. The container for the collected samples is positioned directly beneath the funnel. Both the funnel and the container are made of stainless steel and amber glass. The surface area of the deposition surface and the volume of the container vary among studies. Funnel diameters range significantly, from 100 mm (= 0.0079 m^2) in the study by Giannis [36] to 320 mm in the study by Dris *et al.* [27]. In fact, in the study by Yu Chen *et al.*, a sampling bucket with a diameter of up to 520 mm (0.85 m^2) was used [64]. The volume of the collection container also varies accordingly, from 1 liter [36] to 20 liters [27, 55]. A study conducted in Vietnam used a funnel with a diameter of 250 mm and a 10-liter glass container [29]. At the end of each sampling period, the funnel is rinsed multiple times with deionized water, and the rinse water is collected in the container below, then transported to the laboratory.

Regarding sampling duration, studies choose proper sampling periods based on their objectives, but generally, extended periods are needed. Sampling durations can range from several days [69] to several weeks, or even months [68]. Throughout the sampling process, it is crucial to maintain the rainwater level in the container below the critical level to prevent overflow.

The advantages of the deposition sampling method for microplastics include its simplicity, ease of fabrication, and low cost. This method is convenient for sampling in remote or uninhabited areas, as it does not require an electrical power source. However, the method is influenced by several factors such as local weather conditions, the altitude of the sampling equipment, and human activities, making it challenging to compare results across different sampling locations.

5.2. Active sampling

The active sampling technique uses a pump to collect air samples. Depending on the type of airborne particulate matter (by size), a proper dust collector head is selected. Airborne particles, including MnPs (if present), are retained on the surface of the filter. After sampling, the filter is preserved and processed using suitable methods before being analyzed by instruments. Depending on the structure of the sampling head, this technique can be used to collect total suspended particles (TSP) or to separate particles by different size fractions.

According to the statistics in Table 2, 14 out of a total of 28 studies (50%) used active sampling to collect MnPs in outdoor air. Among these studies, the majority used the technique for total particle collection, with very few employing it for sampling particles by different size fractions. A review of 24 studies on MnPs in both indoor and outdoor air, published between 2015 and 2021 by Mansoor Ahmad Bhat *et al.* [22] shows that 6 out of 24 studies employed active sampling techniques.

The data in Table 2 also shows that most studies used glass-fiber filters for particle collection, with a rate of 64%. Other types of filters, such as PTFE, quartz fibre, aluminium oxide, cellulose nitrate, and mixed cellulose ester membrane filters, were used, but to a significantly lesser extent. The pore size of the filters varies widely, ranging from 0.2 µm to 2.0 µm, with the 1.6 µm pore size being the most commonly used.

The active sampling technique allows for the collection of samples within a short period and can particularly be used to sample different size fractions. However, applying this technique can be challenging in remote or isolated areas where there is no access to a power source to operate the equipment continuously for extended periods.

6. ANALYTICAL METHODS

Currently, there is no standard method for the analysis of microplastics in general and microplastics in the air specifically. The laboratory analysis procedures commonly used in studies consist of two main steps: sample preparation and instrumental analysis.

6.1. Sample preparation

Total atmospheric microplastic fallout samplers

The deposition of atmospheric MPs involves a comprehensive sample processing procedure, summarized from the studies presented in Table 2 and illustrated in the diagram in Figure 1 (left). However, variations in execution or material choices may occur at each stage of the process across different studies.

First, most studies filtered samples to capture particulate matter on various types of filters, including glass fiber [27, 28, 62], stainless steel [61, 33], quartz fiber [55], nitrocellulose [38], PTFE [58], cellulose nitrate [36], and cellulose [63]. After filtering, the samples are typically oxidized using 30% H_2O_2 or Fenton's reagent to remove organic matter. The soaking time and concentration of the oxidizing agents can vary among studies. A few studies skip the filtration step before organic matter digestion, instead adding an oxidizing agent (6-14% NaClO) directly to the sample to decompose organic matter [59] or evaporating the sample to dryness at 50°C before chemical oxidation [62].

Following the organic matter oxidation process, the sample is filtered through several types of filter papers, including stainless steel [33], PTFE [58], and cellulose nitrate [61]. Most studies then proceed with sample purification using density separation to isolate microplastics from other materials. High-density salt solutions, such as $ZnCl_2$ (1.6-1.7 g/ml), are typically employed to separate microplastics from impurities. In this flotation process, microplastics rise to the surface, allowing sediments to be discarded. The floating microplastics are then filtered through a variety of filter papers, including Anodisc membranes [33, 58], silver membranes [30], polycarbonate (PC) [30], cellulose [30, 63], quartz fiber [56], and cellulose nitrate [36]. Finally, the samples on the filter are analyzed using instruments to identify the MnPs.

Table 2. Sampling and analytical methods for MnPs in air.

Location	Country	Sampler type	Sampling techniques	Separation and digestion	Analytical techniques	Reference
Paris	France	Total atmospheric fallout	Passive sampling: Stainless steel funnel (area = 0.325 m^2) used in conjunction with a 20 L glass bottle.	Filtered on glass fibre GF/A Whatman filters (Sigma–Aldrich, 1.6 µm pore size).	Stereomicroscope	[27]
Paris	France	Total atmospheric fallout	Passive sampling: Stainless steel funnel (area = 0.325 m^2) used in conjunction with a 20 L glass bottle.	Filtered on quartz fiber GF/A Whatman filters (1.6 µm pore size)	Stereomicroscope, micro FT-IR (µ FT-IR)	[55]
Paris	France	Total suspended particulates	Active sampling: Quartz fiber GF/A Whatman filters (pore size = 1.6 µm; ⌀ = 47mm)	Direct observation and analysis	Stereomicroscope, µ FT-IR	[56]
Shanghai	China	Total suspended particulates	Active sampling: GF/A glass microfiber filters (pore size = 1.6 µm; ⌀ = 90 mm)	Direct observation and analysis	Stereomicroscope, µ FT-IR	[29]
Asaluyeh country	Iran	Total suspended particulates	Active sampling: PTFE filter papers (pore size = 2 µm; ⌀ = 46.2 mm)	Digested with 30% H_2O_2 for 8 day and then separated using NaI solution (1.6 g/mL).	Polarized light microscopy, flourescence microscopy, and determined by SEM/EDS	[57]
Dongguan	China	Total atmospheric fallout	Passive sampling: glass bottle (30 cm × ⌀15 cm, i.e., opening area is 0.0177 m^2, volume is 5.31 L.	Filtered through 1.0-µm glass microfiber filters (Whatman GF/B)	Digital microscope, SEM, µ FT-IR	[31]
Yantai	China	Total atmospheric fallout	Passive sampling	Filtered on nitrocellulose filters (5µm); Some of these samples containing organisms were digested with H_2O_2 30 %.	Stereomicroscope, ATR-FTIR, µ FT-IR	[38]
Northwest and Central Germany	Germany	Aerosol samples; Total deposition samples	- Active sampling: aluminium oxide filter (pore size 0.2 µm, ⌀ = 25 mm) Anodisc25, Whatman, Germany; Size-selective sampling of airborne particulates using a cascade impactor, Particles were divided into five size fractions, with the fractions > 2.5 µm and 2.5 - 1.0 µm collected on Anodisc filters for analysis. - Passive sampling: Total atmospheric deposition. A stainless steel funnel (⌀ = 257 mm), an amber glass bottle volume 2.2 L	Filter and impactor samples of airborne particles were analysed directly on Anodisc filters by Raman spectroscopy and no additional sample processing was necessary. Fenton purification ($FeSO_4 + H_2O_2$), followed by MPs density separation ($ZnCl_2$, 1.7 g/mL). Enzymatic digestion, followed by Fenton oxidation, then MNs density separation ($ZnCl_2$, 1.7 g/mL).	Aerosol samples: Raman spectroscope Deposition samples: µ FT-IR	[33]
Pyrenees mountains	France	Total atmospheric fallout	Passive sampling: - Palmex Rain Sampler with a sampling area of 0.014 m^2 (⌀ = 135 mm); - Particulate Fallout Collector with sampling area of 0.03 m^2 (⌀ = 200 mm)	Filtered on PTFE filters (0.45µm). Digested with 30 % H_2O_2 at 55 ^{0}C for 7 days and then digested for another 7 days with a further 5mL 30 % H_2O_2 added. Density separated using $ZnCl_2$ solution (1.6g/mL)	Stereomicroscope, micro-Raman (µ Raman)	[58]
The north, south and center of Hamburg	Germany	Atmospheric deposition	Passive sampling: PE-funnel (⌀ = 12 cm)	Sample was treated with NaClO (6 - 14 %) solution, filtered through a 55 mm cellulose membrane, stain with Nile Red reagent.	Fluorescence microscope. µ-Raman	[59]
Pearl River	China	Suspended	Active sampling: Whatman GF/A glass microfiber	Direct observation under a stereomicroscope	Stereomicroscope,	[37]

Location	Country	Sampler type	Sampling techniques	Separation and digestion	Analytical techniques	Reference
South China Sea		atmospheric particles	filters (1.6 µm pore size, (⌀ = 90 mm)		µ FT-IR	
East Indian Ocean						
Guangzho	China	Atmospheric deposition	Passive sampling: sampler equipped with a 22 L stainless steel bucket (⌀ = 25 cm, height: 45 cm) was used to collect the atmospheric deposition samples	Treated using 30 % H_2O_2 for 24 hours at room temperature in the dark. After that, microplastics samples were collected onto a nitrocellulose filter (0.45 µm; 47mm)	Microscope, FT-IR	[43]
Ahvaz City	Iran	Atmospheric particles	Active sampling: Samples of PM were collected on pre-weighed, 203 × 254 mm rectangular glass-fibre filters (1.6 µm pore size; Whatman G653) using a Tisch high volume air sampler; Using PM_{10} samples to determine the presence of microplastics	Shaken dust-containing filters in deionized water, treated with H_2O_2, density-separated with $ZnCl_2$, centrifuged, filtered, dried, and microplastics counted.	Optical microscope, µ Raman; SEM/EDX	[60]
Kuala Nerus and Bangi	Malaysia	Total atmospheric deposition samples	Passive sampling: stainless funnels attached to a 2.5 L amber glass bottle; area of funnel collecting are 0.031 m^2 and 0.015 m^2	Filtering samples through a cellulose acetate membrane (0.45 µm pore size), removing organic matter using 10 % potassium hydroxide (KOH), and separating MP with a 1.37 g/cm^3 zinc chloride ($ZnCl_2$) solution. For MP quantification, samples are filtered onto a polycarbonate filter (2 µm pore size) and stained with Nile Red solution. For MP identification, samples are filtered onto silver membrane filters (0.45 µm pore size).	Digital camera with an orange filter (HOYA orange (G); µ FT-IR	[30]
Chagar Hutang	India	Atmospheric microplastic fallout	Passive sampling: A glass funnel was placed on top of the 30-liters stainless steel container	The water samples were vacuum filtered using Whatman Grade 1 filter paper (11 µm pore size), treated with 30 % hydrogen peroxide for digestion, followed by density separation with zinc chloride, and the supernatants were filtered again for visual identification.	Stereomicroscope; Confocal raman microscope	[39]
Plymouth	England	Material suspended in air Material deposited from the atmosphere	Active sampling: air was sampled though a Whatman GF/A, ⌀ = 25 mm, 1.6 µm pore size glass filte. Passive sampling: 10 cm diameter glass funnels into two, 1 L amber glass bottles.	Active samplers: Direct observation and analysis Passive samplers: filtered using a 47 mm diameter, 0.45 µm pore size Whatman cellulose nitrate filter.	Stereomicroscope, FT-IR	[36]
Jakarta:	Indonesia	Total atmospheric	Passive sampling: A manual glass rain gauge (200	The sample was then screened	Microscope;	[61]

Location	Country	Sampler type	Sampling techniques	Separation and digestion	Analytical techniques	Reference
		deposition samples	mm diameter of mouth opening and 2000 ml volume	using two filter levels (stainless steel, ⌀ 3 in., size 200 µm and 5000 µm). H_2O_2 and $FeSO_4$ for degestion of samplers.	FT-IR	
Najning	China	Deposition atmospheric microplastics (DAMPs) Suspended atmospheric microplastics (SAMPs)	Passive sampling: stainless-steel bucket with a 15 cm inner diameter and a 30 cm height Active sampling: middle-flow atmospheric particulate samplers, flow rate was 100 L/min. GF/A glass microfiber filter (1.6 µm, ⌀ 90 mm; Whatman, U.K.	DAMPs: Dried at 50 °C, treated with H_2O_2, filtered through a glass microfiber filter (5 µm, ⌀ 47 mm), density separated using NaCl, filtered, and dried SAMPs: Direct observation was performed under a stereomicroscope, followed by analysis using FT-IR.	Stereomicroscope; FT-IR	[62]
Shiraz	Iran	Dry atmospheric deposition samples Wet atmospheric deposition samples	Passive sampling: stainless steel dish (whose depth was 30 cm and aperture diameter ranged from 25 to 43cm)	Filtered through a 2 µm pore size S&S filter paper (Blue Band, grade 589/3), digested in 35 mL of 30 % H_2O_2, refiltered through clean 2 µm filters and dried.	Stereomicroscope. µ Raman	[63]
Chengdu	China	Toltal bulk depositions samplers	Passive sampling: stainless steel bucket with a diameter of 0.52 m (volume of ~0.11 m^3)	Digested using 100 ml of 30 % H_2O_2 for 24 h at room temperature → a 10 h flotation was performed with saturated NaCl solutions (1.2 g/cm^3) → concentrated onto a 0.45 µm PTFE filter.	Optical microscope; µ FT-IR	[64]
Pathum Thani	Thailand	Dry atmospheric deposition samples Wet atmospheric deposition samples	Passive sampling	Wet Peroxide Oxidation ($FeSO_4$ + H_2O_2) and density separation (NaCl)	Stereomicroscope. FT-IR	[11]
Seoul	Korea	PM_{10} sampler	Active sampling: particulate matter sampler (KN-L25P1) PM_{10} equipped with a cellulose nitrate (CN) filter (pore size 0.45 µm, ⌀ = 47 mm)	Sonication, density separation using Lithium metatungstate, digestion with Fenton reagent	µ FT-IR	[32]
Ho Chi Minh city	Vietnam	Total atmospheric fallout samples	Passive sampling: 250 mm diameter glass funnel placed on a 10-L glass bottle to collect rain water	Filtered	Stereomicroscope	[29]
Geladandong	China	Air samplers	Active sampling: pumped HiVol sampler (TW2200, Tuowei Instruments, 60 m^3. Atmospheric samples were collected using glass fiber	Direct observation under a stereomicroscope	Stereomicroscope, µ FT-IR	[41]

Location	Country	Sampler type	Sampling techniques	Separation and digestion	Analytical techniques	Reference
			filters.			
Harbin	China	Suspended atmospheric microplastic	Active sampling: The MiniVol portable atmospheric particulate sampler (Airmetrics, USA) with (10 ± 0.1) L/min of intake flow rate in a total of 1 m^3. A mixed cellulose ester membrane with 1µm pore size and 47 mm diameter placed in Whatman GF/A glass microfiber filters was used to obtain SAMPs.	Direct observation and analysis	Stereomicroscope. FT-IR	[42]
The coastal areas of the Japan Sea Auckland city Whanganui and in the montane region of Tongariro	Japan New Zealand New Zealand	Atmospheric particulate samples	Active sampling: High volume air sampler (HV-RW, Sibata, Japan) was used, 1000l/m^3 quipped with a glass fiber filter (nominal pore size of 0.6 µm; GB-100 R; Advantec, Japan); The sampler was operated at 150 L/min collected onto 47 mm glass fiber filters for the Whanganui and Tongariro locations	Treated with 40 mL of ethanol to remove fluorescent compounds before analysis using Raman.	Confocal Raman	[34]
Tibetan Plateau	China	Airborne particles	Active sampling: An intelligent middle-flow total suspended particulate sampler; glass microfiber filter (Whatman GF/F, 0.7 µm pore size, ⌀ = 90 mm)	Washed and digested with 100 mL H_2O_2, then filtered through a 0.45 µm pore size, 47-mm diameter poly(tetrafluoroethylene) (PTFE)	Fluorescence microscopy; µ FT-IR	[40]
Wenzhou City	China	Total suspended particulates	Active sampling: An intelligent middle-flow total suspended particulate sampler; glass microfiber filter (Whatman GF/F, 0.7 µm pore size, ⌀ = 90 mm)	Washed into a glass beaker and digested with 100 mL H_2O_2 and then heated to 70 ºC for 1 hr. Filtered through a 0.45 µm pore size, 47-mm diameter PTFE for Nile red staining.	Fluorescence microscopy; µ FT-IR	[35]

In addition to numerous studies that employ complex processes to separate and purify microplastics from raw samples, some studies bypass interference removal steps using oxidizing agents or density separation. Instead, they directly observe microplastics on the equipment after filtering the samples [27, 55].

Suspended atmospheric microplastics

In general, for suspended particulates samples, the sample preparation process is simplified compared to settled dust samples. This simplification can significantly affect the efficiency and accuracy of the analysis. Many studies, including those conducted by Wang *et al.* [37], Dris *et al.* [56], K. Sarmite *et al.* [33], Giannis *et al.* [36], and others, do not require treatment processes to remove interfering substances

Using oxidizing agents like H_2O_2, Fenton's reagent, or density separation methods with high-density halogenous salt solutions. Instead, microplastics, along with other substances on the filter surface after sampling, are analyzed directly using the equipment.

Chang *et al.* [32] reported that the analytical results are comparable even when the sample undergoes minimal processing compared to samples treated with H_2O_2 and density separation. Luo *et al.* [40] also recommend omitting density separation and decomposition if the sample has minimal contaminants on the filter. However, it is important to note that while these simplified methods can be effective, they might not always remove all potential interferences, which could affect the precision of the results. Only a few studies perform the complete sample preparation steps as depicted in Figure 1 (right). In these cases, the filter sample is oxidized with H_2O_2 and then filtered through cellulose paper [57, 60]. The subsequent step involves separating MnPs from the sample by density using $ZnCl_2$ solution and capturing them on cellulose filter paper [57, 60]. This thorough preparation process can enhance the accuracy of the analysis by ensuring that MnPs are adequately isolated from other materials, but it also requires more complex and time-consuming procedures.

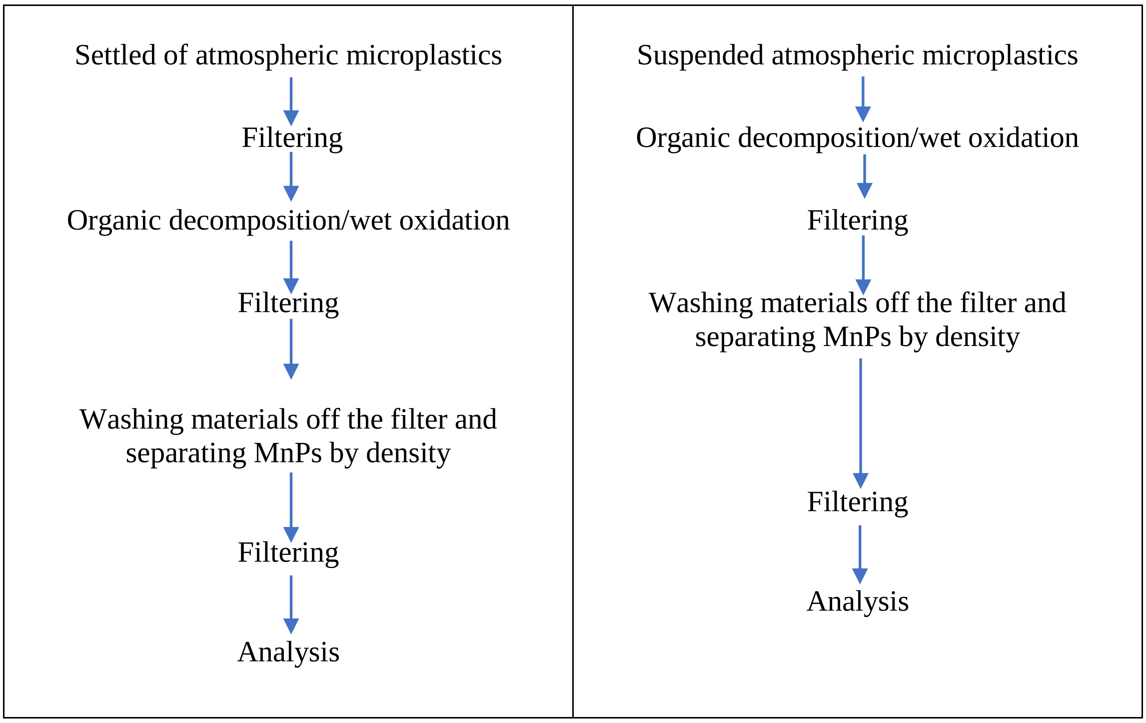

Figure 1. Sample preparation steps for MnPs analysis in air from settled (left) and suspended particulate matter (right) (*Compiled from References cited in Table 2*).

Choosing the proper sample preparation method is crucial as it can influence the overall accuracy and reliability of the analytical results. Therefore, understanding the strengths and limitations of each method, and selecting the one that best suits the sample type and research objectives, are essential for achieving reliable outcomes.

6.2. Analystical techniques

6.2.1. Determining physical characteristics

Determining the physical characteristics of MnPs aims to observe the presence of MnPs in the air, focusing on attributes such as shape, size, color, and surface characteristics, with size determination being the most crucial. The advancement of a method is reflected in its detection limit for the smallest size of MnPs in the air. The methods used to identify them are as follows:

Optical microscopes and digital microscopes: These are common laboratory instruments used to observe objects. Depending on the configuration of each type of device, objects can be observed at specific sizes. However, this method generally only allows the observation of MPs particles with sizes ranging from 0.3-0.5 mm and above [70].

Scanning electron microscopy (SEM): SEM is often applied to determine the size, shape, and surface characteristics of ultrafine and nano plastics. It is widely used in studies involving pristine nanoplastics that have been characterized before being added to samples to validate methods or in biological exposure experiments [70]. Additionally, due to its capability to observe detailed surface features, SEM is suitable for assessing MnPs degradation in the environment.

The stereomicroscope method is employed to observe the surface, color, and size of microplastics (MnPs) in collected samples. However, the observable particle size depends on the equipment's resolution. According to Stefania Mariano *et al.* [71] , stereomicroscopy can detect particles around 100 µm in size, while particles smaller than 100 µm, particularly if transparent, are very difficult to observe. This method was the first used to study fallout microplastics in Paris, France [27]. It remains the most commonly used technique for determining the physical properties of MPs [72]. Of the 17 publications on MnPs in the air from 2015 to 2019, 9 utilized stereomicroscopy, with the smallest reported particle size being 20 µm [68]. As shown in Figure 2 (left), 50% of studies since 2015 have employed stereomicroscopy to identify the physical properties of MnPs in the air, followed by optical microscopy at 19% and fluorescence microscopy at 13%.

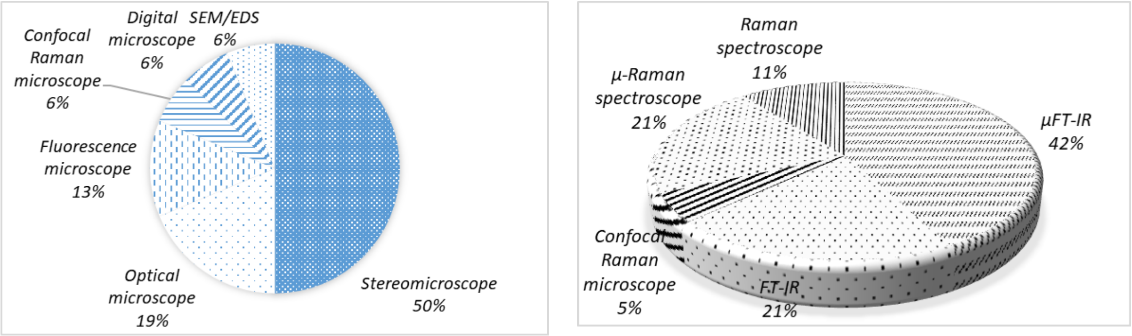

Figure 2. Techniques for analyzing physical (left) and chemical properties (right) of MnPs in ambient air (2015 – present) (*Compiled from References cited in Table 2*).

Using optical microscopy, digital microscopy, and stereomicroscopy allows for the counting of MP particles in samples, particularly with stereomicroscopy [72], thus enabling the determination of the concentration of MnPs in a given volume of air (MnP/m³). However, environmental samples used to determine MnPs often have complex compositions. Particularly, when MnPs are small particles, distinguishing them from other particulate matter in the sample becomes more challenging. To enhance the selectivity of the observation method, recent studies have employed staining of microplastics after performing some impurity removal processes. Stained microplastic particles will fluoresce when excited at the appropriate wavelength. This fluorescence is observed using a fluorescence stereomicroscope. According to Christian Schwafert *et al.* [70], this is a popular tool for analyzing the fate of ultrafine to nanoscale microplastic particles in organisms, for example, to track particle movement within tissues. In studies on MnPs in the air, fluorescence staining methods have also been used by several authors [73-76]. However, the sample preparation stage for this method is quite elaborate to remove non-target substances that may also stain with the dye. Additionally, a notable limitation of the fluorescence staining method is the difficulty in identifying black-colored PVC [77]. Consequently, tire particles, if present in the sample, cannot be detected using this method.

6.2.2. Determining chemical characteristics

Microplastics and nanoplastics, primarily composed of polymers, can be identified using optical analytical methods such as FTIR and Raman spectroscopy, as well as mass spectrometry techniques like Pyrolysis-Gas Chromatography/Mass Spectrometry (Pyr-GC/MS) [72, 78].

Fourier-transform infrared spectroscopy (FT-IR)

FT-IR is commonly employed as the primary analytical tool for microplastic identification [22, 78]. According to Cuihe Yang *et al.* [78], FT-IR spectra displays the characteristic absorption features of microplastic particles at specific infrared wavelengths. To determine the composition of microplastics, the sample spectra are compared to reference spectra from the Polymer Library. However, the spectral match between actual and reference data typically reaches only around 70 % accuracy [78]. FT-IR operates in Attenuated Total Reflectance mode (ATR-FT-IR) for particles larger than 500 µm, and in Focal Plane Array mode (FPA-FT-IR) for smaller particles, with a resolution of approximately 10 - 20 µm [70]. For very small microplastics, micro FT-IR (µ FT-IR) is preferred for identification. Yumei Huang *et al* reported that 10 out of 16 studies between 2015 and 2020 used µ FT-IR, with the smallest detected particle size being 50 µm [72]. According to Yulan Zhang [68], 9 studies utilized µ FT-IR, while 4 used FT-IR in a total of 17 studies from 2015–2020, with the smallest detected particle size being 20 µm. Figure 2 (right) also illustrates that FT-IR spectroscopy remains the dominant method used in studies published from 2015 onwards for characterizing the chemical composition of airborne MnPs, with µ FT-IR accounting for 42 %, followed by FT-IR at 21 %.

Raman spectroscopy

Raman spectroscopy uses high-frequency laser beams to excite materials, causing them to emit photons. Although sub-micron size analysis is possible, the current smallest detectable size is 10 µm, with expectations to reduce this to 2 µm in the future. Current studies use near-infrared lasers at 785 nm to reduce fluorescence [68]. Presently, both µ FT-IR and micro Raman (µ Raman) spectroscopies allow for the direct analysis of small microplastics on filters without the need for visual pre-sorting, opening the possibility for automation. The preferred filter in use is the Anodisc (aluminum oxide) with a pore size of 0.2 µm. Studies by K. Sarmite *et al.* [33], and A. Steve *et al.* [38, 69] also use this filter for analysis. Both µ FT-IR and µRaman are effective in identifying MPs > 20 µm, with advancements enabling automated analysis and counting of MPs. Compared to µ FT-IR, µ Raman spectroscopy theoretically allows for the analysis of MPs down to sizes below 10 µm. In practice, published studies from 2015 to the present, when using a combination of visual methods with µ FT-IR and µRaman spectroscopy, have only detected the presence of MPs in the air at sizes of several microns or larger (mostly > 10 µm). The analysis of microplastics < 1 µm in environmental samples remains in the early stages of technological advancement [79]. Meanwhile, fine and ultrafine dust particles generally have a significant impact on human health.

Pyrolysis-GC/MS

The pyrolysis-GC/MS (Pyr-GC/MS) method is conducted by pyrolyzing the sample at high temperatures in a pyrolysis device, producing volatile or semi-volatile products. These products are then directly injected into the GC/MS system for further analysis, similar to conventional GC/MS methods. However, this method cannot determine the shape and size of particles, as the MnPs are pyrolyzed and transformed into other compounds during analysis. To achieve high efficiency using this method, the particle size needs to be smaller than 100 µm [79].

If MnPs in the air are sampled by size fractionation, using a cascade impactor to collect dust fractions such as $PM_{0.1}$; 0.1 µm < PM < 0.5 µm; 0.5 µm < PM < 1.0 µm; 0.1 µm < PM < 2.5 µm, etc., and each fraction is analyzed on a Pyr-GC/MS system, it is possible to identify the type of polymer within the corresponding size range. Thus, combining the size-fractionated air sampling method for MnPs with Pyr-GC/MS analysis can help address the limitations in current studies of MnPs in the air.

Although Pyr-GC/MS is an advanced method for identifying microplastic composition, its application to MnPs in the air remains uncommon due to equipment limitations, complex analytical procedures, and the requirement for highly skilled technicians. Recently, some authors such as Elvis D. Okoffo *et al.* [80] and Risa Nakano *et al.* [81] have used this technique to identify MnPs in water and in *Daphnia magna* (a freshwater crustacean). However, due to the complexity of environmental samples, pyrolysis may generate many different products, causing interference in the analysis spectrum. Additionally, the pyrolysis products are highly dependent on the pyrolysis temperature. Therefore, many factors must be considered to confirm the marker of a specific polymer present in the sample.

7. CONCLUSIONS

MnPs are an emerging global pollutant. Research on their presence in ambient air was first published in 2015. In recent years, the number of studies on airborne MPs has steadily increased. However, studies on NPs remain limited, and there is almost no concrete data on their presence in ambient air.

The occurrence of MPs in ambient air, along with their concentration as well as physical and chemical characteristics, has been identified across various environments worldwide, ranging from urban and industrial areas to coastal regions, oceans, and even remote mountainous areas with no human activity.

Sampling methods for MnPs in the air include atmospheric deposition sampling and suspended particulate sampling. Atmospheric deposition samples are more prevalent in published studies than suspended particulate samples.

The method for atmospheric deposition sampling of MPs is passive sampling, utilizing glass or metal funnels to collect dust, with a connected container placed under the funnel to gather both dry and wet deposition (rainwater). Airborne MPs are collected using air pumps in active sampling methods. The filters used during the sampling process vary in material and pore size. Currently, there are no standardized protocols for MnP air sampling.

Stereomicroscopy, along with µ FT-IR and µ Raman spectroscopy, are the primary instruments used to characterize the physical and chemical properties of atmospheric MnPs. Before being analysed on these instruments, samples are often treated with H_2O_2 to remove organic matter and then separated using a high-density solution like $ZnCl_2$ to isolate MnPs from the sample.

Current sampling and analytical methods are insufficient for the full identification and classification of NPs. The lack of standardization in sampling methods not only complicates the comparison of study results but may also lead to inconsistencies in scientific findings. In the future, it will be necessary to develop and apply specialized active and passive sampling methods for both MPs and NPs, along with more sensitive analytical techniques, such as electron microscopy or advanced methods like pyrolysis-GC/MS for detailed chemical characterization of NPs.

International collaboration is also required to establish common standards for analyzing MnPs in the air. This will not only facilitate the creation of a global database on the presence and distribution of MnPs but also allow future studies to be easily compared and cross-referenced.

In summary, significant progress has been made in understanding atmospheric MPs, but research on NPs is still in its infancy. To better understand their impact on the environment and human health, more in-depth research efforts are needed, along with improvements in analytical methods and standards to effectively monitor and control this emerging pollution issue.

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Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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