Anthropocene airborne microfibers: physicochemical characteristics, identification methods and health impacts

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Abstract

The toxicity of fibrous particles in ambient air can be higher than that of particles of other shapes; a phenomenon referred to as the fiber paradigm. Microfibers (MFs) can be classified into organic and inorganic types. Airborne inorganic fibers originate from the suspension of dust from roads, construction sites, industries, and also natural dust storms. While the use of carcinogenic mineral fibers, such as asbestos, is now restricted, their substitutes, such as artificial mineral fibers, are still widely used due to their comparable properties. With the rapid growing consumption of plastic products in recent decades, plastic MFs have emerged as a new source of anthropogenic pollutants, as well as markers of the Anthropocene, focusing scientific attention in terms of environmental concerns. MFs in the ambient atmosphere can lead to adverse human health effects following ingestion via the gastrointestinal tract or inhalation through the respiratory system. Accurate collection and identification of MFs, standardization of analysis procedures, and the understanding of the underlying health hazards are critical for scientists and governments to develop public health mitigation strategies. This review classifies ambient atmospheric MFs according to their morphology and compositions. Current understandings on the physical and chemical characteristics of mineral and plastic MFs are summarized. A comparison of the various identification methods used for atmospheric MFs is presented, and a standardized protocol is proposed. The toxicity and health impact mechanisms of atmospheric MFs are also discussed. We recommend the development of sensitive, accurate and rapid detection methods, with a strong emphasis on source apportionment.

Keywords

Anthropocene; Atmospheric; Classification; Human health; Identification methods; Microfibers; Physiochemistry; Plastics; Toxicity

1. Introduction

1.1 Microfiber pollution

Microfibers are any natural or artificial fibrous materials of threadlike structure with a diameter less than 50 μm, length ranging from 1 μm to 5 mm, and length to diameter ratio greater than 100 [1]. Inhalable fibers, defined by the World Health Organization, are particles with a length >5 μm, diameter <3 μm, and a length : diameter ratio of >3, and are potentially harmful to human health [2]. MFs widely exist in ambient air and display various configurations, including mineral and organic particles, with even some fly ashes containing fiber aggregates [3]. Similar to airborne particulate matter (PM), such as PM_{10} and $PM_{2.5}$ (particles with an aerodynamic diameter less than or equal to 10 and 2.5 micrometers), MFs have distinct toxicological mechanisms and health effects (Table 1) according to their physiochemical properties and sources. Studies have shown that the toxicity of fibrous atmospheric particles can be more serious than that of other shapes, i.e., the fiber paradigm [4,5] (Fig. 1). This paradigm delineates the importance of length, thinness and biopersistence to a fiber, whereby the absence of one or more of these physicochemical properties results in a loss of pathogenicity [6]. MFs in the ambient atmosphere mostly enter the human body through inhalation, however, the fibers can also be ingested. Once internalized, these pose a potential threat to human health [7] (e.g., inflammation, fibrosis and cancer).

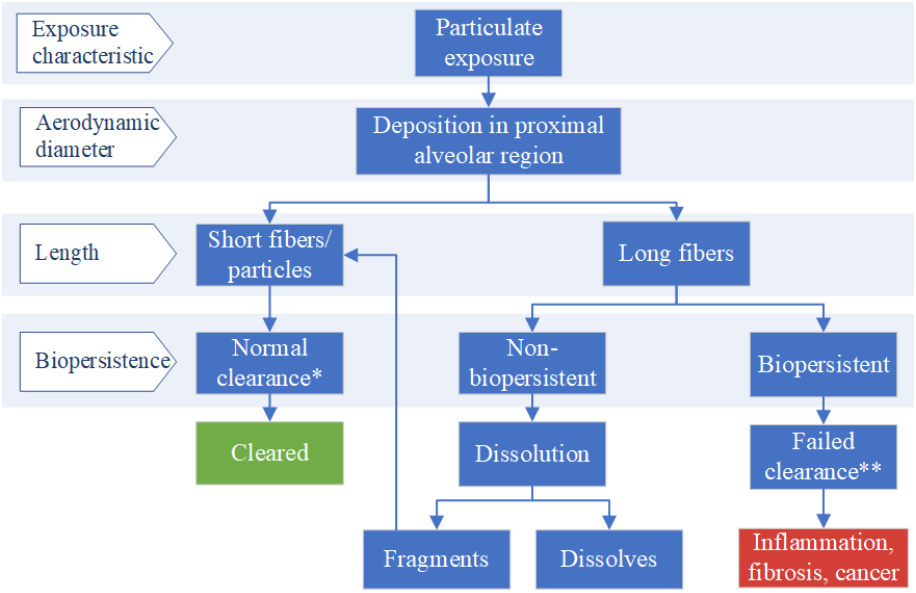

Fig. 1. The influence of length, thinness and biopersistence to fibers. * = normal clearance by alveolar macrophages. ** = failed clearance due to frustrated phagocytosis.

Table 1. Classification and characteristics of MFs in the ambient atmosphere.

Group	Type	Sub-type	Morphology	Elemental composition	Possible sources	Health effects
Inorganic MFs	Natural mineral MFs (Fig. 4)	Sulfate	Regular	S, Ca, K	Natural minerals, atmospheric heterogeneous reactions	Hazardous elements release. Malignant pleural mesothelioma [8,9].
		Silicate	Regular/ Irregular	Al, Si, Fe, Ca, Mg, K Si, O		
		Oxide Carbonate	Regular	Ca, Mg, O		
	Man-made mineral MFs (Fig. 5)	Silicate	Regular	Al, Si, Ca, Mg, K, O	Building materials Decorative materials,	
		Metal	Regular	Mg, Cr		
Organic MFs	Plastic MFs (Fig. 6)	Regular, spiral, smooth surface	Regular	C, H, O	Textile, plastics	Plastic additives release [10]
	Natural organic MFs (Fig. 8)	Tubular, textured surface	Regular	C, H, O, N, P	Bacteria, fungi, plants	Allergies

1.2 Microfibers in the atmosphere

MFs in the ambient atmosphere have numerous, heterogeneous and complex sources. Since the end of the 19th century, natural mineral fibers have been widely used in many industries due to their high heat resistance, insulation properties, tensile strength and durability [11]. Since the beginning of the large-scale production of plastics in the 1950s [12], the release of plastic waste has increased year by year over

the globe [13]. Disposable plastic waste from medical products has increased significantly since the COVID-19 pandemic [14]. MFs in the ambient atmosphere are derived from the aging of plastic products, wear and tear of building materials, emissions during cleaning and laundry, and tire wear [15,16]. The morphological characteristics and chemical compositions of airborne MFs differ from source-to-source, which can be used to facilitate their source apportionment.

Although airborne asbestos fibers are now rare, other inorganic MFs in the atmosphere are of significant concern. The dangers of natural mineral fibers to human health were recognized as early as the 20th century, as these MFs can be easily transported and dispersed into the atmosphere, soil or water due to their small size and light density [17,18]. The International Agency for Research on Cancer (IARC) listed asbestos as a class I carcinogen in 1987 [19], and later, erionite, a fibrous form of natural zeolite that has physical characteristics resembling amphibole (2012) and fluoro-edenite, a non-asbestos mineral fiber (2017), were also listed as carcinogens by IARC [20] (Fig. 4 k,l). Although the use of asbestos for new construction is now forbidden in most countries, the existing asbestos in buildings are still managed rather than being removed [21]. Nevertheless, asbestos products remain in use in some regions, and various substitutes such as other natural 'asbestiform' mineral fibers (Fig. 4) and man-made mineral fibers (MMMFs) (Fig. 5) have been used in various industries. Some inorganic fibers are similar in composition, shape, surface behavior, or bio-durability when compared to regulated carcinogenic fibers, and their potential health hazards have not received an adequate attention from toxicologists [20]. This indicates that further study is needed on determining the types, characteristics and toxicology of inorganic fibers.

1.3 A new type of air pollution particle

Plastic MFs, as a newly recognized type of air pollutant, are ubiquitous in the global environment, and their ecological and health effects have attracted increasing attention, even becoming a marker of the Anthropocene [22]. In 2014, the United Nations Environment Programme formally listed microplastics (MPs) as one of the top

ten global environmental problems to be resolved [23]. Under the long-term effect of solar radiation or physical, chemical, and biological degradations, plastic products can be decomposed into micro- or nano-plastic particles, and pollute the soil, water, and atmosphere. Currently, most research concentrates on MP pollution in water and soil environments (Fig. 2). Under the influence of geological processes and activities, plastics have accumulated in sediments and have become part of Earth's geological spheres, termed as the 'plastisphere' [24,25], with evidence of a new types of plastic material incorporated into the environment as a 'plastic-rock' system [26]. Researchers found that carbon atoms at the surface of the polyethylene films were chemically bonded to silicon in the rock with the help of oxygen atoms [22]. These plastic-rock complexes serve as hotspots for MP generation, since the rates of generation in environmental plastic-rock systems are orders of magnitude greater than those reported in laboratory experiments [26]. MPs with strong biological durability, i.e., slow degradation rates, threaten the ecology and environment, as well as human health. The relatively small size of atmospheric MP particles means that if internalized into the human body the potential health risk could be greater. In recent years, it has been established that atmospheric transport is the main mechanism for MPs to enter remote areas [27].

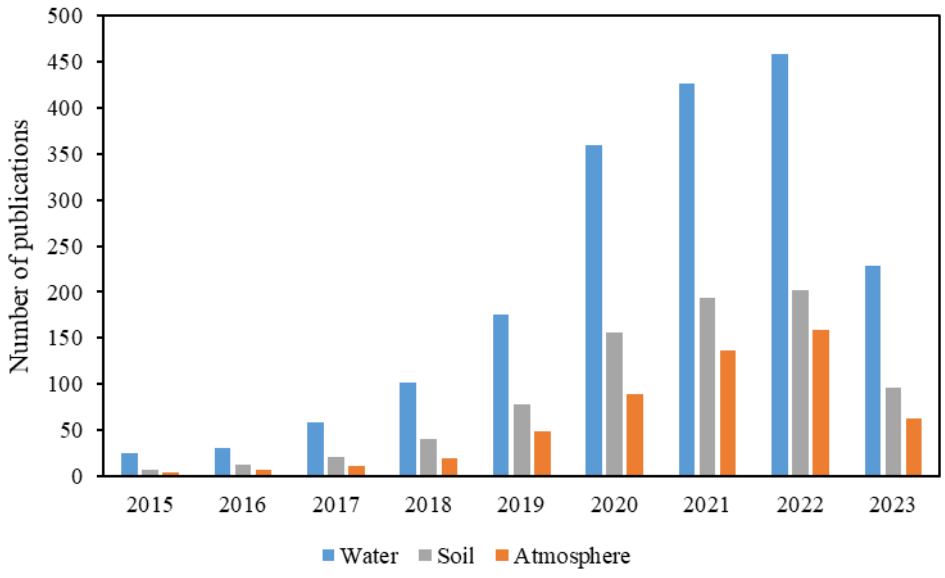

Fig. 2. The number of publications focused on MF pollution in the water, soil, and air. The data are obtained from the Web of Science Database (Date of data acquisition:7/6/2023).

1.4 Inorganic and organic MFs

MFs can typically be identified by their physical characteristics and chemical compositions, using a large variety of techniques. Crystallographic methodologies can distinguish natural mineral MFs and MMMFs. However, many studies of inorganic MFs in the atmosphere are limited to low-resolution instruments, such as light or petrographic microscopes [28]. In studies identifying asbestos, MFs can be collected on membrane filters, sized and counted at reasonably high magnification, with the outline of the MFs [29]. Optical microscopes are widely used for asbestos identification, allowing the specific mineralogy of the asbestos fibers to be identified. High-precision electron microscopes are employed for detailed morphological and chemical analysis rather than routine identification and determining fiber burden due to their higher cost.

1.5 Characterisation and classification of MFs

Visual identification using bench-top microscopy can distinguish plastic MFs from other particle types based on their physical properties and appearance, including elasticity, hardness, color, luster and structure [30]. By using appropriate instruments (e.g., RS, FTIR, and SEM), not only can the plastic MFs be visually identified, but also the functional group, and physicochemical properties can also be determined. The identification of plastic MFs can be rapidly undertaken using a fluorescence microscope and dyeing the fibers with a specific stain like Nile Red [31]. The more precise identification of plastic MF types is usually conducted using instruments equipped with high-precision spectra (e.g., hyphenated scanning electron microscope (SEM)-Raman system) [32]. However, the study of plastic MFs is a relatively new field of research and sampling methodologies (Fig. 3) have not been universally standardized.

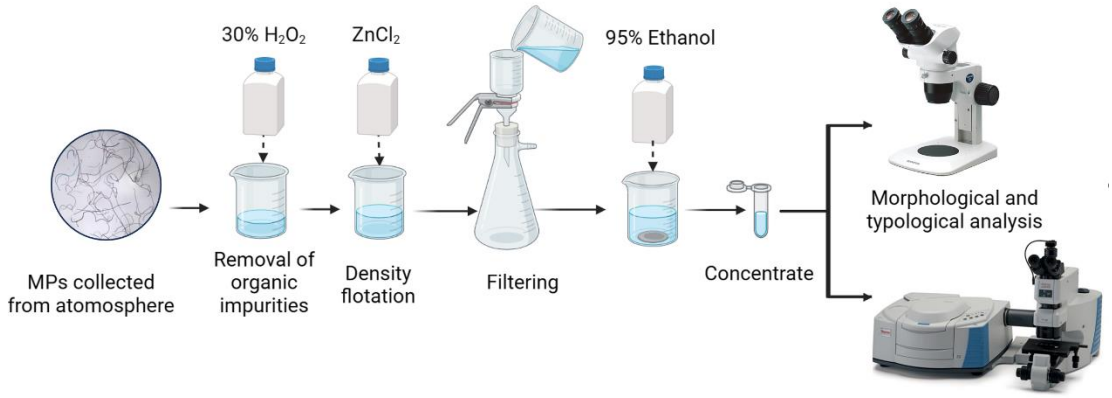

Fig. 3. Common treatment processes for characterizing atmospheric MPs. MPs are treated with H_2O_2 to remove organic impurities. Zinc chloride solution is used for density separation. 95% ethanol is used to concentrate microplastics. The morphology of MPs is analyzed by stereo microscope, and the type is determined by spectrometer.

Although research on the characteristics and types of MFs in the ambient atmosphere is increasing (Fig. 2) [33], there is a paucity of information about this new area of atmospheric research. Firstly, many studies only focus on specific MFs (e.g., plastics, vehicular tires, building materials, synthetic textiles, personal hygiene products, and furniture finishings), thus lacking a comprehensive overview of all types of MFs in the atmosphere. The classification of atmospheric MFs is often not clear, resulting in comparative challenges when analyzing different statistical datasets. There is also a lack of accepted standardized procedures for the monitoring, collection, and physiochemical characterization of MPs. Moreover, the data outputs (i.e., morphological, and chemical) from the use of a wide range of analytical equipment may lend bias over the research results.

This review has classified atmospheric MFs according to their origins and physiochemical compositions. The relative merits of different identification methods have been addressed, along with a proposed standardized procedure for categorization. The potential effects of MFs on human health, environment, climate, and ecology have been discussed. The assessment and management of MF pollution in the atmosphere and recommendations for future research directions have been considered.

2. Types and physicochemical properties of atmospheric MFs

2.1 Types of atmospheric MFs

MFs in the ambient atmosphere can be sub-divided into inorganic and organic categories. Inorganic MFs include natural mineral fibers (Fig. 4) and MMMFs (Fig. 5). Organic types include synthetic plastic MFs (Fig. 6) and natural organic MFs (Fig. 8) (Table 1).

Natural mineral fibers are crystalline, and their crustal sources in the atmosphere are predominately derived from dust storms and fugitive dusts. MMMFs are fibrous industrial materials, typically amorphous or cryptocrystalline, and produced by the melting of glass or rock (e.g., basalt), slag (e.g., residue from smelting processes), and clay. They include glass fibers and wools, rock wools, slag wools and refractory fibers [34]. The sources of plastic fibers are derived from factory production, abrasion of plastic products, washing of clothes and use of common household products. The main components are C and H. Natural organic fibers are mainly composed of C, H, O, N, and P, including sporopollenin (i.e., chemically inert biological polymer derived from outer walls of plant spores and pollen grains), wool, and cotton.

2.2 Physicochemical properties of atmospheric MFs

2.2.1 Physicochemical characteristics of natural mineral MFs

Natural mineral fibers (Fig. 4) in the ambient atmosphere have been extensively studied [28,35]. Among these, asbestos fibers have been of most concern, and are contained in several types of rocks such as serpentinite, magnesite and ultramafic rocks [36]. Six asbestos minerals are included in the asbestos exposure standards, including chrysotile, amosite, crocidolite, tremolite, actinolite and anthophyllite [2,8,9,37]. Chrysotile asbestos, commercially referred to as ‘white asbestos’ has been the most commonly used asbestos [38]. The fibers appear as slender and curved when observed under light microscopy [24,37,38] (Fig. 4j). They are resistant to elevated temperatures and corrosives, i.e., ‘biopersistent’ (Table 3), in the environment [7].

Other natural mineral fibers include antigorite and balangeroite [40,41], the

amphiboles winchite, richterite and fluoro-edenite [42] and erionite [20,43]. Talc and some clay minerals are referred to as 'elongate' mineral particles (EMPs) [44]. EMPs are not strictly regulated and may be as dangerous as regulated asbestos because of their similar physical and chemical properties. For example, mullite occurs naturally in baked clay layers between volcanic flows (Fig. 4). However, in the ambient atmosphere it is found in partially recrystallized industrial coal fly ash. In typical spherical fly ash particles, mullite is a refractory mineral forming fibrous scaffolding crystals in an amorphous matrix [45]. The biological durability of mullite is greater than the matrix [3]. After exposing rats to fly ash for 6 months, Rothenberg et al. (1989) found that about 1% of the particles in the rats lungs were fibers [46]. Thus, mullite does not exist, as far as we know, as free atmospheric fibers, but fibers can be released in the lung once a fly ash particle has been respired. The toxicity of these mullite fibers is still unclear.

Mineral MFs can also be sub-divided into insoluble and soluble types. Insoluble MFs include asbestos, zeolites, and other refractory minerals. Soluble mineral MFs, such as epsomite (Fig. 4h), are morphologically similar to carcinogenic insoluble mineral fibers. The surface of epsomite is often covered by regular-shaped fragments and irregular-shaped nanoscale particles (Fig. 4f) containing trace elements (As, Co, Fe, Mn, Ni, Sr, Ti, Zn) and radioisotopes (^{210}Po and ^{228}Th), which have been suggested to be carcinogenic in the lungs [8,9].

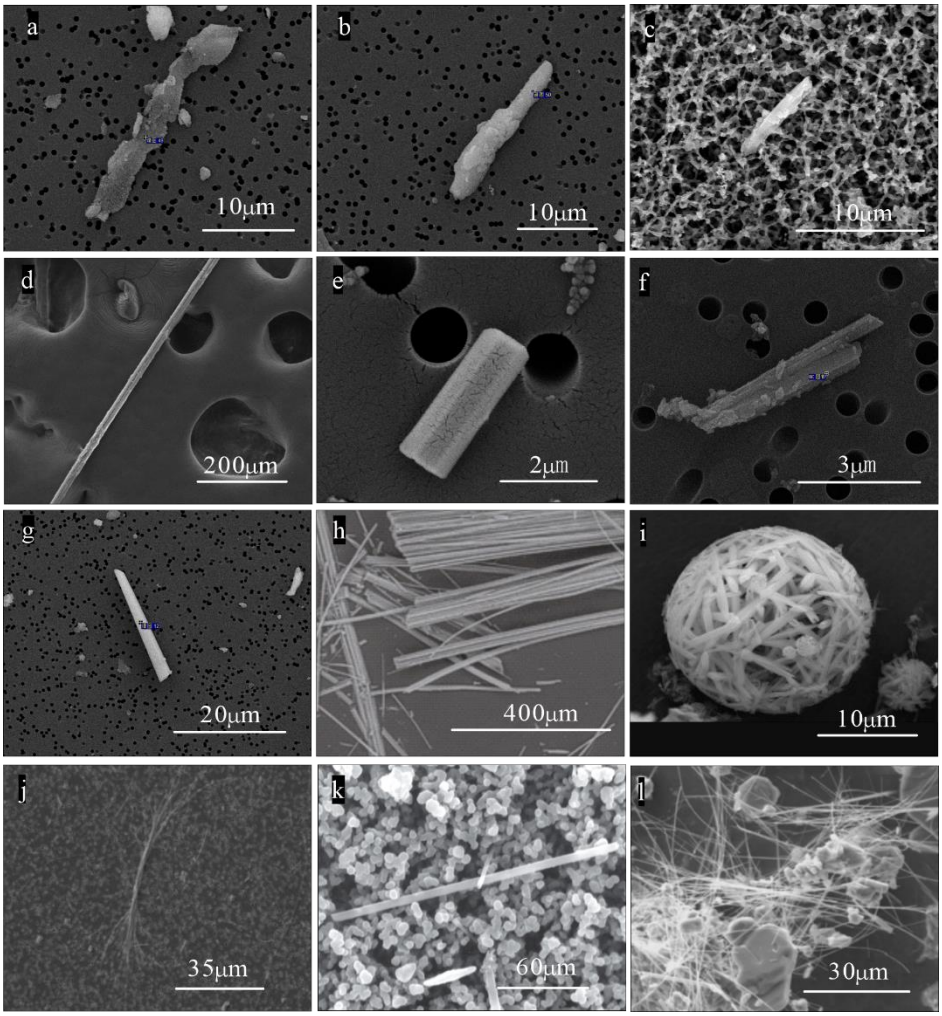

Fig. 4. SEM secondary electron images of natural mineral MFs (a, b- Silicate MF; c, d- Asbestos MF; e, f- Sulfate MF; g- Carbonate MF captured and imaged on polycarbonate filters, h- Epsomite [9]; i- Mullite [3]; j- Chrysotile asbestos [47]; k- Erionite [48]; l- Fluoro-edenite [49].

2.2.2 Physicochemical characteristics of MMMFs

The MMMFs are commonly used as substitutes for previously-used asbestos and other natural mineral fibers [50], and are recently widely used as insulating materials. They are amorphous inorganic fibers produced from glass, rock, slag, or other processed mineral materials as their raw materials. The salient features of MMMFs include their smooth surfaces (Fig. 5), and consistent chemical compositions (Table 1). Zeng [34] compared the dissolution rates and times of MMMFs against asbestos in human lung fluid, with both materials having original diameters of 2.5 μm (Table 3), demonstrating the lower biological durability of glass fiber. The lower biodurability is

partly due to microscopic cracks on the surface of the glass fibers that were created during the manufacturing process of 'wire drawing'. The damaged surfaces of the glass fibers can contain some hydrophilic cations, so that the crack can expand and deepen under the attrition of the lung fluid, and the fiber integrity decreases, accelerating biologically mediated dissolution rate. Numerous studies have shown that fiberglass is not carcinogenic or won't cause serious diseases [51], though it is now regulated as a nuisance dust. The principal difference between asbestos and glass fibers is that glass fibers are single fibers that break across the fiber as opposed to asbestos that splinters along the length of the fiber. This facilitates lung clearance and prevents the initiation of serious diseases. However, as a nuisance dust, glass fibers can cause eye, skin (i.e., dermatitis) and respiratory tract irritation. Aluminosilicate refractory fibers will persist longer in the deep lung than glass and rock wool (Table 3). Moreover, compared with other MMMFs, aluminosilicate refractory fibers are usually smaller in diameter, and easily inhaled [34] and are considered hazardous in occupational settings [52].

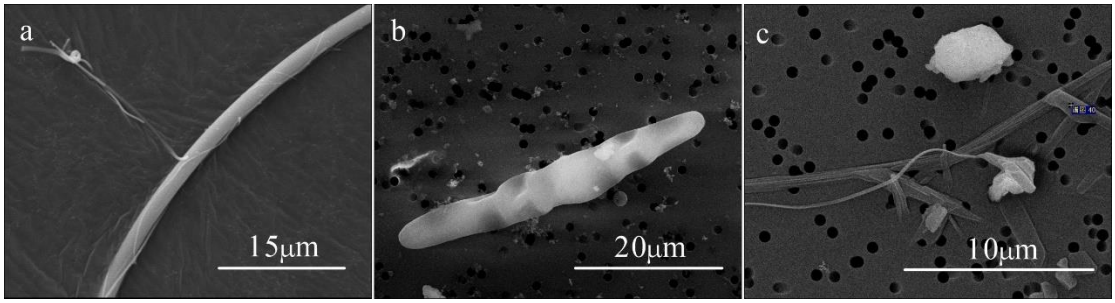

Fig. 5. SEM secondary electron images of MMMFs, (a- Glass wool; b- Man-made siliceous fiber; c- Magnesium metal fiber) captured and imaged on polycarbonate filters.

2.2.3 Physicochemical characteristics of organic MFs

Plastic MFs are from artificially manufactured materials and can function as carriers for numerous additives. Their physical and chemical characteristics are the basis of toxicological assessments. Airborne MPs can be sub-divided into 5 groups according to their morphologies [53]:

(1) Cylindrical fibers with a consistent thickness.

(2) Irregular flat fragments.

(3) Films that are thinner than flat fragments.

(4) Rounded or spherical particles (granule).

(5) Aged particles with rough surfaces and broken edges.

Atmospheric plastic MFs (Fig. 6) are generally composed of a single chemical compound, and do not display internal structures. They are often colorful, including amongst others blue, purple, red, white, black, and transparent. With the aim to minimize identification errors during microscopy, the following preliminary identification criteria for MPs over the size range of 0.5-5 mm were proposed [54,55]:

(1) The particles have no visible organic tissue and cell structure.

(2) The particles do not break during stretching and extrusion.

(3) The color of the particles is uniform.

(4) The fibers are not segmented, and the thickness is uniform.

(5) The particles are not shiny.

The main polymer types reported in worldwide studies [15] are polyethylene, polypropylene, polyethylene terephthalate, polyvinyl chloride and polystyrene.

The typical distribution of MPs shapes in the atmosphere does not resemble that found in other environments such as water or sediment. Fok [56] summarized 91 studies on the shape of MPs in water and sediments in China, and found that fibers were the most dominant shape. Most studies [53,57–62] in the ambient atmosphere also indicated that fibers are the main shape of MPs (Fig. 6). However, a study in Germany [63] found the highest proportion of shapes in atmospheric fallout was fragments. It is recommended that a standardized shape description is required for future studies, given the discrepancies between the shape descriptors (e.g., cylindrical, irregular flat, films, rounded, aged) in Liu et al. (2022) [53] and the data (i.e., fiber, fragment, film, granular, other) shown in Fig. 6.

Semi-synthetic fibers are regenerated cellulose fibers typically used in clothing with trade names such as Rayon, Modal, Lyocell and Cupro. They are made from

natural cellulose fibers that are chemically modified to improve their physical clothing properties such as water resistance, stain proofing, wrinkle free and antistatic. Clothes made from these materials are known to shed fibers during their lifetime. In some studies, semi-synthetic fibers are classified as plastic [58]. Studies in many regions have shown that semi-synthetic fibers, almost certainly shed from clothing into the ambient atmosphere, are even more common than synthetic plastic fibers [64].

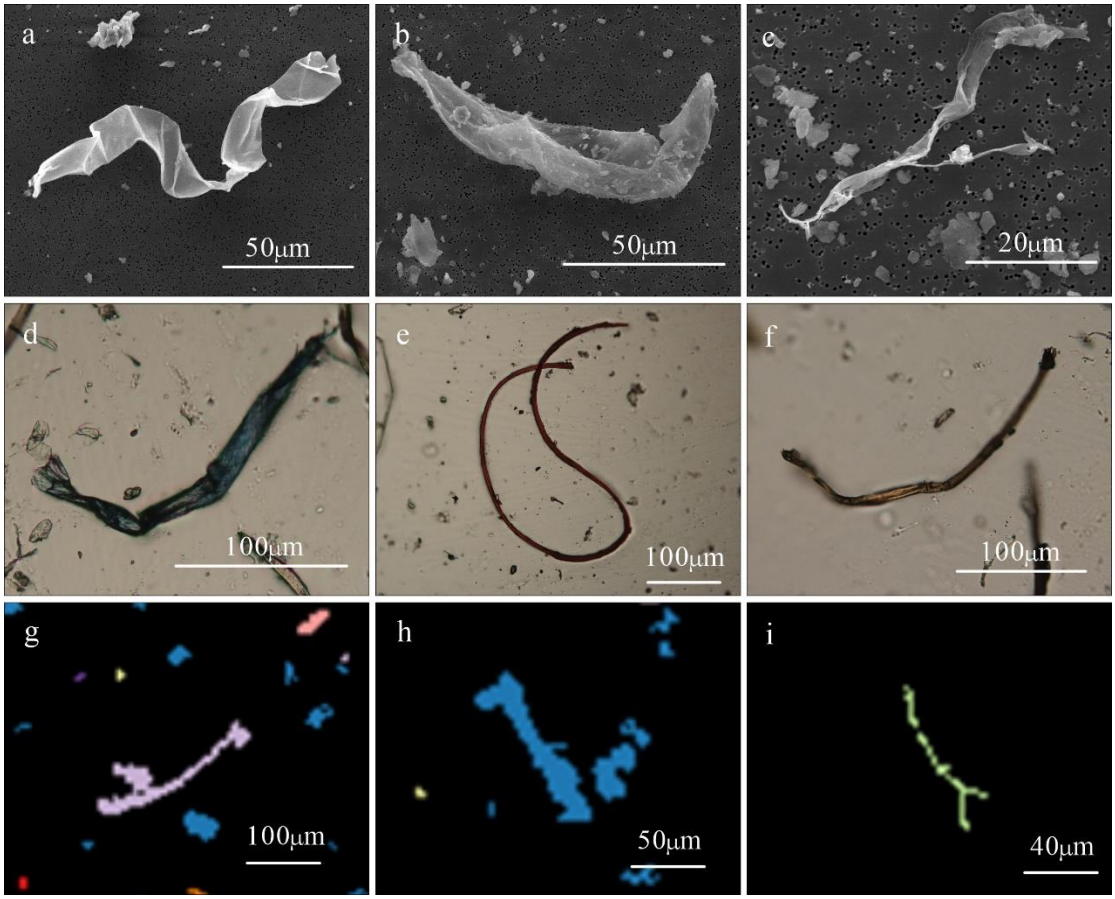

Fig. 6. Images of atmospheric plastic MFs (a, b, c- SEM secondary electron images of plastic MFs captured on filter substrates; d, e, f- Optical microscope transmitted light images of plastic MFs mounted on glass slides, d- Plastic MF in blue; e-Plastic MF in red; f- Plastic MF in yellow; g, h, i- Laser direct infrared microscope image of plastic MFs imaged on corrected slides.

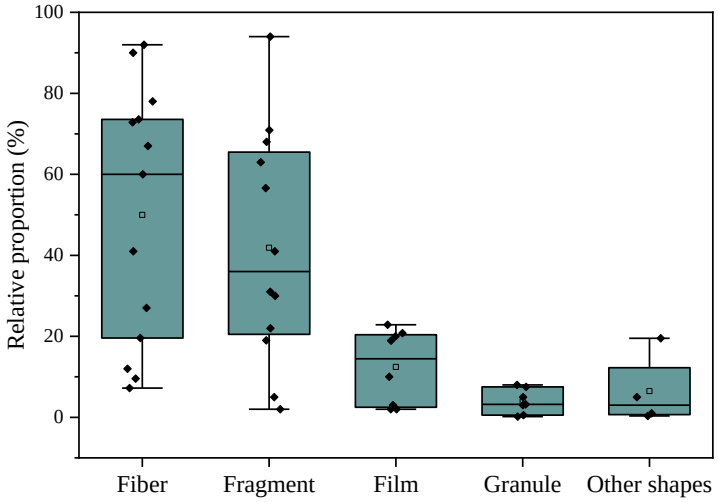

Fig. 7. The proportion of different shapes of atmospheric MPs in different regions including Beijing, Xi'an, Shanghai, Shihezi city, Mexico, Hamburg, London, Victoria, west Pacific Ocean, Christchurch, New Zealand, French Pyrenees, Persian Gulf [53,57–63,65–69].

In addition to man-made plastic MFs, which are the main component of organic MFs, there are also natural organic MFs in the atmosphere. C, H and O are the main elements of these natural organic MFs, which can be identified using analytical SEM. Sporopollenin microfibers (Fig. 8c-f) are a large fraction of bioaerosol particles, and their surface is smooth, striated, or rough. Natural fibers can also be derived from anthropogenic sources such as cotton or wool clothing. Although the elemental composition of various natural organic MFs is similar, their morphology can be quite different when seen under microscopy. Cotton MFs (Fig. 8a) are very distinctive with a twisting morphology and regular wrinkles on the surface [70]. The most obvious feature of animal hair MFs, such as pet dogs or cats, are regular scales on the surface (Fig. 8b) [71].

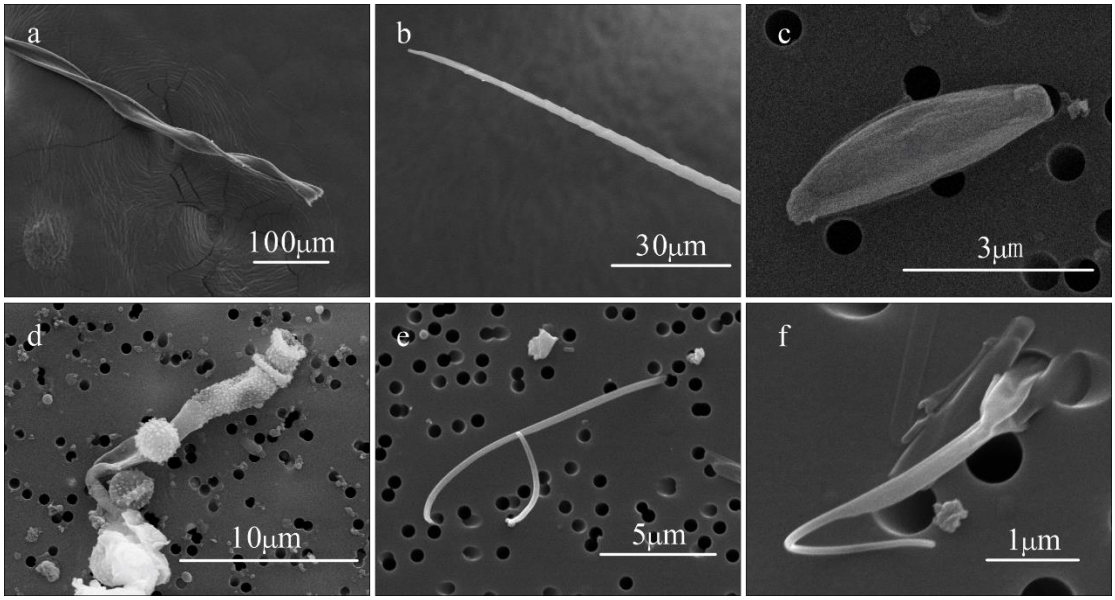

Fig. 8. SEM secondary electron images of natural organic MFs (a- Cotton MF; b- Wool MF; c, d, e, f- Sporopollenin MFs) captured and imaged on polycarbonate filters.

2.3 Spatial and temporal distribution of MFs

Human activities are the determinant factor for the emission of MFs, especially plastic fibers. Mineral MFs concentrations tend to be higher in mines and construction sites, compared with other areas [72]. In contrast, the concentration of MPs in urban areas is usually significantly higher than in rural areas [59]. The source analysis of atmospheric MPs by Liu et al. (2022) showed that fragments were sourced mainly from industrial activities, whereas films and fibers were affected by traffic flows and routine human activities [66]. It is generally believed that the intensity of human activity plays a significant role in the concentration and type of MFs in ambient air.

Meteorological factors influence the transport of airborne particles, and therefore, have an effect on the distribution of MFs. However, the correlations are complex and sometimes contradictory [69,53,58]. Statistics show that in areas of natural asbestos occurrence in geological formations, asbestos concentrations in the air are affected by ambient humidity ($R = -0.811$) and temperature ($R = -0.757$) [73]. The wind direction, wind speed, and rainfall may influence the deposition flux of MPs [61]. A study in Xi'an, China, showed that the abundance of atmospheric plastic MFs was highest in spring [53], revealing the seasonal influence. However, the research by Shruti et al. (2022) did

not recognize a correlation between the distribution of MPs shapes and seasons [58]. Hu used Atomic Force Microscope-Infrared Spectroscopy (AFM-IR) to study the effects of heat on the physical and chemical properties of MPs, and found that increasing temperature leads to a significant increase in brittleness and subsequent higher release of plastics into the environment [74]. Atmospheric transport is an efficient mechanism for the diffusion of plastic MFs due to their small size and density [75]. Approximately 75-90% of plastic MFs derived from land-based sources are ultimately deposited into the marine environment [76]. Therefore, atmospheric MPs will eventually pollute both terrestrial and marine ecosystems through deposition [77,78]. In addition, MPs may enter the atmosphere from the land because of wind re-suspension. Studies have shown that MPs might also be released from water and transferred to the atmosphere through a natural process called 'bubble bursting' [79]. The mobility and interconnectivity of the land, atmosphere, and water environments means that MPs can diffuse and transfer between all of these environments.

3. Sampling and identification methods of atmospheric MFs

3.1 Sampling methods for atmospheric MFs

Atmospheric MFs can be collected using the methods and equipment commonly used to collect other airborne particulate pollutants such as PM_{10} and $PM_{2.5}$ and Total Suspended Particles (TSP). These methods can be sub-divided into active and passive sampling [80].

Active sampling systems typically consist of an electric vacuum pump, single or multi-stage particle cut-off impactors (to separate the different size fractions), and filters or substrates to load particles. These sampling methods can also obtain data on the sampling time, air volume processed, and the number or weight of collected particles, based on which the atmospheric concentration of MFs can be calculated. An advantage of active sampling is that it can quantitatively collect atmospheric MPs from outdoor or indoor air at different heights. Li et al. (2020) collected TSP using a Minivol sampler at a height of 1.5 m above the ground surface [81]. A disadvantage is that

depending on the type of instrument and PM concentration levels, the amount of collected particles may be small, resulting in a limitation in terms of material available for sample analysis. Cellulose ester membrane polycarbonate or nucleopore filters are the preferred membranes for active fiber sampling [82]. The pores in nucleopore filters are of uniform size, and their collection surfaces are smooth, which is useful for visual or microscopic analyses, however, concerns have been raised about possible particle 'bounce-off' , and subsequent loss of sample, when using these filters. Cellulose ester membrane filters must be treated with acid and alcohol-based solvent to collapse the sponge texture into a thin and continuous plastic film allowing better fiber recognition [29]. The use of fibrous filters, such as quartz or glass fiber filters, is not recommended since they hamper visual identification.

A common passive sampling method is to collect atmospheric settling, or 'dust fall' particles using stainless steel funnels and glass containers. The funnels have a smooth surface that facilitates the atmospheric sediment sliding into the glass bottles or other containers. Another semi-passive sampling method is to use a vacuum cleaner or fine brush as collection tools to collect a measured area or weight of dust, then transfer the dust to a sample bag. Evangeliou et al. (2020) collected fallout samples using Aerochem Metrics model 31 wet/dry collectors (ACMs), which included precipitation sensors that opened the wet bucket, and closed the dry bucket during precipitation and vice versa [83]. Liu et al. (2022) collected the atmospheric dust fall with an antistatic brush and dustpan and stored the bulk samples in a sealed aluminum foil bag [69]. Passive sampling methods are ideal for atmospheric deposition of particles because of simplicity and convenience, as they do not require a power source and are suitable for outdoor and long-term sampling [80]. Weather conditions may affect the quality of sampling, so it is necessary to record these in detail to assess the impact of weather on atmospheric deposition [77]. Collected samples containing plastic MFs might require additional processing such as chemical digestion and flotation for enrichment, and contamination can also be an issue (Fig. 3) [63,84].

3.2 Identification methods of atmospheric MFs

3.2.1 Identification of mineral MFs

1) Morphological analysis of inorganic MFs

Optical microscopy is a common method to observe the morphology of MFs. Both phase-contrast optical microscopy (PCOM) and polarized light microscopy (PLM) can be used to count and characterize the shape and profile of MFs with widths over 0.25μm. PCOM is an optical microscopy technique that converts phase shifts in light passing through a transparent specimen to brightness changes in the image [29]. Although the PCOM method is relatively fast and inexpensive, it cannot analyze MFs with widths less than 0.25 μm [28]. Some fibers and crystalline particles are birefringent, and can be distinguished from other particles by PLM [17]. PLM can be used to mineralogically identify asbestos fibers according to their parallel extinction along the fiber axis, but the detection limit of PLM is also quite high (>1 mm) [85]. For finer asbestos fibers collected from the ambient atmosphere, Van Orden et al. (2008) summarized the rule of differentiating asbestos and non-asbestos MFs by microscopic morphology, that is, the cleavage and terminal morphology generated by the breakage of the two are different [86].

Electron microscopy such as SEM, transmission electron microscopy (TEM) and atomic force microscopy (AFM) are accepted methods to characterize the microscopic morphology of MFs [87,88]. Eypert-Blaison et al. (2018) compared the effect of PCOM and TEM in the determination of mineral fiber concentration in atmospheric PM samples, and concluded that PCOM underestimated the concentration of MFs [89]. The microstructure of the surface of an individual particle can be observed by SEM [18]. TEM is mainly used to study the internal structure of single particles [35]. The preparation of samples for TEM analysis is more complex and time-consuming compared to SEM. The resolution of AFM is much higher than SEM and the observation of particle surface morphology is more specific, however, AFM images can be hard to interpret. Cho et al. (2013) developed a high-throughput microscope (HTM) system that enables the automatic counting of fibers with minimal human intervention [90]. However, HTM can only be used for asbestos in solution with the feasibility

improved by dispersing the asbestos fibers in solution.

2) Composition analysis of inorganic MFs

X-ray diffraction (XRD) can identify the mineralogy of natural mineral MFs from the crystal structure [18]. For MFs with similar morphology, chemical and physical properties, Micro-Raman Spectroscopy (Micro-RS) can also distinguish the types of minerals [91]. Additionally, Micro-RS can characterize fiber minerals without sample preparation, avoiding anthropogenic contamination [87]. Infrared spectrometry (IS) is suitable for the characterization of clay mineral fibers, because only the clay mineral fiber's spectrum is stable, which makes it possible to distinguish them [92].

Selected Area Electron Diffraction (SAED) can be used to distinguish mineral and non-mineral fibers. When the electron wave strikes the crystalline mineral, it is scattered by the atomic structure of the crystal producing recognizable electron diffraction patterns. Crystalline MFs will generate diffraction patterns of regularly distributed spots in concentric circles, whereas amorphous MFs will generate a series of dispersed concentric circles. The principle of SAED is to limit the diffraction area by inserting an adjustable aperture in the object image plane so that the electron diffraction analysis can be conducted on a microscopic area on the particles. The *in-situ* analysis of single atmospheric mineral MFs can be undertaken [86].

In practical analytical procedures, the characterization of MFs can use a combination of various methods. For example, Bloise et al. (2016) performed detailed characterization of asbestos fibers by PLM, XRD, SEM, and SEM-EDX (Scanning Electron Microscope coupled with energy dispersive X-ray spectroscopy) [18]. Fornero et al. (2006) identified asbestos mineralogy by differential scanning calorimetry , thermal gravimetric analysis, and Raman spectroscopy (RS) [87]. Giordani et al. (2022) used a combination of SEM-EDX, X-ray diffraction, inductively coupled plasma atomic emission spectroscopy, and alpha spectroscopy to study in detail the morphological, crystallo-chemical, mineralogical and radiological characteristics of natural MFs [9]. Different testing techniques and analysis of MFs approaches can complement each other, so combining multiple methods can indeed provide more

474 comprehensive information.

475 The current research methods are summarized (Fig. 9,10), and a standard analytical
476 sequential procedure for the efficient and accurate identification of atmospheric
477 inorganic MFs is proposed as follows:

478 (1) Inorganic fibers in atmospheric particulate collections are difficult to separate
479 from the non-fiber particles. Methods based on size, sieving or gravity will
480 usually not work. This requires the fibers to be visually identified and then
481 analyzed as part of the whole sample.

482 (2) The shapes and sizes of morphologically identified MFs can be obtained by
483 electron microscopy.

484 (3) Basic analytical SEM-EDX is conducted on the identified MFs to determine
485 elementally whether it is an inorganic fiber. Organic MFs will only contain C,
486 H and O as major components.

487 (4) If the particle is determined to be an inorganic fiber, then SAED can be used to
488 determine whether it is crystalline or amorphous.

489 (5) Crystalline fibers are assumed to be natural and classified as natural mineral
490 MFs. Amorphous fibers are assumed to be man-made and classified as
491 MMMFs.

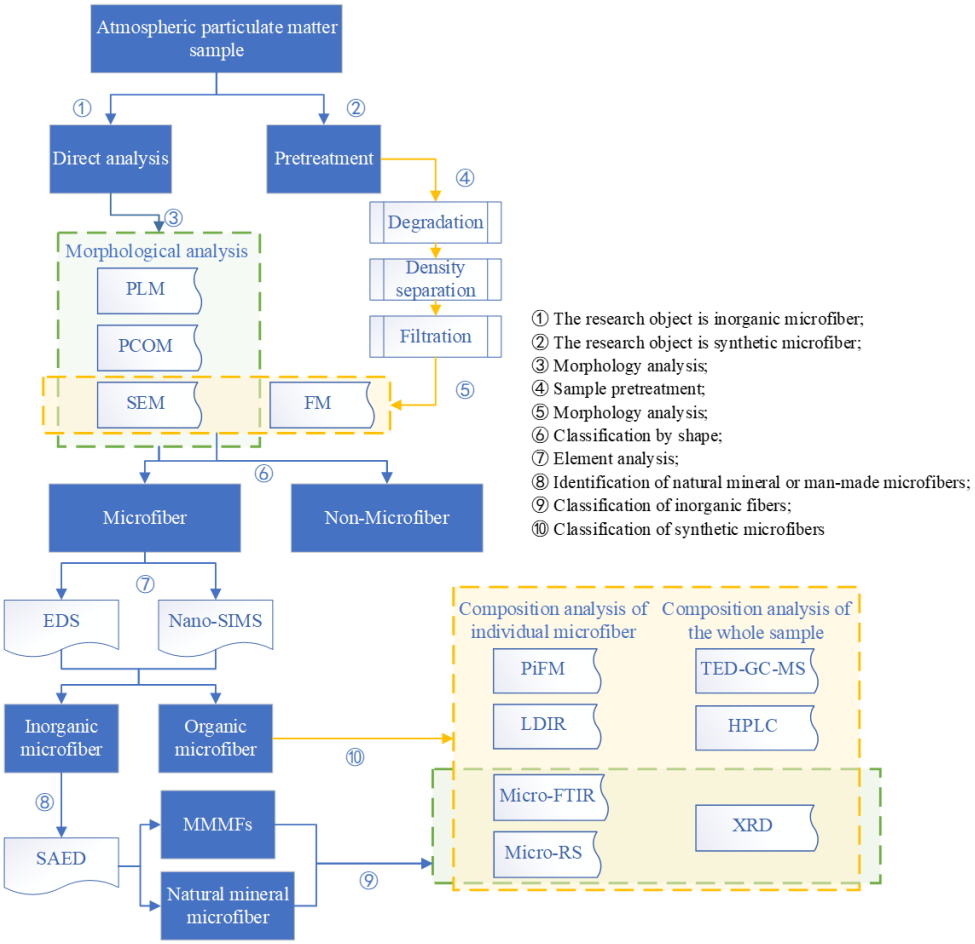

Fig. 9. Workflows showing the research procedures for investigating atmospheric microfibers.

3.2.2 Identification methods of plastic MFs

1) Morphological analysis

The analytical procedures to identify plastic MFs (MPs) are much more complicated than those of mineral samples. In general, MPs in atmospheric PM bulk samples need to be separated to facilitate subsequent analyses. Commonly used density flotation reagents are saturated solutions of $NaCl_2$, NaI, $ZnCl_2$ or $CaCl_2$ [93]. Digestion treatments can separate MPs from other organic impurities; however, this is strongly influenced by the chemistry of the MPs and the contaminants, and will require tests and verification to ensure the methods work properly. Two types of reagents are frequently used for MP sample processing: alkaline and acidic. Common acidic reagents include H_2O_2 solution and Fenton's reagent (i.e., H_2O_2 and $FeSO_4$) to oxidize contaminants. Alkaline reagents include KOH and NaOH. Specific enzymes and other acids (e.g., NaClO, $NaClO_4$, HNO_3, HF and HCl) can also be used as digesters. Chloroform is a

good digestion reagent for natural organic matter [94]. Some studies have classified semi-synthetic fibers as a kind of MP, but the acid-base digestion may cause the loss of semi-synthetic fibers in the pretreatment stage [95].

MPs are distributed in almost all environments in many sizes, shapes, and colors (Fig. 6). The morphological characteristics of larger sized MPs can usually be observed by means of an optical microscope. Some colored MPs are visually identifiable under a standard optical microscope including their surface structure, color, and shape. However, this method cannot identify white, black and opaque MPs, leading to a possible underestimation of the total amount of MPs [96]. Therefore, advanced methods and instruments are needed for more reliable identification. Since MPs can be combined with fluorescent dyes, it is more efficient to use fluorescence microscopy (FM) to characterize the morphology and quantity of dyed MPs [94]. A commonly used fluorescent dye is Nile red [97]. Rhodamine B [98], pink, blue, and a range of Kentucky synthetic dyes [31] can also be used as plastic-adsorbable fluorescent colorants. Erni-Cassola et al. (2017) used FM and image analysis software to conduct high-throughput detection and automatic quantification of small plastic particles (20-1000 μm) [99]. Fluorescence staining analysis is inexpensive, but FM cannot be used for composition analysis. MPs with small particle sizes or black coloration are difficult to stain, so the fluorescence intensity is weak. In addition, due to the irregular shape of plastic MFs, it is more challenging to dye and detect when compared with granular and fragmented particles [100]. Therefore, fluorescent quantitative methods are usually combined with spectral instrumentation to characterize the composition of MPs [66].

High resolution electron microscopes equipped with EDX, such as SEM-EDX and TEM-EDX, can be used to analyze the morphology and elemental composition of MPs. Due to the simple elemental composition of most MPs, mainly C, H and O, SEM-EDX and TEM-EDX are useful for preliminary identification. However, MPs may be incorrectly mistaken for other natural organic particles based on morphology and elemental analysis only, so it is recommended to select MPs in advance wherever possible [102]. If it is determined that a MF is a MP, EDX can be used to both characterize the elemental composition of plastic MFs and also any nanoparticles

adhered to the surfaces [16].

2) Compositional analysis of plastic MFs

Spectral analysis identifies the chemical composition, structure and relative contents of the material according to the spectrum of the substance [103]. IR (infrared spectroscopy) and RS are both common methods for the detection of plastic MFs [33,53,59,64]. IS uses the absorption spectrum, and RS uses the scattering spectrum; both of which reflect the molecules information of the substance in particles. Compared to RS, the signal from IS is stronger and less destructive to the sample. Infrared light has a high sensitivity to C=O bonds, so that IS also detects the oxidation characteristics of samples [103]. The horizontal pixel resolution of instruments of IS technology, such as micro-fourier transform infrared (Micro-FTIR) is 2.7 μm [103], so the detection limit is only above 20 μm [104]. RS can detect in higher sample humidity and has a higher pixel resolution of 1μm compared to FTIR [53].

Photo-induced Force Microscopy (PiFM) is a recently developed technology. It relates the advantages of AFM and IS, allowing the collection of the particle 3D morphology in combination with chemical identification at nanoscales with high spatial and spectral resolution. The operating modes of PiFM include point scanning, line scanning and area scanning. The lateral resolution of PiFM is 5 nm, which is significantly better than Micro-RS and Micro-FTIR [105].

MFs can also be identified by heating due to their low melting point. After being heated at relatively low temperatures, the MPs melt and are transformed into round and shiny particles [106]. Campbell et al. (2017) used hot needle testing to heat suspected MPs at 130 °C for 3-5 seconds to observe whether they melted [107]; this is an accepted technique used in the antiques trade to identify modern plastic fakes. However, the results are inconclusive due to the multiple chemical types of plastic particles, varying degrees of thermal deformation, and the subjective interpretations.

The degradation products of polymers can be extracted, and the solid-phase adsorbed by thermal extraction and desorption combined with gas chromatography-mass spectrometry (TED-GC-MS) at elevated temperature for the qualitative and

quantitative detection of MPs. TED-GC-MS allows the analysis of MPs in environmental samples (> 20 mg) without the removal of other organic matter [103]. Size exclusion chromatography (SEC) is a chromatographic technique for separating samples according to their molecular size. SEC is commonly used to analyze the molar mass of polymers with a high detection efficiency. SEC is limited to detecting some specific types of MPs, and must be combined with spectral methods for quantitative analysis [103]. This chromatographic method is quite efficient but cannot analyze individual particles.

The typical approach would be to combine two or more analytical methods for characterizing plastic MFs. Belzagui et al. (2021) evaluated the degradability of cigarette butts containing large quantities of MFs by Attenuated Total Reflection-Fourier Transform Infrared Spectrometry and gravimetric analysis, and observed low degradation rates of these fibers [108]. Liu et al. (2022) studied the micro- morphology and composition types of MPs in atmospheric dust fall in Beijing, China, applying Laser Direct Infrared Spectroscopy and SEM [69].

Based on an evaluation and comparison of the various research methods and instruments used to study organic MFs (Table 2), we summarize an optimum research procedure to investigate atmospheric organic MFs (Fig. 9), with a view to efficiently and accurately identify organic MFs in the atmosphere. The natural organic MFs degrades faster under the natural condition, so it is less harmful to human health. Therefore, the detection of natural organic fiber can follow the single particle research method of Shao et al. (2022) [109]. Before the investigation of the plastic MFs, the sample needs to be pretreated. Then, the morphology and concentration of plastic MFs can be observed and calculated by microscopy. Chromatographic and mass spectrometric methods are usually chosen to study the functional group composition of plastic MFs, and thus, determine the type of plastic MFs.

597 Table 2. Advantages and disadvantages of identification techniques for atmospheric MFs.

Identification techniques	Detection equipment	Identified properties	Limit of detection	Advantages	Disadvantages
Phase-contrast optical microscopy (PCOM) [28] (Minerals and plastics)		Shape, quantity	> 0.25 μm	Low cost	Time consuming, low resolution, only for transparent fibers
Polarized light microscopy (PLM) [29] (Minerals)		Shape, quantity	> 1 mm	Low cost	Time consuming, low resolution,
X-ray diffraction (XRD) [18] (Minerals)		Type, crystal structure	> 5%	High efficiency	Only for mineral fibers
Thermal Gravimetric Analyzer [87] (Plastics)		Type	> 5 mg	High efficiency	Required large sample quantity
Scanning electron microscopy (SEM) [109] (Minerals and plastics)		Surface characteristics and quantity, elemental composition	1 nm	Provides instructive data for characterizing microstructures (fracture, corrosion, grains, and grain boundaries)	Time-consuming
Transmission electron microscopy (TEM) [109] (Minerals and plastics)		Internal characteristic sand quantity, element composition	0.2 nm	High magnification, information on inner structures of samples (crystal structure, morphology, and stress state)	
Raman Spectroscopy (RS) [87] (Minerals and plastics)		Type, aging degree	> 1 μm	Accurate identification of the type of polymer	

Infrared Spectroscopy (IRS) [110] (Mineral and plastics)		Type, aging degree	> 10 μm		
Fluorescence microscopy (FM) [94] (Plastics)		Shape, quantity	15 to 20 nm	Low cost	Pre-processing required
Thermal Extraction and Desorption combined with Gas Chromatography-Mass Spectrometry (TED-GC-MS) [103] (Plastics)		Type, content	4 μg provides up to 600 C per run	High efficiency, no sample sorting required, short analysis time (2 to 4 hours per run)	Requires unique thermal degradation product for identification and quantification, PSA, and morphology not included expensive solvents for SEC
Size Exclusion Chromatography (SEC) [103] (Plastics)		Type, content	Pore or mesh size deter mine lower size of M Ps. detected	High efficiency	
Photo-induced force microscopy (PiFM) [105] (Minerals and plastics)		3D morphology, elemental composition, type	> 5 nm	High precision, accurate identification of type polymer	Limited range of environments in which the method can be applied (e.g., biological)

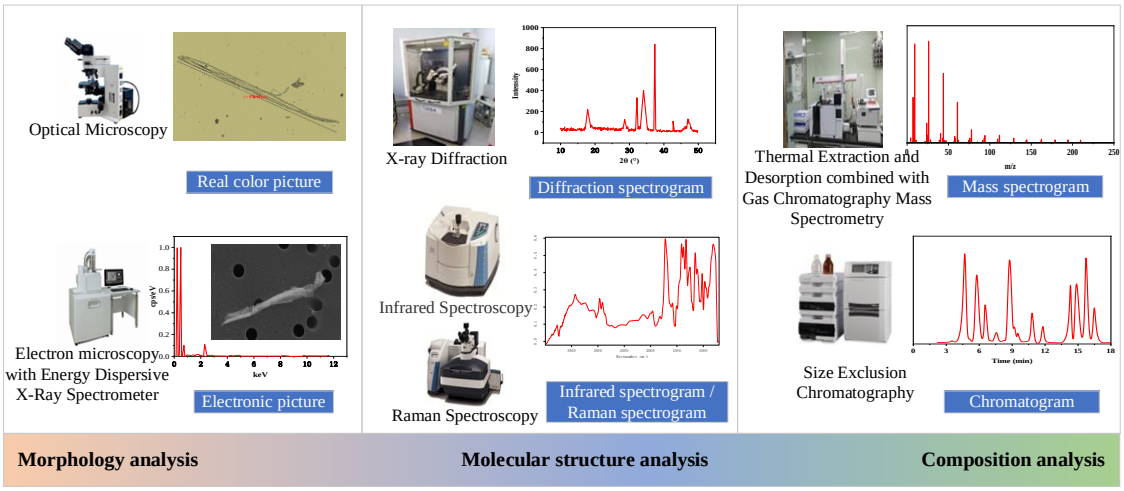

Fig. 10. Visualization result examples obtained from commonly used microfiber analytical methods.

4. Health impacts and mechanisms of atmospheric MFs

Although MFs are mostly found in marine organisms, their impact on human health

603 cannot be ignored, especially atmospheric MFs. The effect of MFs on human health has
604 various clinical manifestations, and several mechanisms have been proposed. Studies
605 have shown that exposure to asbestos fiber, especially occupational exposure, will lead
606 to an increase in the incidence rate of mesothelioma and lung, laryngeal and ovarian
607 cancers, and is also associated with pharyngeal, gastric and colorectal cancers [36]. In
608 addition to asbestos, other MFs such as amphibole, and zeolite minerals and synthetic
609 glass fibers are also associated with the development of malignant pleural
610 mesothelioma [8]. A study of 51 villages in Turkey found that the concentration of
611 fibers in the outdoor environment, where asbestos and zeolite deposits were found, was
612 8 to1,020 times higher than that in the indoor environment [72]. The proportion of
613 villagers suffering from calcified pleural plaques was 5.4% and 9.3% in two villages,
614 respectively [72]. According to long-term epidemiological studies and several animal
615 carcinogenicity tests, substantial amounts of zeolite fibers contained in housing
616 construction materials in Cappadocia, Turkey, were found to be responsible for the local
617 mesothelioma epidemic (IARC, 2017). Inhalation of MMMFs leads to pulmonary
618 fibrosis and respiratory cancer by repeatedly inducing persistent inflammation [111].
619 Studies have shown that exposure of workers in factories producing MMMFs is
620 associated with a higher risk of developing pneumoconiosis [112]. MMMFs can induce
621 the unbalanced expression of cancer-related genes in rat lung tissue, leading to the
622 inactivation of tumor suppressor gene P16 and the activation of proto-oncogenes (C-
623 JUN and C-FOS). Among them, glass and ceramic fibers have more obvious effects
624 than rock wool [50]. In particular, the refractory ceramic fiber (RCF2) significantly
625 changed cell morphology, induced DNA damage and apoptosis [113]. MFs are
626 engulfed by cells and accumulate in human tissues through the circulatory system.
627 Zeolite fibers invade cell membranes by damaging the phospholipid bilayer [43].
628 Cangiotti et al. (2018) found the presence of zeolite fibers in both the cytoplasmic
629 matrix and nucleus after the interaction of zeolite fibers with cells [114]. Among the
630 MPs identified in human lung tissue samples, MFs account for the largest proportion
631 (49%), with the length ranging from 12 to 2,475 μm and the width ranging from 14 to
632 88 μm [136]. Wu et al. (2022) found MPs in the blood clots of clinical patients, ranging

in size from 2.1 to 26 μm [7].

The first factor to consider when assessing the risk of inhalation exposure to MFs is their morphology, i.e., length and diameter [116]. In addition, surface active properties, biopersistence, releasable chemical composition and catalytic ability of MFs constitute very important factors related to toxicity and carcinogenicity (Fig. 11) [114,117].

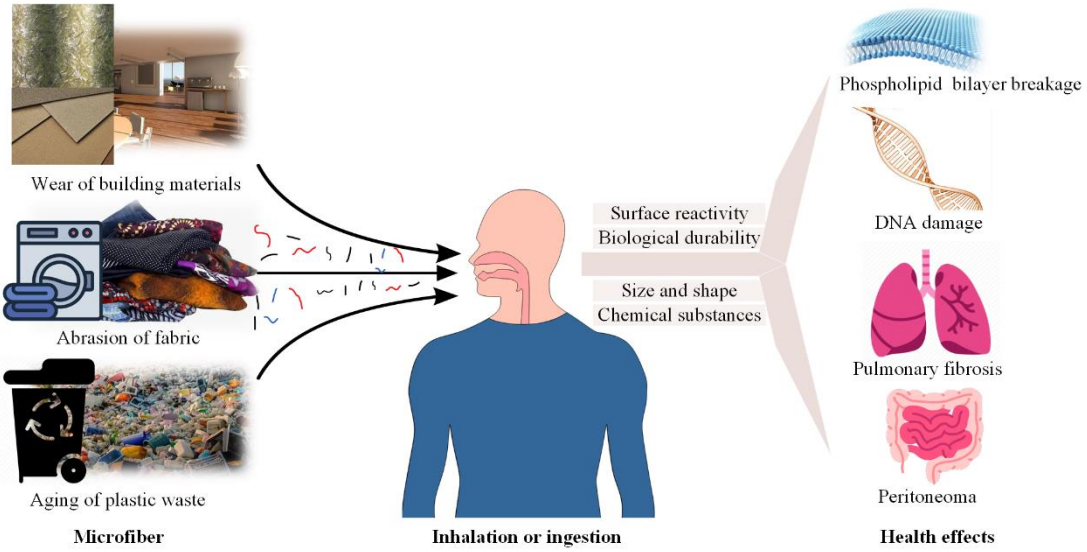

Fig. 11. Mechanisms of health effects of atmospheric MFs. Microfibers derived from the wear and tear of building materials, fabrics and plastic waste products may be inhaled or ingested into the human body, leading to a number of diseases.

4.1 Effects of morphological characteristics on atmospheric MF toxicity

Particle size and shape play a major role in controlling the deposition, movement and removal of MFs in the human body, and are considered to be important factors in the pathogenesis of particles [118]. The length of MFs may influence particle-cell interactions by generating mechanical stresses on cell surfaces [116]. The mechanism related to the mechanical toxicity of MFs is still uncertain and needs further study [33,119].

The particle size and shape also determine the specific surface area of the particles. Larger surface areas provide more points for the particles to adsorb harmful substances.

Dong et al. (2006) studied the destruction mechanism of mineral dust on alveolar macrophages [4]. According to the principle that the cytotoxicity of dust is positively correlated with the content of active OH^-, it was confirmed that the cytotoxicity of fibrous mineral dust is greater than that of granular dust. The study on the ability of mineral fibers to induce fluorescein-dependent chemiluminescence of macrophages showed that the release of superoxide in macrophages was non-specific to mineral fibers of various lengths [120]. The toxicity of fibrous MPs is also higher than that of MPs in other shapes [121]. A study on freshwater zooplankton shows that the acute half-lethal concentration and chronic half-effect concentration of fibrous MPs are 6 times and 9 times lower than those of spherical MP, respectively [5]. An *in vitro* experiment has shown that longer and finer MFs (i.e., length > 8-10 μm, diameter < 0.25 μm) have more severe biological effects [122]. A study has shown that staple fibers with aspect ratio > 1:3, length < 5 μm and diameter < 3 μm are the majority in the atmosphere around buildings, so the risk should also be considered [37].

4.2 Effects of surface activity property on atmospheric MF toxicity

Surface activity also plays an important role in the toxicity and carcinogenicity of MFs [123,124]. Some minerals, such as zeolite and clay, are widely used as catalysts. The function mechanism of minerals as catalysts is usually related to their ability to provide or receive electrons or protons, provide stable surfaces for reaction components, and exclude molecules of specific shape or size from the catalytic sites [116]. Mineral MFs can generate superoxide radicals by redox reaction on their surface in H_2O_2 or saline solution [125]. At physiological temperatures, mineral MFs can provide chronic electron sources (or sinks) for redox reactions [116]. The ability of inducing H_2O_2 decomposition to produce OH radical differs little among different types of mineral MFs [126]. Weitzman and Weitberg (1985) studied the toxicological effects of asbestos fibers and found that they can spontaneously catalyze lipid peroxidation, which may be the mechanism of tissue damage [127]. A study on the mechanism of toxicity and carcinogenicity of serpentine MFs has shown that when these MFs enter the human

683 body as antigens, they will stimulate the formation of reactive oxygen species (ROS),
684 nitrite, Prostaglandin E2, cyclooxygenase, hydroxyl and nitric oxide free radicals,
685 providing conditions for the formation of lesions and tumors [128].

686 Total Fe content is one of the most important factors in the pathologic bioactivity
687 induced by MFs [129]. MFs containing more iron, such as asbestos, will destroy the
688 coordination of biological iron after entering the human body [117]. Iron absorbed on
689 the surface of the fiber, especially Fe^{2+}, as a catalyst, is considered to be the main cause
690 of the production of ROS, which can participate in the oxidation reaction to produce
691 stress response in cells [130]. In addition, low-nuclearity Fe at a certain crystallographic
692 position may also provide sites for the catalytic reaction of reactive oxygen [131].
693 Typically, iron is associated with iron-rich impurities (oxides, hydroxides or sulfates)
694 found on the surface of mineral MFs in the form of nanoparticles [132]. SEM
695 micrographs and EDS analysis [20] revealed iron-rich particles on the surface of
696 mineral MFs, which are more enriched in iron relative to the fibers themselves.

697 Fresh MFs have a stronger ability to produce OH radicals than aged MFs. The data
698 from a study on silica dust showed that freshly ground silica induced a greater
699 cytotoxicity to the integrity of the cell membrane [133]. Choi et al. (2021) conducted
700 aging treatment of plastic MFs by ultraviolet irradiation, and found that aging of PP and
701 PS MFs would lead to the decrease of enzyme activities, inducing the change of
702 microbial community structure [134].

703 Future studies need to address the exposure level of MFs, especially fibers with
704 larger active surfaces, such as nanofibers, which have greater catalytic activity.

705

706 **4.3 Effects of biological resistance on atmospheric MF toxicity**

707 Biological resistance determines the incubation time of MFs after entering
708 organisms. Dissolution may be an important mechanism for MFs to be removed from
709 the human body. The solubility is usually used as the basis for distinguishing non-
710 dangerous minerals from potentially dangerous minerals. Dangerous minerals remain
711 in the lungs for a long time because of their high biological resistance. Asbestos fibers,

for example, are less soluble and more carcinogenic than other mineral fibers. Some artificial glass fibers are also highly bio-persistent and carcinogenic [135]. Long-term exposure to fine glass wool may lead to pulmonary interstitial fibrosis [136]. The results showed that MMMFs with high durability had the similar or higher carcinogenic risk than asbestos. Adachi et al. (2001) evaluated the carcinogenic risk of MMMFs by injecting nine standard samples of MMMFs into the abdominal cavity of rats and calculating the incidence of peritoneal mesothelioma [124]. MPs have been recognized as persistent pollutants because they can remain in the environment for hundreds or even thousands of years and are therefore considered difficult materials to biodegrade [137]. The aging rate of degradable plastics such as polylactic acid (PLA) is relatively fast [138]. However, the nature of degradable plastics means that more MPs will be produced, leading to different ecological risks [139], so their environmental behavior needs to be further explored.

MFs with high biological resistance can be present in human lung fluid in a weak alkaline state for a longer period of time, so the inhalable MFs in the atmosphere need to be properly controlled. Low biological resistance is also one of the important reasons why natural organic MFs are considered less potentially harmful.

Table 3. The time required for complete degradation of different MFs [31, 126,128].

Type	Density	Kais ng/cm^2·h	Dissolution conditions	Time required for complete dissolution (year)
Asbestos MFs	2·40	0.1	Pulmonary fluid	~300
Refractory MFs	2·65	3		~5
Rock wool	2·85	20		~2
Glass MFs	2·50	100-300		0.1-0.25
Slag wool	2·85	400		0.1
Plastic MFs	0.91-2.31		Water	Hundreds to thousands

4.4 Effects of releasable chemicals on atmospheric MF toxicity

The chemical substances released by MFs are also important components affecting human health. Primary ions (such as iron, other metals, or other toxic elements) in mineral MFs, once entering the body of an organism, can be released into lung fluid

through physical and chemical reactions. Guthrie indicated that one of the main ways of interaction between minerals and body fluids (especially in the short term) is ion exchange [116]. An *in vitro* experiment on pleural mesothelial cells of rats found that cation exchange may influence the cytotoxicity, gene response and apoptosis of pleural mesothelial cells [116]. Plastic MFs may release additives and other pollutants in the human body, resulting in oxidative stress and carcinogenic activity [64]. The flame retardant polybrominated diphenyl ethers released from the MPs will cause disorders in the nervous system, reproductive system, endocrine system and other systems of animals [141,142]. MFs ubiquitously found in the environment are ingested by a wide variety of organisms. Subsequently, MFs can translocate from the gastrointestinal tract into the tissues likely by cellular internalization [143]. Studies have shown that plastic MFs extracts can cause adverse reactions and even death of a variety of fishes, posing a threat to the ecological health of the aquatic environment [144] and thereby threatening human health by accumulating in the body.

5. Environmental, climate and ecological effects of atmospheric MFs

5.1 Environmental effects of atmospheric MFs

Atmospheric visibility is controlled by light absorption and light scattering from PM [145]. Reduced atmospheric visibility can pose safety hazards and danger to human activities. The fact that MFs are widespread in the atmosphere despite the production of plastics having started only over 70 years ago implies that the formation of MFs is quite rapid [146]. Therefore, the issue of the effect of MFs on visibility should not be taken lightly. For MFs of different color systems, different color wavelengths affect the solar absorbance and UV transmittance of the MFs. The darker the color of the MFs, the greater the effect on atmospheric visibility [147]. According to the above analysis, it can be inferred that the control of atmospheric MFs, especially the dark MFs, can mitigate their impact on the environment.

5.2 Climate effects of atmospheric MFs

High concentrations of MFs can perturb the balance of the global climate system and, as a result, may alter the climate. Atmospheric aerosols have an important influence on global climate, directly affecting the scattering and absorption of solar radiation, or indirectly affecting the concentration of cloud droplets or the characteristics of cloud radiation. The absorption and scattering of atmospheric radiation by minerals depend to a large extent on their sources, morphologies (i.e., shape and size), mineralogical characteristics, and mixing state with other substances [148]. Li et al. (2016) simulated the polarization mode of skylight under the influence of the mineral dust particles, and found that the light scattering of non-spherical particles is more complex than that of spherical particles [149]. MP, like other types of PM, can influence the Earth's climate by absorbing and scattering radiation [81]. However, there are significant uncertainties in the geographical and vertical distribution of MFs, which needs further study.

The effect of atmospheric PM on climate is usually quantified in terms of effective radiative forcing (ERF) [12]. The ERF of mineral dust is about -0.03 w/m^2 [150], and that of MPs is about $-0.746 \pm 0.553 w/m^2$ [151]. External mixing of mineral fibers with atmospheric nitrates and sulfates will result in an increase of ERF ($-0.1 w/m^2$) [152]. Tinted MPs display more absorbing than scattering to the visible spectrum, producing a net positive ERF and causing atmospheric warming [27]. Further research is needed to evaluate the range of refractive index of MPs after being combined with pigments, and the range of ERF generated therefrom. Compared with the total ERF caused by aerosol radiation interaction (-0.71 -$-0.14 w/m^2$), the ERF of MFs is very small, being -0.746 ± 0.553 w/m^2 [151]. However, MFs are widely used in buildings, and plastic production has increased rapidly in the past 70 years [153]. There is an urgent need to reform fiber production and waste management practices, in order to control ever increasing abundance and direct radiation effects of MFs in the atmosphere.

5.3 Ecological effects of atmospheric MFs

Both the aquatic and soil environments are important sinks for MPs, thus posing a

major threat to the growth and survival of plants and animals. MFs are commonly found in tissue tests of aquatic organisms [154]. An indoor air study found that there are dense biofilms adhering on surfaces of MFs on air conditioners, which contained several species of pathogenic bacteria [155]. MPs have been shown to cause ecological damage by affecting the rooting ability of plants and soil nutrient cycling [156]. Fibrous MPs have been proven to have more significant effects on the soil-plant system compared to other shapes of MPs [156]. In the aquatic environment, increasing MFs resulted in lower microphytobenthos biomass, fewer diatom-associated fatty acids, and an increase in cyanobacteria [157]. These manifestations would alter the biogeochemical processing of coastal Marine sediments. In the soil environment, polylactic acid MPs had the potential to promote the abundance of microbial phosphorus transporter, nitrogen fixation, and denitrification genes and inhibit nitrification, resulting in massive accumulation and release of ammonia nitrogen [158]. MFs can be directly inhaled and ingested by humans, or indirectly by contaminated animals and plants [159]. The latter mode translates ecological impacts into human health effects.

6. Conclusion and prospectives

With the rapid industrial and economic development of the world, the sources of MFs have substantially increased, requiring focused attention on MFs in the ambient atmosphere. Although the use of asbestos has decreased rapidly after recognizing its toxic efforts. The production and use have not been stopped completely on a global level. For example, only six countries have banned asbestos in Latin America and the Caribbean as of 2022 [36]. Moreover, with the prohibition of natural mineral fibers such as asbestos, the MMMFs, as the substitutes of asbestos, find their way in increased proportion into the ambient atmosphere. In addition, natural and artificial factors will continue to help in releasing mineral fibers from old buildings into the atmosphere, and as long as this situation exists, and malignant mesothelioma will continue to threaten human health. Although there is a trend to replace plastic fibers with plant fibers, plastic products are increasing year by year, as is the plastic waste.

It is critical to establish effective methods to reduce solid waste in the environment [160]. If the proportion of plastic in municipal solid waste is reduced, the growth of plastic pollution can be largely slowed down. Several methods to mitigate MFconcentration in the atmosphere are already being progressively implemented. For example, asbestos tailings are recovered and used as reinforcement fillers to improve the mechanical properties of polypropylene [161]. This treatment reduces disposal costs, avoids secondary contamination, and produces a new type of composite material with enhanced mechanical properties. Fungi have outstanding potential in removing MP, and are expected to partially or completely degrade polymers into energy [162]. The use of degradable plastics can reduce the biological durability of MPs. However, the use of degradable plastics only accounts for a small part in present society. The proper identification of diverse types of MPs in the environment can obtain source information, which will help for planners to adopt effective measures.

The type of MF is probably one of the most important yet overlooked factors that must be considered in the study of MF toxicity and carcinogenicity. This would provide two key aspects of information on MFs, namely composition and structure. Compositional and structural differences will influence the solubility, surface functional groups and redox properties of the MFs. Different solubility is important in terms of biological durability and possible toxicity. Different functional groups on the surface are related to the binding strength of other substances.

The limitations of evaluating plastic MFs are in the standardization of identification techniques, the identification of nano-scale plastic MFs, and the toxicity of plastic MFs. As the sample quantity of airborne plastic MFs is generally small and pre-treatment is required, the different sampling methods, flotation reagents and testing instruments will have considerable impact on the research results. Data on nano-plastics are currently deficient because of the small particle size and difficulty to observe, but in the real ambient atmosphere, nanoscale plastics may be common and have different properties compared to the MPs with larger particle sizes. Fibrous particles are found to be much more harmful than spherical particles. However, due to the difficulty of preparing standard samples of plastic MFs, most previous *in vitro* toxicity studies used spherical

polystyrene particles as the subject of MPs toxicity studies, requiring further advances in this field.

Acronym list

ACR- Acrylic copolymer
AFM- Atomic Force Microscopy
EMPs- Elongate Mineral Particles
ERF- Effective Radiative Forcing
FESEM- Field Emission Scanning Electron Microscopy
FM- Fluorescence Microscopy
FTIR- Fourier Transform Infrared Spectroscopy
HTM- High-Throughput Microscope
IARC- International Agency for Research on Cancer
ICP-AES- Inductively Coupled Plasma Atomic Emission Spectroscopy
IRS- Infrared Spectroscopy
MP- Microplastic
MF- Microfiber
MMMFs- Man-Made Mineral Fibers
PCOM- Phase-Contrast Optical Microscopy
PiFM- Photo-induced Force Microscopy
PM- Particulate matter
PLM- Polarized Light Microscopy
ROS- Reactive Oxygen Species
RS- Raman Spectroscopy
SAED- Selected Area Electron Diffraction
SEM- Scanning Electron Microscopy
TED-GC-MS- Thermal Extraction and Desorption combined with Gas Chromatography-Mass Spectrometry
TEM- Transmission Electron Microscopy
XRD- X-ray Diffraction

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