The Current Status of Atmospheric Micro/nanoplastics

Research: Characterization, Analytical methods, Fate, and Human Health Risk

Hsin-Chieh Kung 1,2,3, Chien-Hsing Wu 4, Nicholas Kiprotich Cheruiyot 2,5, Justus Kavita Mutuku 1,2,5, Bo-Wun Huang 6, Guo-Ping Chang-Chien 1,2,5*

1 Institute of Environmental Toxin and Emerging-Contaminant Research, Cheng Shiu University, Kaohsiung City, 833301, Taiwan
2 Center for Environmental Toxin and Emerging-Contaminant Research, Cheng Shiu University, Kaohsiung 833301, Taiwan
3 Department of tourism and recreation, Cheng Shiu University, Kaohsiung 833301, Taiwan
4 Division of Nephrology, Department of Internal Medicine, Kaohsiung Chang-Gung Memorial Hospital, Kaohsiung 83301, Taiwan, and College of Medicine, Chang-Gung University, Taoyuan 33303, Taiwan
5 Super Micro Mass Research and Technology Center, Cheng Shiu University, Kaohsiung City, 833301, Taiwan
6 Department of Mechanical and Institute of Mechatronic Engineering, Cheng Shiu University, Kaohsiung City, 833301, Taiwan

*Corresponding author’s contacts: guoping@gcloud.csu.edu.tw; Tel: +886-07-735-8800 (G.P.C.C)

ABSTRACT

Atmospheric plastic debris (microplastic and nanoplastic) research is comparatively little than in aquatic and terrestrial environments. Nonetheless, the research is important in understanding the risk and fate of these contaminants in the total environment. Generally, the research is limited by a lack of consensus on the characterization of plastic debris and the standardization of sampling and analysis
protocols. These limitations make it difficult to compare results from studies. In response, criteria for defining plastic debris beyond size characterization have been proposed to include polymeric composition, solubility, physical state, shape, color, and origin. There are also emerging techniques, such as Py-GC/MS, which can measure smaller particles in the nanoscale range, and TGA-FTIR-GC/MS, which can accurately identify more polymers. The identification of microplastics and nanoplastics sources and formation processes is challenging. Since most polymers are inert, the adverse health risks include endocytosis and accumulation in the liver and spleen. However, most of the toxic effects of these contaminants are related to surface-bound compounds, including heavy metals and persistent organic pollutants. Some polymers, such as expanded polystyrene, decompose to form carcinogens. This paper offers an overview of the current knowledge on plastic debris in the atmosphere and will be useful to researchers interested in this field.

**Keywords:** Contaminants release, Continuous fragmentation, Exposure pathway, Hetero-aggregation, Inhalable plastic debris, Sorption

1. **INTRODUCTION**

This review aims to collate all recently published and relevant studies on atmospheric microplastics and nanoplastics to present the current understanding of these contaminants. Microplastics (MPs) and nanoplastics (NPs) find their way into the environment through the fragmentation of larger plastic debris or the negligent or accidental release of plastic nanomaterials used in various industries. Although what constitutes these contaminants is still debatable, most environmental researchers use size characterization to define them. The most widely accepted definition for MPs is plastic particles that are < 5 mm in length.

Research on these contaminants in the atmosphere is less than in aquatic and terrestrial environments. For instance, MP studies have focused on sources (Peng et al., 2017; Liu et al., 2019a), dispersion pathways (Geyer et al., 2017), human exposure
(Zhang et al., 2020b), and environmental sinks, including soil (Ya et al., 2021), freshwater (Yuan et al., 2019), and marine environments (Andrady, 2017). A bibliometric analysis of articles published from 2019–2022 was carried out on the Web of Science using the keywords “microplastics” and “atmosphere”. The VOSviewer map in Fig. 1 visualizes the titles, sources, abstracts, and references of 185 studies. The studies belong to three clusters, with more investigations leaning towards airborne MPs and those in aquatic environments than the interactions between MPs and the environment. In the cluster for airborne MPs, the focus is on the particles in the micrometer particle size range, unlike in aquatic environments where 5 mm particles are still relevant. Low weights in the occurrence frequencies of the phrases “atmospheric MPs” and “atmospheric transportation” in Fig. 1a highlight the current knowledge gaps on atmospheric MPs. Furthermore, exposure and associated health risks following the inhalation of microplastics are inadequately covered, as indicated by the absence of relevant keywords. The research direction, as indicated by the VOSviewer map in Fig. 1b, suggests a shift in the focus of research from marine contamination with MPs to atmospheric concentrations and deposition. The concentration of MPs and NPs in all environmental matrices and their fates in the environment are important to understand their toxicological effects, environmental mass-balances, and devise appropriate remediation actions.

Several review papers and book chapters focusing on the sampling and analysis of microplastics (Rocha-Santos and Duarte, 2015; da Costa et al., 2019; Schwaferts et al., 2019; da Costa and Duarte, 2020; Kusch, 2020; Cerasa et al., 2021), characterization (dos Santos Galvão et al., 2022) and exposure risk (Prata et al., 2020b) have been published recently. However, only one review paper (Zhang et al., 2020c) and a book chapter (Prata et al., 2020a) have comprehensively focused on atmospheric...
microplastics and included sampling and analytical challenges. In addition to presenting the recent advances in characterization, sampling, and analysis methods, this review will also include the fate and transport of MPs and NPs in the atmosphere and their exposure risk to human and ecological health. This review will be useful to researchers interested in understanding the current knowledge on atmospheric MPs and NPs.
Fig. 1. Current classification of studies on microplastics, (a) three clusters on microplastics studies, including airborne MPs, accumulation/interactions of MPs with the environment, and MPs in the aquatic environment, and (b) evolution of studies on MPs since 2019 to 2022.

2. CHARACTERIZATION OF MICROPLASTICS AND NANOPLASTICS

The term “micro-plastics” was first published by Thompson et al. (2004) to refer to the microscopic plastic fragments, ~20 µm in diameter, collected and measured from beach, estuarine, and subtidal sediments. Currently, the accepted definition of microplastics is plastic particles that are < 5 mm in length. Since microplastics were first detected in marine environments, the < 5 mm-in-length criterion was based on the likelihood of such particles being ingested by aquatic life (Arthur et al., 2009; Hartmann et al., 2019).

The greater concern for smaller particles has led environmental researchers to distinguish microplastics from nanoplastics. Some researchers have defined microplastics as particles that are 1–5 mm in length, while nanoplastics have been defined as either 1–100 nm or 1–1000 nm (Gigault et al., 2018; Hartmann et al., 2019).

The definition of nanoplastics borrows from that of nanomaterials (1–100 nm) or that of SI nomenclature (1–1000 nm). “Submicroplastics” has been used to define particles that are 100–1000 nm in length. There remains an apparent discrepancy between the...
definitions of plastic debris in the micro- and nanoscale. In response, Hartmann et al. (2019) proposed using the SI nomenclature to define the size of the plastics: microplastics (1–<1000 µm) and nanoplastics (1–<1000 nm).

Most of this debate has focused on plastic debris in marine environments and can be further extended into terrestrial environments. However, for the abovementioned classification to be useful in atmospheric research, it requires further optimization or consolidation with the established classifications of particles in the atmosphere. In atmospheric pollution research, there is already a widely acceptable classification of suspended particles in the air: total suspended particles (TSP) and particles with an aerodynamic diameter equal to or less than 10, 2.5, and 1 µm (PM$_{10}$, PM$_{2.5}$, and PM$_{1.0}$). The classification has been crucial in the risk assessment of atmospheric particles. Recent studies have used this classification to study plastic debris in the atmosphere (Akhbarizadeh et al., 2021; Abbasi et al., 2023).

Thus far, a more nuanced definition of plastic debris has been proposed that goes beyond size. The seminal work on plastic debris classification, Hartmann et al. (2019), attempted to create a framework for defining microplastics in environmental research by proposing eight criteria based on the physical and chemical characteristics: (i) chemical composition, (ii) solid state, (iii) solubility, (iv) size, (v) shape and structure, (vi) color, and (vii) origin.
To create a definition for what constitutes plastic debris, the authors used the IUPAC’s definition of polymers and included polymers, copolymers, tire wear, and road particles, and composites, which contain synthetic polymers as essential ingredients. In this regard, chemical composition will be referred to as polymeric composition in this study. The properties of common synthetic polymers are presented in Table 1.

Furthermore, the plastic debris should be solid (initial melting or glass transition temperature > 20 °C) and be insoluble in water (< 1 mg L⁻¹ at 20 °C). Shape and structure are also used to categorize plastic debris in the environment. The classification is useful in determining the origin of the plastics and understanding their interaction with the environment (Gray and Weinstein, 2017; Khatmullina and Isachenko, 2017b; Khatmullina and Isachenko, 2017a; Lozano et al., 2021; Zhao et al., 2021). The common shape descriptors in literature are fragments, flakes, pellets, beads, film, fiber, and foam. However, some of these descriptors present biases, e.g., beads and foam, which could cause one to wrongly assume origin and type, respectively. Hartmann et al. (2019) proposed neutral descriptors: spheres, spheroids, cylindrical pellets, fragments, film, fiber, and expanded cellular plastics.

Color can also be used in describing plastic debris in the environment. It is useful in identifying potential sources of plastics and can be an important classification when
studying the consumption of plastic debris by organisms, since some colors can be
easily mistaken as food (Hartmann et al., 2019). For consistency and accuracy, a
standardized color palette should be used in identifying the color of a plastic particle.
Lastly, microplastics and nanoplastics can be classified as either primary or
secondary (Wang et al., 2018). Primary microplastics are intentionally manufactured
and added to various products to achieve a specific purpose or used as starting products
in the plastic manufacturing industry. On the other hand, secondary microplastics are
formed via the disintegration of larger plastic pieces either through abrasion,
photodegradation, thermal-oxidative degradation, thermal degradation, or
biodegradation (Wang et al., 2018; Prata et al., 2020a). However, it is quite difficult to
identify the origin of a plastic particle because of the continuous weathering the particle
undergoes in the environment.
In conclusion, successful attempts have been made to provide a starting framework
for defining plastic debris in the environment. It will still take time for environmental
researchers to adopt a uniform framework. In addition, discussions are still required to
determine the applicability of the framework in studying plastic debris in all
environments, including the atmosphere.
Table 1. Physical properties of common polymers that degrade into microplastics and nanoplastics.

<table>
<thead>
<tr>
<th>Chemical compound</th>
<th>Mechanical properties</th>
<th>Common applications</th>
<th>Specific gravity (g cm⁻³)</th>
<th>Common shape</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polystyrene (PS)</td>
<td>Low heat conductivity, inert, and long-lasting</td>
<td>thermal insulation, food containers, building materials</td>
<td>0.96-1.1</td>
<td>Fragments, films, foams</td>
<td>Hidalgo-Ruz et al. (2012)</td>
</tr>
<tr>
<td>Low-density polyethylene (LDPE)</td>
<td>Plastic bags, drinking straws, curtains</td>
<td></td>
<td>0.91 - 0.93</td>
<td></td>
<td>Browne et al. (2010)</td>
</tr>
<tr>
<td>Polyethylene (PE)</td>
<td>High tensile strength</td>
<td>Shopping bags, bottles</td>
<td>0.91 - 0.96</td>
<td>Fragments, films, foams</td>
<td></td>
</tr>
<tr>
<td>High-density Polyethylene (HDPE)</td>
<td></td>
<td></td>
<td>0.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polypropylene (PP)</td>
<td>High tensile strength, resistance to abrasion, and smooth texture</td>
<td>Textile fibers, packaging materials, straws</td>
<td>0.83-0.84</td>
<td>Fibers</td>
<td></td>
</tr>
<tr>
<td>Polyethylene terephthalate (PET)</td>
<td>High tensile strength, resistance to abrasion, and smooth texture</td>
<td>Textile fibers and packaging materials</td>
<td>1.37</td>
<td>Fibers, fragments, films, foams</td>
<td>Geyer et al. (2017)</td>
</tr>
<tr>
<td>Polyamide/nylon (PA)</td>
<td>High durability and high tensile strength</td>
<td>Textiles, sportswear, carpets, fishing gear</td>
<td>1.0 - 1.2</td>
<td>Fibers</td>
<td>Geyer et al. (2017)</td>
</tr>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td></td>
<td></td>
<td>1.38</td>
<td>Fragments, Films, Foams</td>
<td></td>
</tr>
<tr>
<td>Polyacrylate/acrylic</td>
<td>Transparent, high resistance to breakage, elastic</td>
<td>Road markings</td>
<td>Fibers</td>
<td></td>
<td>Geyer et al. (2017)</td>
</tr>
<tr>
<td>Expanded Polystyrene (EPS)</td>
<td>Floats, cups, expanded packaging</td>
<td></td>
<td>&lt;0.05</td>
<td>Fragments, films, foams</td>
<td>Browne et al. (2010)</td>
</tr>
<tr>
<td>Acrylonitrile butadiene styrene (ABS)</td>
<td>3D printer, protective equipment</td>
<td></td>
<td>1.06-1.08</td>
<td>Pellets</td>
<td>Stephens et al. (2013)</td>
</tr>
<tr>
<td>Polylactic acid (PLA)</td>
<td>3D printer</td>
<td></td>
<td>1.08</td>
<td>Pellets</td>
<td>Stephens et al. (2013)</td>
</tr>
</tbody>
</table>
3. SAMPLING AND ANALYSIS OF ATMOSPHERIC MICROPLASTICS AND NANOPLASTICS

3.1. Atmospheric sampling of plastic particles (microplastics and nanoplastics)

The sampling of plastic particles in the atmosphere follows the established methods for sampling particulate matter (Dris et al., 2017b; Abbasi et al., 2019; Allen et al., 2019a; Chen et al., 2020; Beaurepaire et al., 2021; Ding et al., 2021; Munyaneza et al., 2022; Pan et al., 2022). Passive and active samplers have been used to sample atmospheric plastic debris in both indoor and outdoor air. Passive samplers collect the atmospheric fallout (dry and wet deposition). Since passive samplers do not require electricity, they are useful in remote areas where electricity is inaccessible. For example, Allen et al. (2019a) used two passive samplers to collect microplastics from a pristine mountain catchment area in France. Passive samplers are also inexpensive, have a simple design, easy to handle, suitable for long exposure periods, and have a high spatial resolution (Fan, 2011). Researchers have taken some measures to reduce potential plastic contamination by using stainless steel or glass funnels and containers for the passive samplers (Chen et al., 2020). A major disadvantage of passive sampling is that it underestimates the amount of smaller plastic debris that settles down slower than larger and heavier particles (Prata et al., 2020a).
Active air samplers, including high volume (Ding et al., 2021), moderate volume (Liu et al., 2019a), and low volume air samplers (Abbasi et al., 2019) have been used to sample atmospheric plastic debris alongside other PM$_{2.5}$, PM$_{10}$, or TSP depending on the filter paper dimensions. There has not been considerable adjustment of the sampling procedure when sampling for the plastic debris. Although active sampling provides an opportunity to present plastic debris in air using a more useful unit ($\mu$g m$^{-3}$), it is still to be used by researchers. To accomplish this, an effective sample cleanup procedure should be carried out to remove the non-plastic material without losing the plastic debris (Prata et al., 2020a). Samples can be digested by H$_2$O$_2$ to remove organic matter, and other non-plastic materials can be removed via density separation in salts, e.g., ZnCl$_2$ (Allen et al., 2019a; Liu et al., 2020; Beaurepaire et al., 2021). However, some types of plastics can react or degrade when in contact with strong acids or alkaline solutions, e.g., polyamide.

Because of the ubiquity of plastic debris in the environment, researchers should be extra careful not to introduce them during before and after sampling and during sample handling. da Costa and Duarte (2020) proposed contamination prevention and assessment protocols to be carried out during sampling of plastic debris. The protocol includes wearing natural fiber during the sampling campaign, avoiding or minimizing air currents, cleaning equipment with ethanol, and using non-plastic containers, e.g.,
glass. In addition, replicates of blanks should be carried out simultaneously during sampling and all solutions should be filtered before use (Prata et al., 2020a).

3.2. Identification and analysis of microplastics and nanoplastics

This subsection will present the identification and analysis methods used in studying atmospheric plastic debris. Fig. 2 summarizes the main characterizations of plastic debris in the literature and the methods used in identifying and analyzing them. The qualities, including principles, advantages, and disadvantages of the methods are summarized in Table 2. The other criteria proposed by Hartmann et al. (2019), namely, solid state and solubility, and origin, were not included in the figure. The methods for identification and analysis are discussed in much detail as follows:

Fig. 2. Summary of the common plastic debris characterizations and analysis methods used.
3.2.1. Naked eye inspection

Naked eye inspection is the cheapest and easiest method for identifying plastic debris. This method can be used to identify the color and shape of plastic debris. However, the method is highly unreliable based on the subjectivity and human error. It is also limited to larger particles that can be detected by the human eye and cannot be relied upon to distinguish plastic debris from other materials. Therefore, instrumentation is needed to provide reliable identification and analysis of the materials. For instance, stereomicroscopes can aid in the visual sorting of plastic debris down to 500 µm (da Costa et al., 2019).

3.2.2. Optical and electron microscopy

Optical microscopes use visible light or fluorescence and lenses to produce magnified images of plastic debris that might not be visible to the naked eye. Optical microscopes are useful for single particle analysis and can give information about the shape and color of plastic debris. However, for smaller-size nanoplastics, the resolution of optical microscopes is limited by diffraction (Schwaferts et al., 2019). Optical microscopes are used to visually sort and count plastic particles, a process which is very labor intensive and still prone to human error (Gottardini et al., 2021). In addition, the technique is inadequate to distinguish plastic particles from similar-looking inorganic and organic materials. In response, the application of computer-vision-based
approaches have been developed in identifying and counting plastic particles (Chaczko et al., 2018; Lorenzo-Navarro et al., 2020; Bertoldi et al., 2021; Lorenzo-Navarro et al., 2021). Lorenzo-Navarro et al. (2020) developed a software that could characterize the shape and count plastic particles at a rate twice as fast as a human expert. However, computer-vision-based approaches are still in the infancy stage, and it would take several years for them to be available for environmental researchers.

Staining particles with fluorescent agents, such as Nile Red dye, has been used to improve identifying plastic debris via fluorescent microscopy (Shim et al., 2016; Erni-Cassola et al., 2017; Maes et al., 2017; Shruti et al., 2022). The fluorescent agent is absorbed onto the surface of the plastic particles, rendering them fluorescent under the microscope. In addition, some fluorescent agents, e.g., Nile Red are solvatochromic, which may allow for polymeric characterization based on the density of polymers (Erni-Cassola et al., 2017). However, fluorescent staining has major limitations, including difficulty of adsorption onto fibers, weak fluorescence of certain polymers, such as PET, PVC, and PU, and fluorescent contaminants, e.g., algae (Erni-Cassola et al., 2017; Tirkey and Upadhyay, 2021; Shruti et al., 2022).

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are other analytical methods used to identify the size, shape, and surface characteristics of plastic particles through beaming electrons through particles (Rocha-
Santos and Duarte, 2015; Cerasa et al., 2021). Additionally, electron microscopy is useful in studying the interaction of plastic particles with other natural and synthetic materials, e.g., hetero-aggregation (Lagarde et al., 2016). SEM creates images of plastic particles by detecting the reflected or knocked off electrons, while TEM detects the electrons passing through the particle. Therefore, the information received from the two electron microscopes are different: SEM gives information about the plastic particle’s surface characteristics, while TEM provides internal information about the plastic particle. Furthermore, for TEM analysis, the plastic particle needs to be very thin and the electron acceleration voltage high to allow the electrons to pass through (Schwaferts et al., 2019). This results in higher resolutions than SEM.

Pairing SEM with energy-dispersive X-ray spectroscopy (EDS) has been used to give additional chemical information of the microplastic sample (Wagner et al., 2017; Wang et al., 2017). EDS detects the X-ray emitted by the plastic particle after interacting with the electron beam and generates a spectrum. The elemental composition is identified from the EDS spectrum, and the type of polymer can be identified by comparing the spectrum with literature or standards. However, in most cases, vibrational spectroscopy is needed to verify the polymer composition of the plastic particle.

3.2.3. Vibrational spectroscopy
The infrared and Raman spectra of samples, obtained from Fourier-transform infrared (FTIR) and Raman spectroscopes, respectively, have been the main method used to identify polymeric compositions of plastic particles (Dris et al., 2016; Käppler et al., 2016; Renner et al., 2018; Xu et al., 2019). In addition, visual information has been received through coupling the spectroscopy techniques with microscopy (Renner et al., 2018). Both techniques are based on the interaction between the molecular vibration with radiation but differ in the way energy is transferred to the sample to change the molecule’s vibrational state (Xu et al., 2019).

FTIR and µ-FTIR (FTIR coupled with microscopy) are nondestructive techniques, which allows the samples to be subjected to additional analyses by other instruments after their polymeric composition has been determined. These techniques are reliable and produce high-quality spectra. FTIR also has a well-developed polymer spectral library for easy identification of the polymer (Zhang et al., 2020c). However, because the technique is diffraction-limited, smaller particles are hard to analyze. Therefore, detection can only be reliable for particles that are 10–20 µm and above, depending on the state of degradation of the particle. Sample preparation is very important before analysis because the spectral quality is affected by the presence of water and the complexity of the matrix (Xu et al., 2019). Of the three operating modes, transmission
and attenuated total reflectance modes have been widely used for analysis of plastic debris (Xu et al., 2019).

Raman and $\mu$-Raman spectroscopy are also nondestructive techniques. The advantage of Raman over IR spectroscopy is the ability to analyze smaller particles (up to 1 $\mu$m) (Schwaferts et al., 2019). However, this depends on the complexity of the sample matrix and sample pretreatment. In addition, Raman spectroscopy’s spectral library is not as extensive as IR. Another disadvantage is that the spectral quality of Raman is affected by fluorescence which can be produced by materials, e.g., clay minerals, in the sample matrix (Xu et al., 2019).

Raman and IR spectroscopy are complementary because molecular vibrations inactive in Raman are active in IR and vice versa (Xu et al., 2019; Kusch, 2020). Käppler et al. (2016) concluded that both instruments are needed for reliable polymeric characterization of plastic particles, especially colored particles. In addition, FTIR can perform rapid and reliable analysis of particles of size 500–50 $\mu$m, while Raman can provide detailed analysis of smaller particles (50–1 $\mu$m).

### 3.2.4. Thermo-analytical and chromatographic and mass spectrometric methods

Chromatographic and mass spectrometric methods have been coupled with thermo-analytical methods such as pyrolysis and thermogravimetry analysis (TGA), to analyze polymeric composition of plastic debris (Dümichen et al., 2015; Hermabessiere
et al., 2018; Ishimura et al., 2021; Liu et al., 2021b). These techniques have not been
used in the analysis of atmospheric microplastics and nanoplastics. Unlike spectroscopy
methods, these techniques are destructive which prevents further analysis of the plastic
debris. However, they have the potential of measuring smaller particles in the nanoscale
range (Zhang et al., 2020c).

In pyrolysis-gas chromatography/mass spectrometry (py-GC/MS), the sample is
thermally decomposed in an inert atmosphere and the components separated in GC
before being analyzed in MS. The type of plastic and organic additives in the plastic
are identified by the GC/MS characteristics of the volatile thermal degradation products.
Py-GC/MS offers improved selectivity and sensitivity in plastic debris analysis. It can
analyze samples without the need for pretreatment and solvent extraction, and
simultaneously identify polymeric compositions and organic additives in the plastic
(Fries et al., 2013; Käppler et al., 2018). However, since only a small amount of the
sample can be analyzed by Pyr-GC/MS, there is a concern of sample representativeness
of the technique. Another main disadvantage is the lack of information on the particle
size and particle size distribution. Therefore, the samples could be analyzed by other
techniques, e.g., optical microscopy or vibrational spectroscopy prior to py-GC/MS
analysis.
TGA-based techniques provide information about the polymeric composition of a sample from the characteristic mass loss of the sample over time as temperature changes in a controlled gaseous environment. The volatile degradation products can be adsorbed on a solid phase adsorber and then desorbed in GC/MS, as in the case for thermal extraction-desorption (TED) coupled with GC/MS; directly transferred to MS for analysis (TGA-MS); or simultaneously undergo calorimetric analysis (TGA-DSC) (Dümichen et al., 2015; Majewsky et al., 2016; Mansa and Zou, 2021). Similar to Py-GC/MS, TGA-based techniques cannot provide information on particle size and distribution. However, it can analyze much larger particle sizes than py-GC/MS (Dümichen et al., 2015). TGA-based techniques have also been coupled with vibrational spectroscopy and GC/MS for analysis of microplastics in the environment (Liu et al., 2021b). TGA-FTIR-GC/MS improved the accurate identification of the polymeric composition of the plastic debris, especially differentiating PE and PP from their volatile thermal decomposition products. The properties of other techniques that have been used in the analysis of plastic debris to a lesser degree, including gel permeation chromatography and liquid chromatography, are presented in Table 2.
Table 2. Summary of the analytical techniques used to characterize microplastic and nanoplastic samples

<table>
<thead>
<tr>
<th>Microplastics characterization</th>
<th>Analysis methods</th>
<th>Principle/information obtained</th>
<th>Coupling</th>
<th>Merits and disadvantages</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymeric composition</td>
<td>Fourier-transform Infrared (FTIR) spectroscopy</td>
<td>The sample is irradiated with IR light. IR is adsorbed depending on the molecular structure and measured in transmission or reflectance or attenuated total-reflectance mode.</td>
<td></td>
<td>• Detects up to 10–20 µm • Spectral quality affected by the presence of water • Non-destructive • Detection affected by the complexity of the environmental matrix • Time-consuming</td>
<td>(Käppler et al., 2016; Cabernard et al., 2018; Xu et al., 2019; Cerasa et al., 2021; Zhou et al., 2022)</td>
</tr>
<tr>
<td></td>
<td>Gas Chromatography-Mass Spectrometry (GC-MS)</td>
<td>Coupled with thermal processes e.g., pyrolysis and thermogravimetric analysis. The volatile thermal degradation products are separated in GC and then analyzed by MS.</td>
<td>TED-GC/MS</td>
<td>• Destructive • Size limited (~100 µm) • Results are only in weight percentage</td>
<td>(Käppler et al., 2016; Xu et al., 2019)</td>
</tr>
<tr>
<td></td>
<td>High Performance Liquid Chromatography (HPLC)</td>
<td>Samples are dissolved before separation in an LC column.</td>
<td></td>
<td>• Highly sensitive • Long sample preparation • Identifies additives</td>
<td>(Ainali et al., 2021; Cerasa et al., 2021)</td>
</tr>
<tr>
<td>Microplastics characterization</td>
<td>Analysis methods</td>
<td>Principle/information obtained</td>
<td>Coupling</td>
<td>Merits and disadvantages</td>
<td>References</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------</td>
<td>------------------------------------------------------------------------------------------------</td>
<td>---------------------------</td>
<td>----------------------------------------------------------------------------------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td></td>
<td>Gel Permeation Chromatography (GPC)</td>
<td>Samples are dissolved and passed through a GPC column. The polymers are separated based on their molecular weight.</td>
<td></td>
<td>• Solvents are necessary</td>
<td>(Käppler et al., 2016; Ainali et al., 2021)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Results are only in weight percentage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Analyses only samples that can be easily cleaned</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Analyses only particles of known polymers</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Requires effective solvents</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Raman spectroscopy</td>
<td>Analyzing the monochromatic light inelastic scattering after interaction with the particle to determine the polymeric composition.</td>
<td></td>
<td>• Detects up to 1 µm</td>
<td>(Käppler et al., 2016; Cabernard et al., 2018; Xu et al., 2019; Prata et al., 2020a; Zhou et al., 2022)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fluorescence often impairs the spectra quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non-destructive</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Time-consuming</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spectral interferences from matrices</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Expensive and difficult to operate on a routine basis</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Differential Scanning Calorimetry (DSC)</td>
<td>Changing heat capacities during the solid-liquid phase transition of a polymer. Paired with TGA</td>
<td></td>
<td>• Cheap and easy</td>
<td>(Xu et al., 2019)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reference materials are required to identify polymer types</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Large particles can cause interference</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Transition temperatures affected by additives and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microplastics characterization</td>
<td>Analysis methods</td>
<td>Principle/information obtained</td>
<td>Coupling</td>
<td>Merits and disadvantages</td>
<td>References</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------------------</td>
<td>-----------------------------</td>
<td>----------</td>
<td>-------------------------</td>
<td>------------</td>
</tr>
</tbody>
</table>
| Surface                      | Scanning Electron Microscopy (SEM) | The microplastic sample interacts with electron beams to produce an image of its surface. | • Produces high-resolution images  
• Affected by charge  
• Non-destructive  
• May require coating  
• Requires little or no sample preparation  
• Provides 3D projection | (Rocha-Santos and Duarte, 2015; Cerasa et al., 2021) |
| Transmission Electron Microscopy (TEM) | The microplastic sample interacts with electron beams to produce an image of its internal structures. | • <0.1 nm  
• High resolution  
• Requires tedious sample preparation  
• Sample must be very thin for analysis  
• Provides only 2D images  
• Requires experienced users  
• High magnifications > 50 million times | (Cerasa et al., 2021) |
4. FATE AND TRANSPORT OF ATMOSPHERIC MICROPLASTICS AND NANOPLASTICS

The 2019 report from the Organization for Economic Cooperation and Development (OECD) indicates that only 9% of plastic is recycled. The rest is either mishandled, incinerated, or landfilled (Kim et al., 2018; Erni-Cassola et al., 2019). Due to low biodegradability, mismanaged plastics undergo fragmentation to form MPs, which accumulate in the environment and pose adverse effects on the ecosystem (Ya et al., 2021).

4.1. Sources and Properties Microplastics and Nanoplastics in the Atmosphere

The concentrations of MPs in the atmosphere are affected by emission sources, intrinsic and extrinsic properties, clearance and degradation mechanisms, and prevailing parameters in environmental sinks. The polymer material, properties, typical applications, and specific gravities of microplastics which disintegrate to MPs and NPs are summarized in Table 1. Although the tabulated information is helpful in establishing the contributions from different sources, pointing out the sources of MPs and NPs involves disclosing the addresses of their origins. This is nearly impossible because, like other persistent pollutants, current MPs and NPs pollution are primarily from historical events (Moore, 2008; Geyer et al., 2017); furthermore, they constantly move from one matrix to another (Wang et al., 2021). Broadly, sources of MPs and NPs can be categorized into primary and secondary, contingent on their formation mechanisms (Costa et al., 2010; Gewert et al., 2015).

Primary MPs are intentionally manufactured raw materials applied to produce plastic products, paints, scrubbing media in exfoliating creams and toothpaste, industrial abrasives, filaments for 3D printing, and drug vectors summarized in Table...
1. For instance, skin-cleaning creams mostly use PE-based beads (Habib et al., 2020). Industrial abrasives applied for blasting are usually made of polyacrylate and PE MPs (Auta et al., 2017). Accidental losses of plastic materials during the operation of 3D printers release NPs into the atmosphere (Stephens et al., 2013). In comparing ABS- and PLA-based filament materials for the printers, the latter produced more MPs (Azimi et al., 2016). Usually, primary MPs have regular shapes; however, after exposure to the environment, they undergo degradation to form secondary MPs with irregular shapes and sizes (Rocha-Santos and Duarte, 2015).

Secondary MPs result from the mechanical breakdown of bulk plastics in products such as car tires, road paint, polymer-modified bitumen, fishing gear, synthetic textile fibers, anticorrosive paint coatings, and plastic wastes, including cigarette butts, used hygiene products, and general plastic waste (Rocha-Santos and Duarte, 2015; Liu et al., 2019b). Exposure of polymer surfaces to sunlight, UV, and ground-level ozone causes the peeling of weathered or oxidized surfaces. In opaque plastics, oxidative breakdown occurs on the exposed surfaces only. Continuous macro and micro-fragmentation of the peeling surfaces lead to the formation of MPs and NPs (Andrady, 2017). This form of degradation is fast in virgin pellets lacking UV stabilizers (Cunliffe and Davis, 1982). The concentrations of MPs and NPs from secondary sources are proportional to the population, GDP, number of vehicles, and laundering operations, as evidenced in the comparison of MP concentrations between Paris and Shanghai, where the latter has double the human population (Liu et al., 2019a).

Plastic product lifetime distribution showed that plastics applied in packaging, consumer and institutional products, textiles, electrical, and transportation industries had useful lifespans of 0–20 years, while those used in industrial machines, building, and construction had between 15–60 years of useful life (Geyer et al., 2017).
Disposable surgical masks are common items in the textile industry since the emergence of COVID-19. Generally, they reduce exposure to MPs and NPs during inhalation. However, re-use or prolonged use generates MPs and NPs, as evident in an investigation where the aging of a mask under environmental forces for two months produced 25,000 items (Shen et al., 2021)—the rate of fragmentation increases with vibrations or application of organic solvents such as detergents and alcohol (Shen et al., 2021). Furthermore, poor disposal methods for surgical masks usually create more MPs and NPs during fragmentation by environmental forces.

Indoor and outdoor MPs concentrations differ significantly as seen in Table 3, due to variations in emission sources and dilution processes. Foams, films, and fragments originate from cleaning products, packaging materials and storage containers (Yuan et al., 2019). Recent investigations indicate that bubble-busting during sea sprays transfers MPs and NPs from marine environments to the atmosphere (Trainic et al., 2020; Shiu et al., 2022). In California, the indoor concentrations were 12.6 fragments m⁻³ and 3.3 fibers m⁻³, while outdoor concentrations were 6.6 fragments m⁻³ and 0.6 fibers m⁻³ (Gaston et al., 2020). In contrast, in Shandong Province, China, outdoor MPs during wet deposition contained 95% fibers, 4%, while films and foams formed less than 1% (Zhou et al., 2017). Predominant lengths for fibrous MPs were 100–700 μm (Dris et al., 2017a; Allen et al., 2019b). Overall, indoor MPs originated from traditional cleaning activities for synthetic fabrics such as clothes, furniture covers, and carpets using tools such as brooms. Unlike vacuuming, traditional cleaning practices such as sweeping increase the turbulence in indoor environments and resuspend more microplastics.

The dominant polymer species for MPs in the atmosphere include PS, PP, PE, PET, Polyamide, polyester and poly-silicon, as seen in Table 3 (Liu et al., 2019b; Gaston et al., 2020). In an investigation using micron-Raman, PVC and PE were predominant,
while analysis by micro-FT-Ir indicated that PS, PT, and PET were prevalent (Gaston et al., 2020). During wet and dry deposition in the remote mountains of France, 18% of the fibers were PP and PET (Allen et al., 2019b). In a study of suspended atmospheric MPs in the west Pacific Ocean, textile microfiber was the dominant source, where PET from the abrasion of synthetic fiber clothes formed the largest proportion (Liu et al., 2019b).

4.2. Fate of MPs from the atmosphere and their environmental sinks

Due to low degradation and mineralization rates, the fate of atmospheric MPs largely depends on their retention time in the atmosphere, which is determined by particle size distribution at the sources, specific gravity, shape, fragmentation forces, and prevailing weather conditions (Liu et al., 2019b). The specific gravities of MPs and the predominant shapes shown in Table 1 determine the transportation ranges for most MPs. MPs with low-specific gravity polymers such as PP, PE and PS undergo long-range transportation, as evidenced in French Pyrenees presented in Table 3, which is remote and had a dry deposition rate of 365 MPs m$^{-2}$ day$^{-1}$. Modified PP polymer fibers, with the lowest specific gravity, are the most susceptible to long-range transportation via wind (Allen et al., 2019b). In contrast, heavier polymer MPs such as PET, polyamide (PA) and polyacrylate deposit close to their emission sources (Browne et al., 2010). In an investigation carried out in twelve countries in North and South America, Eastern Europe and Asian countries, the respective average concentrations of ambient air PET and PC were about 5900 μg g$^{-1}$ and 8.8 μg g$^{-1}$ (Zhang et al., 2020a).

MPs and NPs in ambient air environments undergo continuous mechanical breakdown due to structural integrity and fragmentation loss under the influence of physical, biological and chemical elements (Shah et al., 2008). This type of mass loss
occurs without any degradation and it is proportional to the surface area due to its limitation on exposed surfaces. Since MPs and NPs in marine environments are in the size ranges of food for filter feeders, they are easily ingested and subjected to digestive fragmentation inside the GI of some organisms such as Antarctic krill (Moore, 2008).

In a study by Chamas et al. (2020), the speed of the breakdown is quantified using the following equation:

\[
k_d = - \frac{dm}{dt \times \rho \times SA}
\]

where \( k_d \) is the rate of the breakdown, \( \rho \) is the density and \( SA \) is the surface area of the piece of polymer.

The decomposition of organic materials involves breaking long, complex organic molecules into simple organic and inorganic molecules. Degradation herein describes disintegration mechanisms such as chemical modification and depolymerization of MPs and NPs, where the final step is the complete mineralization to form CO\(_2\) and H\(_2\)O (Chamas et al., 2020). In the atmosphere, it occurs under the influence of physical conditions such as heat, light, moisture, oxygen, and ozone (Majewsky et al., 2016; Chamas et al., 2020).

Contingent to the causal agents, degradation can be categorized into bio-, photo-, thermal-, thermo-oxidative degradation, ozonation or hydrolysis (Andrady, 2011). Biodegradation involves the action of microbes (Li et al., 2016; Li et al., 2022a). Photo-oxidative degradation involves the action of the sunlight and is several orders of magnitude higher than the other mechanisms (Andrady, 2011). The viscous matrix of reactants and products involved in thermal degradation for plastics diffusion and segment mobility of the polymer building blocks limit the reaction rate until glass transition, melting, and softening temperatures are attained (Chamas et al., 2020).

Thermo-oxidative degradation is common in MSW in landfills where nominally
biodegradable polymers such as polylactic acid, polyhydroxybutyrate, and poly(3-
hydroxybutyrate-co-3-hydroxyvalerate) degrade at 80–100 °C (Gardette et al., 2013).

Other polymers such as LDPE and HDPE take up to hundreds of years to degrade under
similar environments (Liu and Yang, 2019). Ozonation is known to degrade 90% of
MPs mass in 60 minutes at temperatures ranging from 30–45 °C through cross-chain
linking reactions (da Costa et al., 2016). Hydrolysis is typical for the degradation of
PET. The process is slow under room temperature, but the rate increases under acidic
or basic conditions (Gewert et al., 2015). The increase in the degradation rate was
insignificant after blending the plastic materials such as LDPE with fillers such as starch
(Chamas et al., 2020).

Clearance for MPs in the atmosphere depends on precipitation and wind (Andrady,
2011; Allen et al., 2019b; Trainic et al., 2020). Precipitation correlates positively with
the MPs fallout. The concentration of ambient air MPs decreased with increasing
altitudes (Liu et al., 2019a). Atmospheric transportation is supported by an investigation
where fibre, fragment, and granules compositions in marine air MPs were 60%, 31%,
and 8%, respectively (Liu et al., 2019b). After transportation through wind and
waterways, most of the terrestrially sourced MPs culminate in seas, forming the most
significant portion of marine waste (Auta et al., 2017). The global surface circulation
model of the ocean waters indicates five large ocean gyres which are accumulation
zones for the MPs (Law et al., 2010). A μ-Raman spectroscopy analysis for MPs in the
ambient air surrounding North Atlantic ocean indicated the presence of PS, PE and
poly-silicone polymer compounds, implying long-range transportation. On the other
hand, MPs in the sea water belonged to PS and PP, suggesting local contribution to
MPs.
To interpret results on MPs degradation appropriately, parameters including temperature, relative humidity, microbial loading, additives, surface area, size, and shape of MPs are necessary. Prevailing meteorological parameters, including wind, temperature, relative humidity, and rainfall, affect the transportation of atmospheric MPs and NPs (Liu et al., 2019b; Chamas et al., 2020). Additionally, their solubilities, shape, size, structures, and intrinsic and extrinsic properties of the polymer, including type, molecular weight, additives size and shape of MPs, affect their transportation. Literature indicates that the daytime concentrations are twice those of nighttime hours (Liu et al., 2019b). This is likely due to the availability of emission sources and appropriate environmental parameters for fragmentation.
<table>
<thead>
<tr>
<th>Area of study</th>
<th>Type of environment</th>
<th>Season/ Time</th>
<th>Concentration/ Deposition rate</th>
<th>Size</th>
<th>Dominant Polymer</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal California, USA</td>
<td>Urban</td>
<td>Indoor</td>
<td>3.3 fibers m(^{-3})</td>
<td>58.6 μm</td>
<td>PVC, PE, PS, PE, PET</td>
<td>(Gaston et al., 2020)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outdoor</td>
<td>12.6 fragments m(^{-3})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.6 fibers m(^{-3})</td>
<td>104.8 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ahvaz city, Iran</td>
<td>Urban</td>
<td>Outdoor</td>
<td>late summer–early winter</td>
<td>0–0.017 pieces m(^{-3})</td>
<td>10 μm</td>
<td>PET, PA, PP</td>
</tr>
<tr>
<td>French Pyrenees</td>
<td>Remote catchment</td>
<td>Outdoor</td>
<td>Nov 2017–March 2018</td>
<td>249 fragments m(^{-2})</td>
<td>Fibers: ~750 μm</td>
<td>(Allen et al., 2019b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>73 films m(^{-2})</td>
<td></td>
<td>Fragments: 300 μm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>44 fibers m(^{-2})</td>
<td></td>
<td>PS, PE, PP, PVC, PET</td>
<td></td>
</tr>
<tr>
<td>Shanghai</td>
<td>Urban</td>
<td>Outdoor</td>
<td>March–April 2017</td>
<td>1.42 pieces m(^{-3})</td>
<td>582 (23–9555) μm</td>
<td>PET, PE, PES, PAN, PAA</td>
</tr>
<tr>
<td>Northwestern China sea</td>
<td>Remote</td>
<td>Outdoor</td>
<td>Fall</td>
<td>0.035 pieces m(^{-3})</td>
<td>0</td>
<td>PP, RY, PE, PA, PES, PR</td>
</tr>
<tr>
<td>Hamburg, Germany</td>
<td>Urban</td>
<td>Outdoor</td>
<td>-</td>
<td>275 pieces (fragments and fibers) m(^{-2})</td>
<td>Fragments: &lt;63 μm</td>
<td>PE, EVAC, PTFE, PVA, PET</td>
</tr>
<tr>
<td>Region</td>
<td>Location</td>
<td>Environment</td>
<td>Volume</td>
<td>Fiber Size</td>
<td>Fragment Size</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>----------</td>
<td>-------------</td>
<td>--------</td>
<td>------------------</td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td>Outdoor</td>
<td>-</td>
<td>1.5 pieces m$^{-3}$</td>
<td>Fibers: 300–5000μm</td>
<td>Fragnets: 42–815 μm</td>
<td></td>
</tr>
<tr>
<td>Central Spain</td>
<td>Urban</td>
<td>Outdoor</td>
<td>13.9 pieces m$^{-3}$</td>
<td>Fibers: 84–1709 μm</td>
<td>PAN, PES, PA, PP, PVC,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PE, PS, PU, Pol.</td>
<td>(González-Pleiter et al., 2021)</td>
</tr>
</tbody>
</table>
5. ECOLOGICAL AND HUMAN HEALTH RISK OF MICROPLASTICS AND NANOPLASTICS

Due to their persistence in the environment, MPs and NPs accumulate up the food chain. This section covers exposure pathways and adverse health effects to humans.

5.1. Exposure routes

After disposal of plastics into the environment, they accumulate, fragment, and degrade to form MPs and NPs. Humans are exposed to these particles through inhalation, ingestion, and dermal exposure. Since indoor concentrations are usually higher than outdoor concentrations, exposure for office workers might exceed those in outdoor environments. Also, due to the nature of the industry, individuals working in the polymer industry might suffer higher vulnerabilities in instances of high ground-level concentrations and a lack of protective masks.

Although worn to prevent inhalation of toxic pollutants, aged surgical masks expose individuals to higher MPs and NPs due to their proximity to the air inlets for the respiratory system (Aragaw, 2020). Inhalation of these MPs in individuals with compromised lung clearance mechanisms leads to acute and chronic inflammations in the lung (Gasperi et al., 2018). Accumulation of MPs with lengths exceeding 250 μm is evident in the lungs of human cadavers (Prata et al., 2020b).

MPs inhaled and deposited in the upper and central sections of the respiratory system are usually effectively cleared through mucociliary clearance, sneezing, coughing, and swallowing (Mutuku et al., 2020a). Consequently, they end up in the GI, where they amplify exposure from ingestion of drinking water, seafood, and personal care products such as toothbrushes and scrubs. In an indoor environment, the daily PET
exposure to infants via ingestion was 4000–150000 μg kg-bw-1 day-1 (Zhang et al., 2020a). Contingent to small sizes, nanoplastics bypass most filtration mechanisms in the human lungs and reach deeper downstream sections of the human airways, for instance, the alveolar region. Here, they are removed via phagocytosis and lymphatic transportation. Limitations of the clearance mechanisms at the alveolar area cause the MPs to pass and get into the bloodstream amplifying the concentrations via dermal exposure, which although uncommon, involves microbeads in cosmetic and self-care products meant for exfoliation (Domenech and Marcos, 2021).

5.2. Effects on ecology and human health

Although plastic polymers are generally inert, some researchers have pointed out the potential decline in respiratory and ventilation function due to the inhalation of MPs. Indicatively, MPs have been found in the lungs of a human cadaver, where particle size distribution affects tissue accumulation kinetics and distribution patterns (Pauly et al., 1998; Amato-Lourenço et al., 2021). Endocytosis by epithelial layer cells causes MP retention in the lungs, where they cause intensive oxidative stress (Liu et al., 2021a; Li et al., 2022b). Phagocytosis for MPs of sizes greater than 0.5 μm leads to accumulation in the liver and spleen, which induces acute inflammation and apoptosis (Tang et al., 2022).

Additives make up to 50% of the plastic composition in weight. Some additives include metal-based catalysts like Sb and Zn, which cause adverse health effects to humans (Tolinski, 2015). Because MPs are hydrophobic and possess a high surface area to volume ratio, they are vectors for POPs such as PAHs and PCBs (Moore, 2008). Investigations on the chemical compositions of plastics indicate their most critical components as copolymers and additives. For instance, the compact microfibers in cigarette butts have high concentrations of plasticizers and other compositions,
including NO$_3^-$, PAHs, C$_2$H$_4$O, CH$_2$O, Cd, Pb, and As, which remain adsorbed on the MPs after disposal in the environment (Dobaradaran et al., 2017). Plasticizers such as phthalates are added to plastics to improve their flexibility and durability. Those in face mask fabrics have been shown to induce adverse health effects in humans. UV stabilizers and antioxidants are common additives in polymer processing to prevent their degradation in the environment. Organophosphate ester and brominated flame retardants, including hexabromocyclododecane (HBCD), polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs), are not chemically bound to the polymer structure and usually leach into the environment (Fromme et al., 2014; Kung et al., 2022). Therefore MPs act as vectors for the transportation and bioaccumulation of waterborne organic compounds from low to high trophic levels. MPs harbor harmful microorganisms and shield them from adverse effects in the atmosphere and hence promoting infections (Liu and Schauer, 2021).

The decomposition of Styrofoam, made of expanded polystyrene foam, formed styrene monomer, styrene dimer and styrene trimer, where the former is a known carcinogen while the latter are suspected carcinogens. The decomposition of organic materials involves breaking long, complex organic molecules into simple organic and inorganic molecules. This process usually releases bisphenol A (BPA) and PS oligomer into the water, which are known hormone disruptors and affect the reproductive system.

Accidental ingestion of MPs by organisms causes bio-accumulation up the food chain (Peng et al., 2017). The main effect of MPs on small aquatic and terrestrial organisms is the reduction of feeding efficiency (Moore, 2008). Specifically, for filter feeders in marine environments, ingestion of MPs reduces the capacity to consume nutritional food materials. For larger animals and humans, accumulation in organs is
the main adverse effect. There is also the possibility of intoxication caused by the chemicals adsorbed on the polymers.

Adverse effects on human health include inflammation and inducing the generation of Reactive oxygen species (ROS). Experiments have indicated an increase in antioxidant-related activities upon exposure to MPs, including catalase, glutathione peroxidase, and total glutathione (Wen et al., 2018). Several studies have also linked MPs to occupational diseases for workers in the polymer industry (Mastrangelo et al., 2003; Murashov et al., 2021). Chronic inflammation due to inhalation of MPs causes fibrosis and cancer and is disabling for patients with preexisting respiratory diseases such as asthma and chronic obstructive pulmonary disorder (Adeloye et al., 2015; Mutuku et al., 2020b).

Unreacted monomers in MPs released by polycarbonate, polystyrene and PVC mesoplastics are carcinogenic, mutagenic, and a reproductive hazard. MPs containing additives and dyes, such as PVC, pose increased inflammation than additive-free ones. Literature suggests that some MPs, such as PE, PVC, and PS, have higher capacities to release initially adsorbed PCBs and PAHs than other PM in the atmosphere. In other polymers such as PA and PU, these toxic compounds are almost bonded irreversibly through hydrogen bonding and therefore rarely released into the environment (Liu et al., 2019c). This poses a significant danger due to the high carcinogenic and mutagenic potentials of PCBs and PAHs.

6. CHALLENGES AND OUTLOOK

To date, exposure and risk assessments on MPs are misleading because they fail to identify the specific type of polymer and the interactions between the microplastics
and biota. Another challenge involves deficiencies in the isolation of MPs from natural particles during sampling, analysis, and characterization. Furthermore, accurate information on sources, dispersion methods, standardized metrics, parameters, and timelines required to ascertain the concentrations and degradation of MPs is currently unattainable. Lastly, disentangling the toxicity of MPs from those of non-food natural particles in the micrometer size range, such as clay, chitin, and cellulose is still a challenge in the scientific community.

With the current annual global plastic wastes generation rates and near-permanent contamination of the atmosphere with MPs, environmental protection agencies have restricted landfilling of plastic waste in regions such as the EU. This has compelled the adoption of waste-to-energy treatments, including incineration, gasification, or pyrolysis. However, incineration, the most common of the three, emits persistent organic pollutants, halogens, and heavy metals depending on the incinerator design, operation parameters, feeding material, and air pollution control technology (Verma et al., 2016). A more feasible approach involves the adoption of circular economy, where polymers are recycled for use as long as possible. This limits the volume of plastic waste and, consequently, the emission of MPs and NPs. Furthermore, increased adoption of biodegradable polymers will limit the retention time of mesoplastics in the environment and the MPs emitted.

7. CONCLUSIONS AND FUTURE PERSPECTIVES

Microplastics and nanoplastics are intentionally manufactured in the industry or occur from the continuous fragmentation of plastic products. One of the current
challenges is the lack of standardized procedures for sampling, analyzing, and quantifying plastic debris is evident in the current literature. There are significant efforts made to create reliable criteria for defining microplastics and nanoplastics that go beyond their size characterization. Ordinary MPs shapes include fibers, fragments, films, foams, and flakes where polyester-, polyamide-, and polyacrylate-based fibers dominate the ambient air indoor environments. Indoor concentrations of MPs exceed the outdoor averages in most urban areas. Therefore, to reduce the resuspension of MPs, vacuuming is recommended over turbulent traditional cleaning practices such as sweeping. Limited use of synthetic fiber-based fabrics such as carpets, furniture covers or curtains is recommended. Additionally, air filtration and conditioning systems should be maintained to capture indoor MPs.

The timelines for the degradation of most plastics are in the range of hundreds-thousands of years, where the degradation rate is affected by intrinsic and extrinsic factors of the polymer, prevailing environmental conditions, and actions of organisms with degradation capabilities. To curb pollution involving MPs, legislation such as polluter pays, corporate social responsibilities (CSR), and consistent cleaning operations of water bodies contaminated with plastic debris should be adopted to reduce the chances of MPs formation and inter-transfer among environmental matrices. Finally, environmental protection agencies need to set evidence-based environmental and occupational limits for ambient air MPs and NPs concentrations.

**ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>Acrylonitrile butadiene Styrene</td>
</tr>
<tr>
<td>DSC</td>
<td>Differential Scanning Calorimetry</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy-Dispersive X-ray</td>
</tr>
<tr>
<td>EPS</td>
<td>Expanded polystyrene</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>EVAC</td>
<td>Ethylene vinyl acetate</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier-transform infrared</td>
</tr>
<tr>
<td>GC/MS</td>
<td>Gas Chromatography/Mass Spectrometry</td>
</tr>
<tr>
<td>GPC</td>
<td>Gel permeation chromatography</td>
</tr>
<tr>
<td>HDPE</td>
<td>High-density Polyethylene</td>
</tr>
<tr>
<td>HPLC</td>
<td>High Performance Liquid Chromatography</td>
</tr>
<tr>
<td>LDPE</td>
<td>Low-density polyethylene</td>
</tr>
<tr>
<td>MPs</td>
<td>Microplastics</td>
</tr>
<tr>
<td>NP</td>
<td>Nanoplastics</td>
</tr>
<tr>
<td>PA</td>
<td>Polyamide</td>
</tr>
<tr>
<td>PAA</td>
<td>Poly(N-methyl acrylamide)</td>
</tr>
<tr>
<td>PAN</td>
<td>Polyacrylonitrile</td>
</tr>
<tr>
<td>PC</td>
<td>Polycarbonate</td>
</tr>
<tr>
<td>PE</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>PES</td>
<td>Polyester</td>
</tr>
<tr>
<td>PET</td>
<td>Polyethylene terephthalate</td>
</tr>
<tr>
<td>PLA</td>
<td>Polylactic acid</td>
</tr>
<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>PS</td>
<td>Polystyrene</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
</tr>
<tr>
<td>PU</td>
<td>Polyurethane</td>
</tr>
<tr>
<td>PVA</td>
<td>Polyvinyl alcohol</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl chloride</td>
</tr>
<tr>
<td>PVE</td>
<td>Polyvinyl ether</td>
</tr>
<tr>
<td>RY</td>
<td>Rayon</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission Electron Microscopy</td>
</tr>
</tbody>
</table>
References


