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Review

Microplastic Pollution Research Based on the VOS Viewer Software: Research Trends, Ecological Effects, and Testing Methods

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Abstract: Microplastics (MPs) are receiving increasing attention because of their potential harm to the environment and human health. This research aims to summarize the abundance, toxicological effects, and analysis methods of MPs, as well as present their current status and trends in scientific research. Bibliometric analysis confirmed a substantial rise in annual research papers on MPs, predominantly over the previous nine years. The central research areas relating to MPs include distribution, sources, toxic effects, analytical approaches, and adsorption of MPs with other pollutants. Airborne MPs are a primary source of microplastic pollution in remote areas. Humans may inhale and ingest MPs, leading to the accumulation of these particles in their bodies. Additionally, microplastics can have biological toxicity that poses a potential threat to human health. Standard procedures for sampling and both qualitative and quantitative analysis of microplastics in various environmental media must be established urgently to enable effective comparison of experimental conclusions.

Keywords: microplastics; research trend; ecological effect

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1. Introduction

Plastics are widely used in agriculture, fishing, packaging, transportation, and other fields. Global plastic use has soared from 2 million tons in 1950 to 348 million tons in 2017 [1]. Plastic waste is increasing in the environment, but only 6~26% of it is recycled every year [2]. Plastic has a life span of hundreds of years, and it can generate a large number of microplastics (MPs) through a series of physical, chemical, and biological reactions in the environment. An estimated 6.3 billion tons of plastic waste were generated from 1950 to 2015 [3].

The MPs are defined as small particles or fragments with a diameter of less than 5 mm formed by the breaking or aging of plastic products, which can be further divided into nanoplastics (1~100 nm), submicron-plastics (100~1000 nm), MPs (1~1000 μm), mesoplastics (1~10 mm), and macroplastics (1 cm and larger) [4]. In recent years, MPs as an emerging and challenging research field has developed rapidly [5]. In particular, the research literature shows explosive growth from 2014 to 2023. There is an urgent need for a systematic review of the development of MPs over a long period of time. A dynamic analysis from the microscopic and macroscopic views is needed to provide references and a literature base for subsequent studies. Therefore, this paper uses visual and research trend analysis for the MP literature, discusses the ecological effects and detection methods of MPs, and uses metrological methods to conduct quantitative.

2. Materials and Methods

This study conducted a literature search using the Web of Science core collection from 2004 to 2023, incorporating the subject terms "micro-plastic" OR "micro-plastics" OR "microplastics" OR "microplastic". The search was refined by selecting articles and reviews written in English. After sifting through relevant literature on MPs, metal materials, material mechanics, and physics, a total of 11,777 pieces of English literature were retrieved. The scientific literature visualization software VOSviewer (number: 1.6.19) and Scigama Graphica (number 1.0.34) were utilized in this study.

3. Discussion

3.1. Bibliometric Analysis of MPs

3.1.1. Analysis of the Publications

The number of English publications on MPs has rapidly increased from 2004 to March 2023. In 2015, the United Nations Summit on Sustainable Development proposed Article 14 of the 2030 Agenda for Sustainable Development, calling for the prevention and significant reduction of all forms of marine pollution by 2025. Subsequently, the United Nations General Assembly included the issue of marine MP pollution in its 2017 resolution titled Our Ocean, Our Future: Call for Action in 2017. Both meetings encouraged further research and development on MPs.

The annual and cumulative number of articles on MPs is shown in Figure 1. The earliest article about microplastics in WoS was in 2004, and a few articles were published in the following years. It was not until 2014 that the number of publications on MPs increased rapidly. Especially since 2019, the annual increase in literature related to MPs has been above 1000, and in 2022, it even reached 3548, accounting for 30.12% of the total analyzed publications. As shown in Figure 2, 147 countries have participated in the research on MPs, indicating that the problem of MP pollution exists widely around the world and has gained global attention.

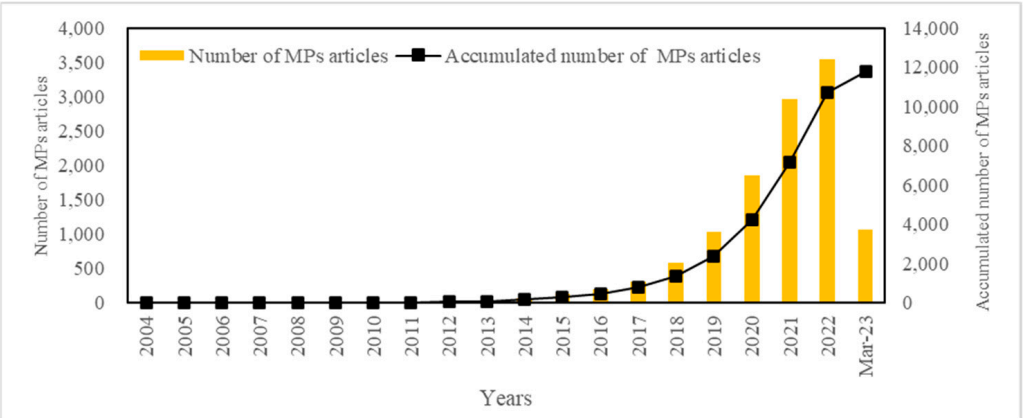

Figure 1. Annual and cumulative number of publications on MPs.

3.1.2. Study Trends Analysis on MPs

MPs pollution is a significant factor in environmental pollution. Due to its characteristic of being easily accumulated and difficult to degrade, it poses a threat to different parts of the world and various environmental media through different transmission means. As a result, research on MPs pollution is globally significant, and numerous countries participate in related research and exhibit relatively close international cooperation. We conducted a statistical analysis of the number of publications and research collaborations among countries using Web of Science data and visualized the results with VOSviewer and Scimago Graphica, as depicted in Figure 3. Nodes in the visualization represent the number of publications made by a specific country. Larger nodes indicate a higher number of publications, while darker nodes indicate a higher count of cooperative publications with other

countries. Thicker connecting lines indicate stronger cooperative relationships between countries. The analysis of Figure 3 reveals that among the countries that conduct research on MPs pollution, China, the United States, the United Kingdom, Australia, Canada, and others have the highest number of publications. We have observed that these countries not only exhibit a robust research capacity but also possess an extensive research network. Therefore, it follows that most of the research on MPs pollution stems from these countries.

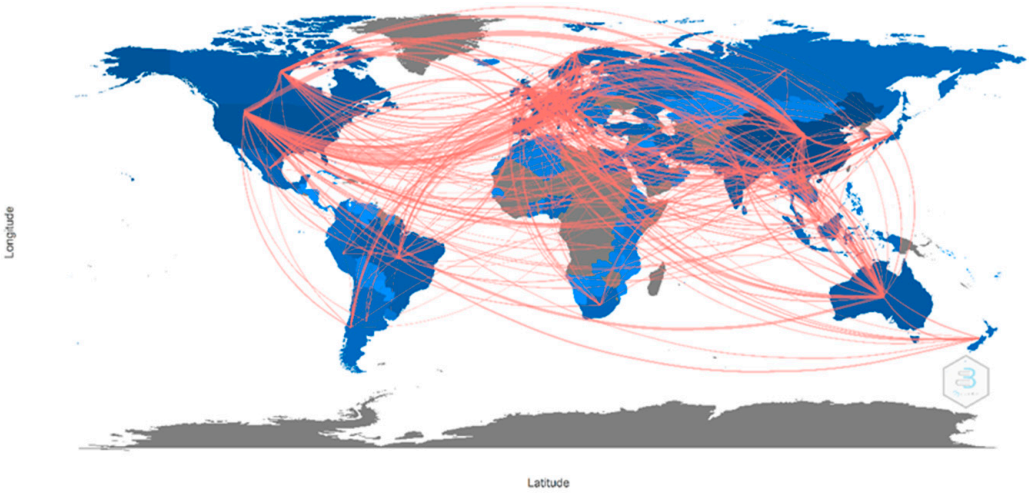

Figure 2. National Cooperation Map.

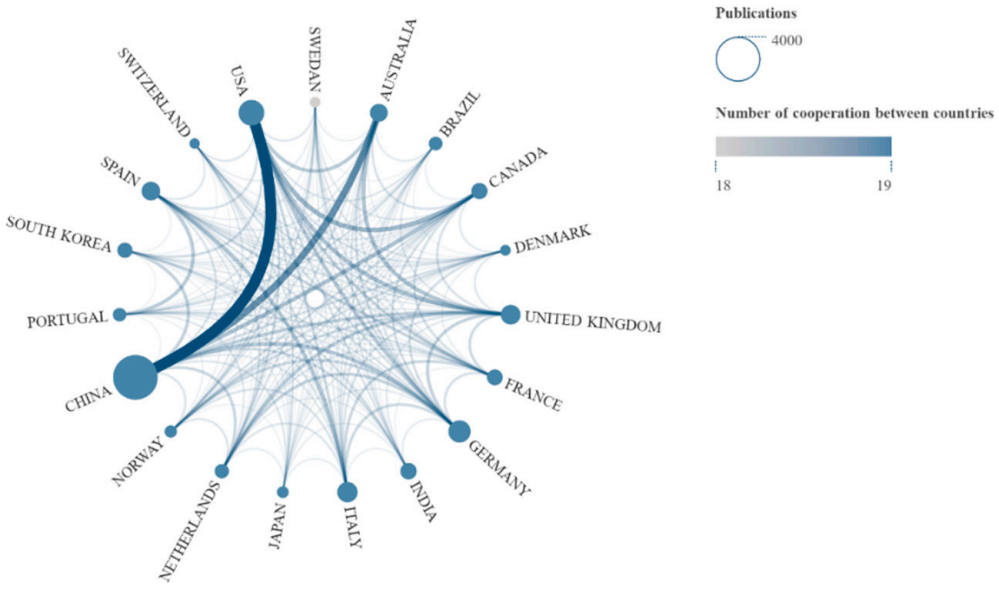

Figure 3. Top 20 national cooperation networks for WoS publications in the field of MPs.

The results of the cluster analysis of keywords are shown in Figure 4. The research hotspots for MPs are concentrated in the following areas: (1) the distribution and sources of MPs; (2) the exposure and toxic effects of MPs; (3) the research methods for MPs; and (4) the adsorption of MPs with other pollutants in the environment.

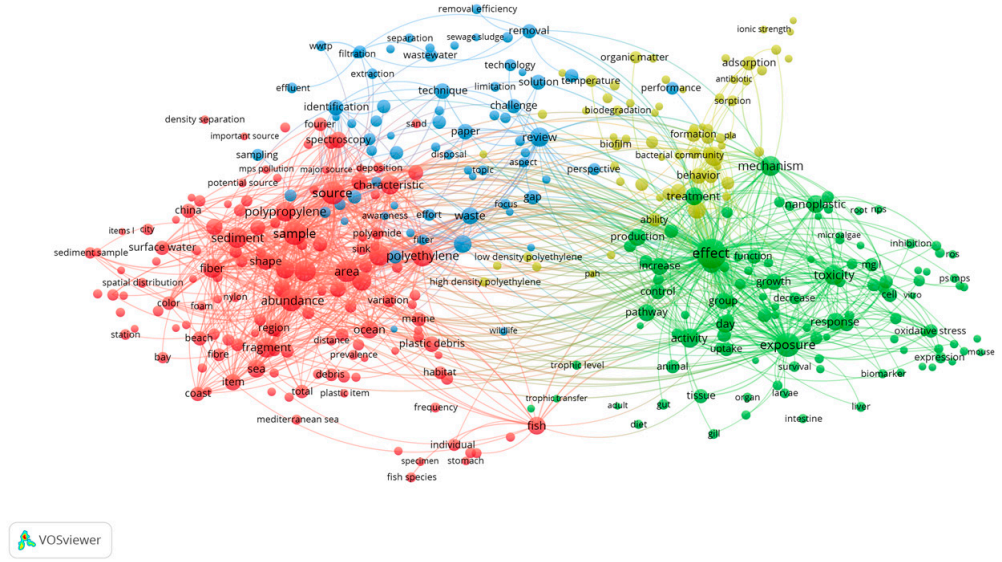

Figure 4. Cluster analysis of MPs.

3.2. Ecological Effects of MPs

3.2.1. Abundance and Distribution of MPs

MPs were initially identified in the sediments near the beach and estuary of Plymouth, which prompted a worldwide upsurge in research on MPs [6]. MPs in oceans, also known as '$PM_{2.5}$ in the ocean,' pose a serious threat to the marine ecosystem by accumulating in marine habitats [7]. Previous studies focused mainly on MPs in the marine environment, but they have also uncovered their presence in soil, surface water, the atmosphere, and organisms. Table 1 presents the characteristics of MPs in different environmental media as reported in international references. Large differences exist in the particle size and abundance of MPs among different regions, even when the MPs are in the same medium. For instance, MPs in the South Indian Ocean were much less abundant, with only 2.3 ± 2.1 items/m^3, whereas the abundance of MPs in the Atlantic Ocean ranged from 6.03 to 10.03 items/m^3 [8,9]. The abundance of MPs at a sampling location is negatively correlated with its distance from the coast. The abundance of MPs at the study location exhibits a negative correlation with its distance from the coast. Additionally, MPs were detected in the waters adjacent to the Galapagos Archipelago, recognized as a prominent tourist destination and one of the most biodiverse ecosystems globally, albeit with a relatively low concentration of MPs in the surface water, measuring only 0.22 ± 0.09 μp/m^3 [10]. The waters near inhabited islands have a much higher abundance of MPs relative to other oceanic areas. For instance, under the surface water of Zhubi Island [11], 90% of MPs found were smaller than 1 mm, with an average of 4933 ± 1396 items/m^3. This phenomenon is mainly attributable to the swift construction of Zhubi Island in recent years, with a consequential impact on neighboring countries. Persistent human activities generate terrestrial sewage that moves vast amounts of MP into the ocean. Moreover, the prevalence of MPs is ubiquitous, and they can be found in ice cores and the sea area below the central Arctic basin [12]. For MPs with a size of less than 1 mm below the central Arctic basin, approximately 52% were found in the ice core, which is higher than the 34% found in the water under the ice. Global warming's consequence, the melting of glaciers, is expected to increase MPs' prevalence in the sea.

Sediment and soil, in addition to the ocean, can serve as substantial sinks for MPs. Samples from the Bohai Sea off the coast of China showed an average MP abundance of 171.8 ± 55.4 items/kg, which may be attributed to the influence of neighboring industrial parks, marine aquaculture areas, and the inflow of the Yellow River [13]. The average MP abundance found in cultivated soil samples from the Yunnan Plateau was 9.8×10^3 items/kg, higher than that in the sediment [14] of the Bohai, with 89.3% of MPs in

soil samples measuring less than 500 µm in size. This result is mainly due to the long-term presence of plastic mulch residues in the soil. Compared to soil and water, MPs in the air are less abundant and smaller in size [15]. In China's cities, such as Shanghai, the average MP abundance ranges from 0 to 4.18 items/L. At a height of 80 m, 33 m, and 1.7 m, particles measuring 23 to 1000 µm in size account for 68.75%, 99.9%, and 88.37% of MPs, respectively [16]. Klein et al. [17] studied MPs in Hamburg's urban air by analyzing atmospheric fallout and found that 95.92% of MPs were 63–300 µm in size, which are more easily dispersed and inhaled by humans. Other studies by Napper et al. [18] and Huang et al. [19] have shown that MPs found in sputum are closely linked with those in the air, as is the case with MPs found on Mount Everest.

MPs have been found in fish caught in Poyang Lake, China, with 82.1% of MPs being between 500 µm and 5 mm in size, while 73.1% of MPs in the surface water of this lake are smaller than 500 µm [20]. These findings suggest that fish may ingest MPs, and larger particles may remain inside the fish. Additionally, MPs have been detected in human blood [21], lungs [22], placenta [23], sputum [19], and feces [24]. Since MPs can penetrate biological barriers and infiltrate organisms, they pose a serious threat to human health.

Table 1. Summary of MP pollution characteristics.

Sample	Composition	Colours	Shape	Abundance	Reference
Sea water	RY, PET, PE, PA, PVDC	PA PE PET RY PVDC	Fibers	2.3 ± 2.1 items/m^3	[8]
Sea water	PES (22%), biopolymers (22%), PP (18%), ACR (14%), PE (9%), PA (8%), PVC (2%), elastomers (1%), others (5%)	Fibers Fragment	Fibers (84%), Fragments (16%)	10.03 ± 2.21 items/m^3	[9]
Sea water	PP (25%), PA (18%), PS (16%), PVC (12%)		Fibers (44%), Fragments (6%), Pellets (44%), films (2%)	4933 ± 1396 items/m^3	[11]
River water	PP, PE, PS	/	Pellets, Fibers, Fragments	Upper reaches: 2.355 ± 0.375 no./m^3 Lower reaches: 5.733 ± 0.85 no./m^3	[25]
Sea water	PES (70%), PA (23%), PVC (7%)		Fibers (79%), Fragments (21%)	0 to 18 items/m^3	[12]
Ice core	PES (57%), PA (19%), PU (6%), styrene/acrylates (6%), PAN (6%), PVC (5%), other polymers (1.3%)			2 to 17 items/L	
Air	PET (29.63), PE (25.93%), PES (18.52%), PAN (11.11%), RY (7.41%), EVA (3.7%), ALK (3.7%)	80 m 33 m 1.7 m	Fibers (67%), Fragments (30%), Pellets (3%)	0 to 4.18 items/L	[15]
Atmospheric fallout	PE (48.8%), EVA (22%), PET (9.8%)	/	Fragments (95%), Fibers (5%)	136.5 to 512.0 items·m^{-2}·day^{-1}	[17]
Soil	/		Fragments (78.3%)	9.8 × 10^3 items/kg	[14]
Snow	PES (56%), AC (31%), PA (9%), PP (5%)	/	Fibers (94.64%), Fragments (5.36%)	30 ± 11 items/L	[18]

PP: polypropylene; PB: polybutadiene; EVA: ethylene-vinyl acetate copolymer; PE: polyethylene; PS: polystyrene; PP: polyacrylic acid; ACR: acrylates copolymer; PA: polyamide; PAN: polyacrylonitrile; PU: polyurethane; PET: polyethylene glycol terephthalate; PVC: polyvinyl chloride; PES: polyester; RY: rayon; AC: acrylic.

3.2.2. Source and Transfer of MPs

MPs in rivers can flow and pollute the ocean. In freshwater, microfibers are one of the main shapes of MPs and mainly come from textile washing. Each wash of an old pair of jeans can release 56,000 ± 4100 microfibers [26]. The polyester emissions from domestic washing machines in Finland are 150,000 kg per year [27]. In the UK, 6490–7165 tons of microfiber can be emitted annually through washing [28]. The release of microfibers is exacerbated by the washing process when the garment is torn, and 84% of the microfibers released come from the torn edges. The amount of microfiber released from the initial wash is usually the largest and decreases with increasing wash frequency until it stabilizes. Detergent, softener, and agitation time all affect the release of microfibers [29]. In addition, microplastics in cosmetics are another source of freshwater. Three-quarters of the brands selected by Fendall et al. had MPs with particle sizes < 100 µm, which means that these microplastics are difficult to capture by wastewater treatment plants [30]. Although sewage treatment plants can remove MPs from wastewater efficiently, a significant amount of MPs is still discharged into rivers due to the large volume of water being processed [31]. Moreover, Yang et al. found that most of the microplastics in municipal wastewater treated effluent were in the shape of fibers [32]. Apart from microfibers, tire dust is another major source of marine MP pollution. Tire dust is the biggest contributor to MP pollution in China, accounting for 53.91% (397.47 million tons) [33]. Simulation models estimate that 0.41×10^6 to 4×10^6 t of MPs are discharged from rivers into oceans each year [34]. Approximately 80% of all MPs found in the ocean come from terrigenous sources [35].

Most of the MPs screened out from sewage are concentrated in sludge, which has become a new source of pollution [36]. For example, when sewage sludge is used as fertilizer, each application causes an increase in the microplastic load in agricultural soils [37]. Effluent from wastewater treatment plants is also often used for soil irrigation, causing varying degrees of soil microplastic contamination even though the abundance of microplastics in the effluent is low [38]. Landfills gather a large amount of waste, of which the leachate and waste weathering can cause microplastic pollution in the surrounding soil, air, and groundwater [39].

The principal source of MPs in remote areas and oceans comes from airborne transportation over long distances [40,41]. Dry and wet deposition can lead to the dispersion of MPs from the air to the soil, rivers, lakes, oceans, and other media [42]. Snow is a major pathway for MPs to contaminate both the Arctic land and marine environments as well as Europe. The concentration of MPs found in Arctic snow samples ranges from 0 to 14.4×10^3 items/L, and in European snow samples, it varies from 0.19×10^3 to 154×10^3 items/L [43]. These findings provide evidence of severe atmospheric pollution caused by MPs. Studies from as early as 2002 report that small plastic objects can be ingested by birds, silkworms, fish, mammals, and crustaceans [6,44,45]. According to Mercoglian et al. [46], MPs from the marine environment can enter the food chain and accumulate in the human body, and it is estimated that the average person ingests between 39,000 and 52,000 MP particles annually through food intake. Organisms expel MPs into the environment through secretions and excreta following ingestion. Earthworms degrade MPs into nanoplastics in their digestive tracts and excrete them into the soil [47] (Figure 5).

3.2.3. Toxicological Effects of MPs

MPs can be ingested by organisms and adversely impact their growth and reproduction. Plastics mainly involve inert materials; however, the manufacturing process involves catalysts, reactants, and certain additives, such as bisphenol A (BPA) and phthalates, which are proven carcinogens [48] that can leach into food items [49]. Due to their durability, hydrophobicity, and extensive surface area, MPs can contribute to the absorption of trace metals (Fe, Pb, Ag, Hg, Cu, Zn, and Ni) [50–53] and organic pollutants such as polycyclic aromatic hydrocarbons and polychlorinated biphenyls [54,55] on their surface. The consumption of MPs in food, water, or ambient air results in detrimental health effects on human beings.

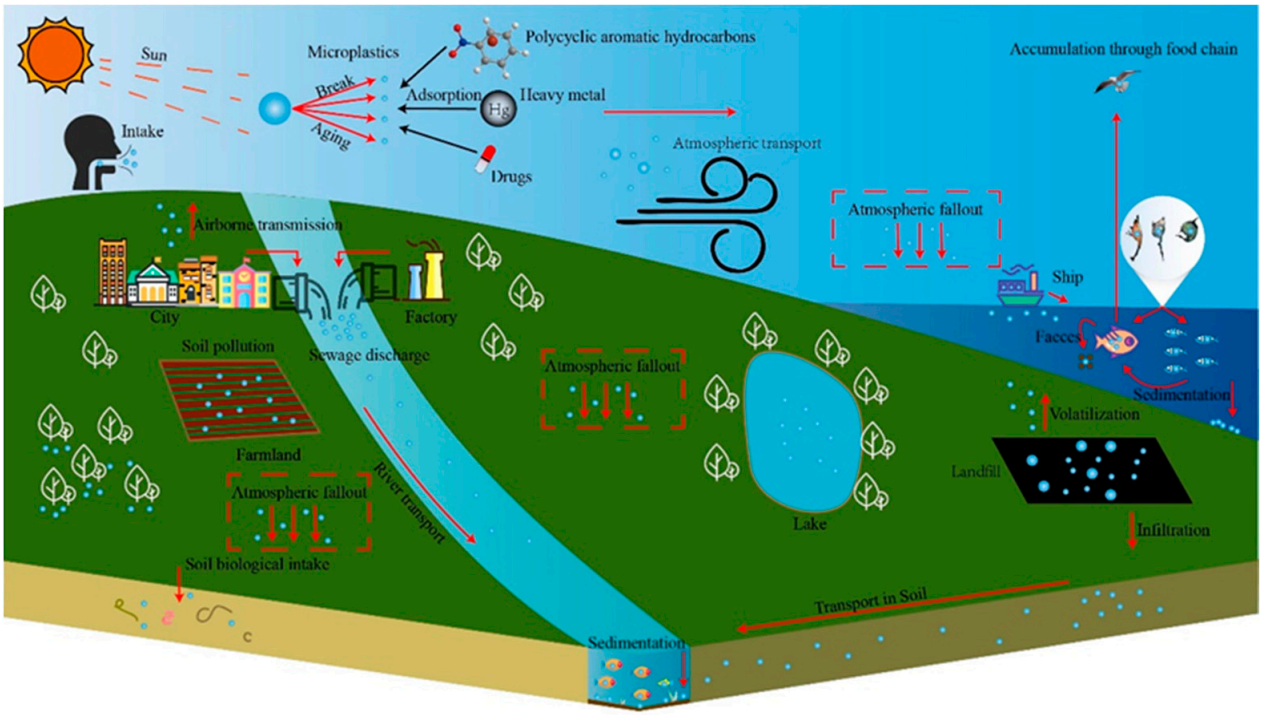

Figure 5. The transport of MPs.

Microalgae serve as primary producers and play a significant role in balancing the marine ecosystem. Chen et al. [56] reported that a low concentration of MPs could stimulate the growth of Phaeodactylum tricornutum, while excessive MP concentrations could suppress the growth of microalgae. Earthworms are crucial soil consumers and are often referred to as "ecosystem engineers". However, their vital role in the soil environment can be hindered by MPs. These MPs have been shown to inhibit earthworms' sperm production and coelom cell vitality [47]. Studies have demonstrated that even 70 µm MPs can cause intestinal damage to zebrafish [57]. In addition, MPs of varying sizes were observed to reduce the average body length of Caenorhabditis elegans by 4.89–11.44% and its embryo production by 14.40–25.22% [57]. Specifically, nematodes subjected to 1 µm-sized MPs were found to exhibit high mortality rates. The neurotoxicity of PS MPs increases with age. Prolonged exposure to 100 µg/L of aged PS MPs was observed to significantly affect glutamate, serotonin, and dopamine levels in Caenorhabditis elegans [56]. Furthermore, MPs with a size less than 0.1 µm can penetrate cells through the circulatory system and deposit in the liver. Extended accumulation of these MPs can cause DNA damage in both mitochondria and nuclei, ultimately leading to liver fibrosis [58]. MPs in soil and water can be absorbed by plant roots and transported to their branches via transpiration [59]. According to Chai et al., the presence of MPs changes soil properties, which can negatively affect the growth and photosynthesis of mangroves (Kandelia obovata) [60]. Moreover, the presence of MPs in soil triggers the activation of tolerance responses in rice through the endogenous production of jasmonic acid and antioxidant enzymes [61].

MPs are ubiquitous and pose a significant threat to human health through inhalation, ingestion, and dermal contact. MPs enter the body, are transferred through the body's circulatory system, and are deposited in the body's organs and tissues [19,21–23]. Repeated inhalation of PS-MPs leads to cellular damage and inflammation in the human bronchi [62]. Furthermore, bisphenol A (BPA) exposure has been linked to a higher risk of cardiovascular disease, particularly among individuals with high levels of exposure. Pregnant women are particularly vulnerable to the adverse effects of BPA, including hypertensive disorders during pregnancy and lower birth weight in newborns [63,64].

Tire rubber-derived chemicals are highly toxic [65], and vehicular traffic is the primary contributor of tire rubber particles, which are predominantly airborne. Although tire

rubber particles are rarely studied, they pose potential health risks to humans, including gastrointestinal, hepatotoxic, neurotoxic, and reproductive toxicities. Further research is needed to examine the potential toxicological mechanisms of MPs and nanoplastics for human health. Investigations should also evaluate the bioaccumulation of MPs and nanomaterials, along with their adsorption of pollutants. Such bioaccumulation may amplify toxic effects through the food chain, thereby negatively impacting human health. Evaluating the amount of MPs in the air and their inhalation by humans during certain periods can determine the degree of impact on human health.

3.3. Detection Method of MPs

3.3.1. Sample Collection and Processing

Various methods have been developed to collect MPs from different environmental media. For instance, peristaltic pumps can be used to draw water samples, which are then filtered to capture MPs. Stainless steel screens or trawls may also be employed to collect MPs in water [25,66]. Additionally, biological and environmental samples are utilized to investigate MPs. Fish samples can be obtained from government sources or local fishermen, while blood and sputum samples can be obtained from volunteers [19,21,67]. Stainless-steel grab buckets and shovels are commonly used to collect soil and sediment samples [68,69], while wood brushes are used to collect dust samples [70]. Glass settling cylinders and total suspended solids particle collectors are used to collect air samples [71]. The pretreatment process comprises filtration, flotation, or digestion. The presence of organic and inorganic substances in a sample impedes the precise detection of the number of MPs, their respective polymer types, and the size of particles. The density separation method is commonly employed to purify MP samples. MP samples are placed in a solution of defined density, and separation occurs based on the differences in polymer density, resulting in substances with low density floating and separating from sediments with higher density. The frequently used density separation solutions include H_2O (1.0 g/mL), NaCl (1.2 g/mL), NaBr (1.6 g/mL), $CaCl_2$ (1.35 g/mL), $ZnCl_2$ (1.5 g/mL or 1.7 g/mL), NaI (1.6 g/mL), HCOOK (1.5 g/mL), and $ZnBr_2$ (1.71 g/mL), as reported in references [14,19,68,72,73]. Most of these solutions exhibit a greater density than typical polymers, resulting in the segregation of samples from each other (Figure 6). The efficiency of $ZnBr_2$ in separating the samples is the highest, followed by NaI, while H_2O is the least efficient. Nevertheless, the utilization of $ZnBr_2$ is not ideal due to its high cost and significant environmental impact. Therefore, NaCl remains a prevalent option as it is cost-effective and eco-friendly.

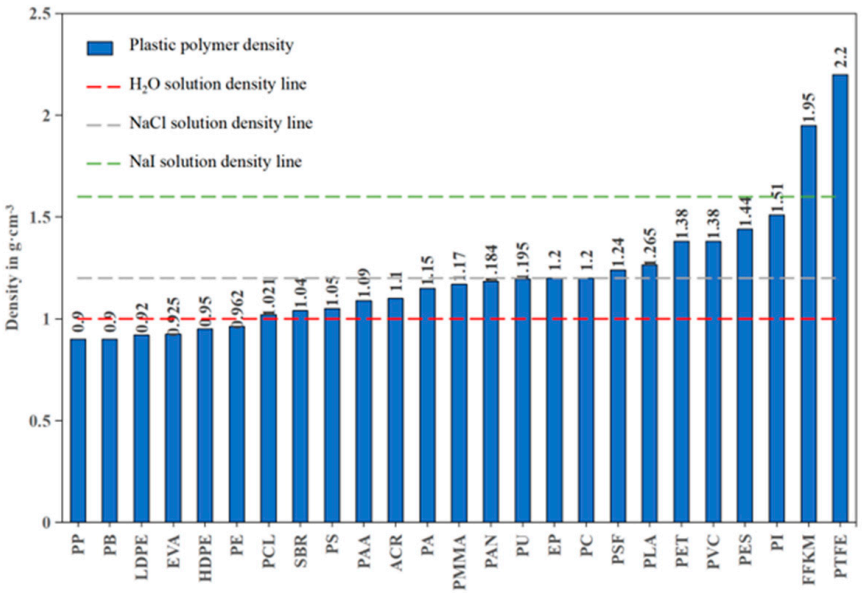

Figure 6. The density of the common plastic polymer.

Organic substances often possess a lower density than density separation solutions, causing them to remain afloat in the supernatant with MPs or interlaced within the organic substances. The density separation method alone is insufficient for eliminating organic substances present in MP samples; hence, the digestion method is necessary. Digestion steps generally involve the use of H_2SO_4, HNO_3, KOH, NaOH, $HClO_4$, HCl, H_2O_2, Fenton reagents, and enzymes. The digestion effect is influenced by the digestion solution duration, temperature, and concentration. Dissolving environmental samples is attainable through the utilization of NaOH and KOH, but it causes saponification reactions of the carbonate bonds present in PET and PC, which in turn causes minute plastic fragments to dissolve. Although an acidic solution is effective in eliminating organics in samples, its usage is not recommended, particularly for strong acids that cause the dissolution of varied plastics [74,75]. H_2O_2, on the other hand, causes oxidation and overheating of MPs to effectuate HCl or HI creation [76]. Comparatively, the combination of Fe (II) and H_2O_2 called Fenton's reagent provides a more efficient oxidation system that is less damaging to polymers than H_2O_2 alone [25,74].

3.3.2. Identification of MPs

Following the collection and pretreatment of MP samples, it is mandatory to conduct qualitative and quantitative analyses of MPs. Currently, there is no standard methodology. However, some of the techniques are outlined in Table 2. Visual inspection [14,66], spectroscopy [67,68], pyrolysis gas chromatography-mass spectrometry (Py-GC-MS) [25], and scanning electron microscopy (SEM) [15] are the most frequent techniques used to detect MPs. Although a fast, inexpensive, and straightforward method, visual inspection has certain limitations, such as the inability to accurately differentiate MPs in the sample [70,77]. Combining the visual method with spectroscopy facilitates the identification of the polymer types of dubious particles with precision. In their study, Xiong et al. [78] utilized a stereo microscope to collect particles, followed by confirmation of MP particles using a Raman spectrometer. Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy are popular techniques for detecting MPs. Fourier transform micro-infrared spectrometry (μ-FTIR) has size limitations as it is unable to identify samples smaller than 20 μm. Raman spectroscopy is susceptible to interference from bioluminescent substances in the sample and is typically used to detect MP particles larger than 1 μm [79].

Table 2. Sampling of MPS in different environmental matrices and corresponding analytical techniques.

Sample Types	Sampling Methods	Pretreatment Methods	Analysis Methods	Reference
Water	Peristaltic pump	/	Stereomicroscope micro-FTIR	[8]
	Stainless steel screen (0.355 mm by 0.125 mm mesh size)	H_2O_2 (30%) for digestion	Stereomicroscope	[66]
	Plankton net (333 μm mesh size)	Fe(II) (0.075 mol·L^{-1}) and H_2O_2 (30%) for digestion and NaCl (6 mol·L^{-1}) for purification	Py-GC-MS	[25]
Biological sample	Collect fish samples from local fishermen	KOH (10%) for digestion	Micro-Raman	[67]
	Donations from patients with lung diseases	HNO_3 (68%) for digestion and $ZnCl_2$ (1.7–1.8 kg·L^{-1}) for purification	LDIR	[19]
Sediment	Shovel	NaI (1.6 g·cm^{-3}) for purification andH_2O_2 (30%) and Fe(II) (0.05 mol·L^{-1}) for digestion	Microscope	[14]

Table 2. *Cont.*

Sample Types	Sampling Methods	Pretreatment Methods	Analysis Methods	Reference
Sediment	Stainless steel shovel	Stainless steel screen for filtering particles, $ZnCl_2$ (1.6 g·mL^{-1}) for purification, and H_2O_2 (30%) and Fe(II) for digestion	μ-FTIR	[68]
Air	Total suspended particulate matter collector	/	Stereomicroscope μ-FTIR	[71]
	Portable air sampler	/	SEM-EDS	[15]
	Passive sampler for atmospheric MPs	/	ATR-FTIR, μ-FTIR	[42]

The Fourier transform attenuated total reflection infrared spectroscopy (ATR-FTIR) with high resolution (<2 cm^{-1}) and atomic force microscope infrared spectroscopy (AFM-IR) imaging systems are capable of identifying submicron microplastics and nano-plastics [80,81]. According to Andrea Kappler et al., FTIR imaging is a quick and dependable method for analyzing microplastics that range in size from 50–500 μm, while microplastics with a size of 1–50 μm are more accurately analyzed by Raman imaging but with greater time consumption [82]. The most advanced laser infrared (LDIR) imaging technology can assess 1000 items of particles or fibers (20–300 μm) within 1–2 h, significantly enhancing time efficiency and experimental accuracy [83].

Py-GC-MS identifies the polymer type by analyzing the pyrolysis products of the sample, which are destructive. This method does not require sample pretreatment, and only a small amount of sample (5 mg) is analyzed per measurement [25]. TED-GC-MS combines thermogravimetric analysis (TGA) and thermal desorption gas chromatography-mass spectrometry (TD-GC-MS), making up for the deficiency that Py-GC-MS cannot determine the quantity and size distribution of microplastics [84,85]. Axel Muller et al. used thermal extraction desorption gas chromatography-mass spectrometry (TED-GC-MS) to measure tire wear particles in the soil, which is more reliable and representative than Py-GC-MS analysis results [86]. SEM can be used to observe the microstructure of MPs, such as biofilm attached to the surface of MPs and cracks and holes on the surface of MPs. SEM combined with an energy dispersive X-ray fluorescence spectrometer (EDX) or energy dispersive spectrometer (EDS) can distinguish microplastics according to the morphology and element composition of sample particles [87].

Rapid advancements in artificial intelligence have paved the way for researchers to perform both quantitative and qualitative analyses of microplastics using deep learning and machine learning techniques. Shi et al. employed a deep learning model that conducted image segmentation and shape classification of microplastic electron microscopy images. This method reduced the time to segment MPs microscopy images automatically from half an hour manually to just a few seconds, all while having an accuracy rate of 98.33% for shape classification [88]. LDIR and machine learning models were utilized by Tian et al. for the purpose of identifying MP samples [89]. Dark-field microscopy and residual neural networks were used in medical experimentation to identify polystyrene microplastics in cells with an average accuracy greater than 85% by He et al. [90]. The continuous growth of available datasets has the potential to continually improve the accuracy of machine learning and deep learning models. Moreover, AI-assisted technologies can significantly aid in the automatic quantification and classification of microplastic samples, resulting in reduced usage of complex, expensive, and time-consuming instrumentation. This improved technology will promote more effective and accurate monitoring of microplastic contamination.

4. Conclusions and Future Directions

MPs are ubiquitous in water, soil, air, and living beings and are unevenly distributed in different environmental media and regions. Generally, the concentration of MPs in soil,

sediment, and ice is significantly higher than in other environments. Sediments in inland lakes or rivers usually have higher MP concentrations than those in the ocean, and the abundance of MPs increases closer to the land in the same sea area. However, the detection of MPs in remote areas indicates that MP pollution is a widespread issue due to human activities impacting the MP concentration in the environment. However, the scarcity of long-term and comparable data for MPs makes it challenging to assess their long-term impact on the environment.

MPs are resistant to degradation and can easily spread and accumulate in different types of environmental media. Atmospheric and aquatic transport are the main means by which MPs travel long distances. Atmospheric transport is the primary distribution pathway for MPs, but it has often been overlooked. The atmospheric and aquatic transport of MPs is the main source of these particles in remote areas. Dry and wet deposition can transfer MPs from the air to water and soil. To prevent and control MP pollution, it is essential to control plastic use and minimize plastic waste generation. To avoid MPs settling in bowls and cups and preventing inhalation by humans, it is recommended to cover them when not in use. Concurrently, it is important to enhance the monitoring of microplastic pollution in soil and sewage treatment plant effluent to prevent the entry of MPs into oceans, lakes, or irrigated soil, which can have negative impacts on plant growth and photosynthesis. To prevent agricultural film residues from polluting farmland, there needs to be a promotion of the use of degradable agricultural film or recycling of the agricultural film. Furthermore, the washing machine outlet should have a mesh filter added to it to decrease microfiber emissions. MPs can pollute the human circulatory system and accumulate in bodily tissues. MPs are ubiquitous in water, soil, air, and living beings. However, the scarcity of long-term and comparable data for MPs makes it challenging to assess their long-term impact on the environment. The atmospheric and aquatic transport of MPs is the main source of these particles in remote areas, and further research is needed to understand the distribution of MPs in various environmental settings. Moreover, toxicity studies of MPs' ability to adsorb pollutants are inadequate, calling for long-term research in the field.

Several methods have been employed to examine MPs, but their results are challenging to compare. Consequently, the development of comprehensive techniques for detecting, collecting, and processing samples from various environmental sources is critical. A spectroscopic analysis methodology is recommended for analyzing MPs. For analysis sizes greater than 500 μm, spectroscopy using Raman or μ-FTIR is recommended to identify and quantify MPs. For analysis sizes less than 500 μm but greater than 20 μm, spectroscopy using LDIR is recommended for both qualitative and quantitative analysis of MPs. Sodium iodide (1.8 g/mL) and Fenton reagent are recommended for digestion and density separation. Currently, due to the absence of standardized methods for sampling, identifying, and quantifying various environmental samples, varying methods for sample collection, pretreatment, and identification in different experiments make it challenging to compare study results. Thus, developing and studying standardized analysis and identification protocols for MPs in the atmosphere, organisms, oceans, sediments, and soil is essential. Artificial intelligence-assisted technology can quickly and accurately quantify and classify microplastic particles, which are still immature but have great potential for development at a low cost. Future research at the intersection of artificial intelligence and microplastic contamination should be accelerated to enable the identification and quantification of microplastics in microscopic images of environmental samples.

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