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Review

Unraveling Microplastics: Sources, Environment and Health Impacts, and Detection Techniques

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Abstract

Microplastics (MPs) have become a widespread environmental contaminant, raising concern due to their persistence, capacity to transport pollutants, and potential risks to ecosystems and human health. Their increasing global production, prolonged degradation, and ubiquity in aquatic environments underscore the need for improved monitoring and mitigation strategies. Current findings indicate widespread MP contamination, including within the human body, emphasizing significant ecological and health concerns. This review examines the definition, sources, environmental transport mechanisms, associated risks, and current detection methods for MPs in natural and engineered water systems. The methods discussed encompass a broad range of analytical and sensing technologies used to identify, characterize, and quantify MPs across diverse environmental matrices. The review highlights that no single technique is sufficient for comprehensive MP analysis; instead, the combination of multiple methods enhances sensitivity, specificity, and reliability. Progress in automated sample preparation, advanced sensing platforms and standardized methodologies is key to improving detection efficiency and comparability across different studies. In particular, the extensive body of scientific literature underscores the imperative for standardized and harmonized protocols regarding data collection and analysis, as well as homogeneous limits of detection and units of measurement. Reducing MP pollution will require interdisciplinary collaboration, regulatory action, and increased public awareness to protect environmental integrity and human health.

Keywords: microplastics; environmental pollutants; drinking water; detection methods; human exposure

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1. Introduction

The pervasive nature of microplastics (MPs) has emerged as a critical environmental concern, driven by diverse anthropogenic sources ranging from primary industrial pellets to the secondary fragmentation of macro-debris. Once released, these pollutants undergo complex long-range transport mediated by hydrodynamic and atmospheric processes, facilitating their accumulation in remote ecosystems.

MPs can remain in the environment for centuries before being completely decomposed by photodegradation and thus re-entering normal biogeochemical cycles, particularly in the marine environment [1]. In addition, MPs can be consumed by various marine life [2]. MPs can also combine with other pollutants, such as organic contaminants, antibiotics, heavy

metals, and bacterial pathogens, thereby influencing and possibly enhancing the transport behaviour of environmental contamination. This global high-level problem needs comprehensive and coordinated strategies that integrate prevention, monitoring, and remediation approaches across multiple scales. In particular, the early detection and quantification of microplastics in natural and engineered water systems have emerged as critical steps in understanding their distribution, assessing associated risks, and informing policy decisions. However, the field currently faces significant challenges in the harmonization of detection methods, as discrepancies in sampling, extraction, and spectroscopic identification protocols hinder the comparability of global datasets. In addition, current analytical methods are often labor-intensive, time-consuming, and require specialized laboratory facilities, which limit large-scale and real-time monitoring efforts. Consequently, there is a growing interest in the development of advanced sensing technologies capable of enabling rapid, sensitive, and reliable detection of microplastics in complex environmental matrices. These innovations are essential not only for improving the assessment of microplastic pollution but also for supporting effective mitigation strategies and guiding future regulations aimed at reducing the ecological and human health impacts associated with plastic contamination.

1.1. Objectives

The primary objective of this review paper is to synthesize the current state of research on microplastics while identifying methodological challenges, key knowledge gaps, and inconsistencies across existing studies. In doing so, it seeks to highlight the critical need for standardized protocols and harmonized reporting practices.

Specifically, this review aims to:

1. **Examine the sources and transport dynamics of microplastics,** beginning with a discussion of their definition and distinguishing between primary and secondary microplastics in both terrestrial (e.g., urban runoff, sewage sludge) and marine environments. This section further describes transport pathways, accumulation patterns, environmental persistence, and the possible role of microplastics as vectors for chemical and biological pollutants.
2. **Report on the ubiquitous occurrence of microplastics in water bodies,** with particular emphasis on drinking water as a critical exposure pathway for human health. The pronounced heterogeneity in data reported across the global literature underscores current limitations in sampling strategies and analytical standardization.
3. **Analyze ecological and human health impacts,** especially synthesizing findings on human exposure pathways and reviewing clinical evidence of tissue accumulation and associated pathophysiological effects. Both established impacts and emerging toxicological concerns are addressed.
4. **Critically review detection, identification, and quantification techniques,** including optical microscopy, micro-Fourier transform infrared spectroscopy, Raman micro spectroscopy, and pyrolysis–gas chromatography/mass spectrometry, comparing their advantages, limitations, and applicability across different particle size ranges.
5. **Expose limitations and gaps in the literature**. Particular attention was devoted to identifying methodological heterogeneity, inconsistencies in measurement units and detection limits, and variability in analytical protocols.

1.2. Methodology

This review is based on the critical analysis of 289 peer-reviewed scientific publications addressing the sources, environmental distribution, health impacts, and detection techniques of MPs. The literature search was performed using the following major scientific databases: Web of Science, Scopus, and PubMed, and covered studies published up to 2025. The search

strategy employed combinations of keywords: microplastics, sources, water, environmental distribution, human health, toxicological effects, and analytical detection methods.

After the removal of duplicate records, articles were screened based on titles and abstracts, followed by full-text evaluation to assess their relevance to the scope of the review. Studies were included if they provided original experimental data, methodological developments, or comprehensive analyses relevant to microplastic sources, environmental pathways, biological effects, or detection methodologies.

The selected publications were subsequently classified into thematic categories, enabling a comparative assessment of current approaches. Particular attention was devoted to identifying methodological heterogeneity, inconsistencies in measurement units, and variability in analytical protocols, with the aim of highlighting key limitations in the existing literature and emphasizing the need for standardized measurement frameworks and coordinated mitigation strategies.

2. Definition of Microplastics

The term "microplastics" was introduced in 2004 by Professor Richard Thompson, a marine biologist at the University of Plymouth in the United Kingdom [3]. Then, the National Oceanic and Atmospheric Administration (NOAA) defined in 2009 an upper size limit: "Pieces of plastic particles smaller than 5 mm" [4]. In 2015, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), added a lower limit, including for the first time, nanoplastics (NPs) down to 1 nm: Microplastics are particles in the size range from 1 nm to 5 mm [5]. The European Chemical Agency (ECHA) in their Annex XV Restriction Report on Intentionally Added Microplastics of August 2019 provides an additional constraint for fibers: a length of 3 nm $\leq$ x $\leq$ 15 mm and a length-to-diameter ratio of >3 [6]. However, whether to include nanoscale in the definition of MP is always under debate. The most recent, all-inclusive, and more descriptive definition of MP is provided by Joao and Roisin in 2019: "Microplastics are any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 µm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water" [7]. Figure 1 gives an overview of plastic debris based on size in scientific studies and reports from various organizations [8]. Table 1 reports some examples of primary and secondary MPs.

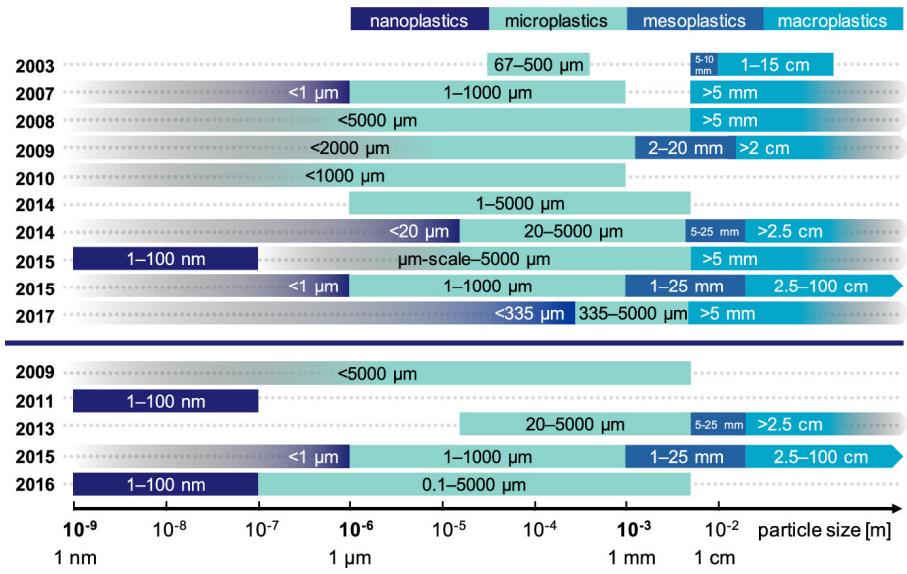


Figure 1. Differences in the categorization of plastic debris according to size as applied (and/or defined) in scientific literature and institutional reports. Reported from Ref. [8].

Table 1. Examples of Primary and Secondary MPs.

Category	Definition	Examples
Primary MPs	Microplastics are intentionally manufactured in small sizes for specific purposes	- Microbeads in cosmetics and personal care products (facial scrubs, exfoliants, toothpaste) - Pre-production plastic pellets (nurdles) - Abrasive media used in industrial blasting (air-blasting technology for cleaning surfaces) - Industrial plastic pellets (raw material used in plastic manufacturing) - Microcapsules in detergents, fertilizers, and pharmaceuticals
Secondary MPs	Microplastics are generated from the fragmentation, degradation, or weathering of larger plastic items.	- Fragments from bottles, bags, and packaging materials - Fibers from synthetic textiles (e.g., polyester, nylon) - Tire wear particles - Degraded fishing gear (nets, ropes) - Paint flakes (from road markings, ship hulls, household paints) - Degraded fishing nets and ropes (exposure to sun and saltwater breaks them into MPs) - Broken pieces from larger plastic objects (toys, containers, household items, etc.) - Cigarette filter debris (filters made of cellulose acetate degrade into MP)

It appears that a necessary level of standardization has yet to be achieved, beginning with the very definition of microplastics and further compounded by the complexities of analyzing disparate environmental matrices and ecological systems.

3. Sources and Transport

3.1. Sources

As a focus of today's environmental problems, the prevalence of MPs in daily life has attracted widespread attention. Research has been conducted to collect and analyze MPs from air [9,10], freshwater [11,12], seawater [13,14], soil [15–17], wastewater [18–20], sediment [12,21,22], and even Antarctic snow [23]. MPs come from a variety of sources that are ubiquitous in our living environment, from household items to industrial products, almost everywhere. The major sources of MPs are shown in Figure 2. According to the reference [24], MPs release pathways include (a) human (e.g., synthetic textiles, personal care products), (b) transportation (e.g., erosion of synthetic rubber tires), and (c) industrial (e.g., plastic pellets) sources.

Within this framework, MPs can be divided into two major categories: primary MPs, which are originally manufactured at small sizes, and secondary MPs, which result from breakdown, degradation, and weathering of larger plastic debris. The most common compositions of MPs released in the environment are polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyester (PES), polystyrene (PS), polyvinylchloride (PVC), polyamide (PA), and polymethyl methacrylate (PMMA).

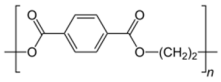
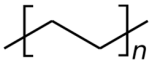
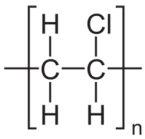
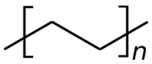
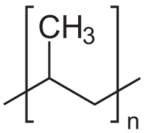
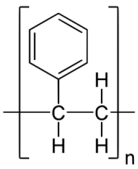
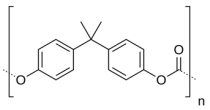
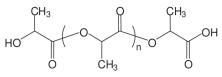
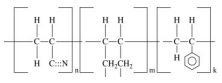
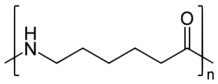
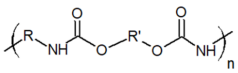
Primary MPs are intentionally manufactured for industrial or domestic use and are directly released into the environment as small plastic particles or microbeads. They are commonly found in personal care and cosmetic products such as facial cleansers, shower gels, toothpaste, and cosmetics to provide a cleaning or polishing effect [25–29]. They are also used in industrial processes such as sandblasting, where plastic particles (PE and PP) are employed as an abrasive medium [30,31]. Despite efforts to regulate the use of microbeads in several countries, their presence in marine environments remains significant due to the lack of universal regulation.

Figure 2. Schematic representation of the major sources of MPs.

Secondary MPs arise from the fragmentation of larger plastic items due to physical, chemical, or biological processes. Often induced by weathering, such as photodegradation from ultraviolet (UV) light, heat, mechanical abrasion, and biodegradation. In all these processes, a significant role is played by the semicrystalline nature of 70% of commercial polymers, which are made of alternating crystalline and amorphous layers [32]. This leads to the presence of MPs in different ecosystems and thus even in food and water supplies. Common sources of secondary MPs include plastic bottles, fishing nets, fishing bait boxes, bags, and other items that deteriorate over time in natural environments [33–35]. Plastic packaging is one of the important sources of MPs, especially food and beverage packaging. Clothing made of synthetic fabrics like polyester, nylon, and spandex is also a major source of MPs. These fabrics shed microfibers during washing, wearing, and drying, releasing significant amounts of secondary MPs into water bodies and the environment [36–38]. A single load of laundry can release thousands of microfibers, which contribute significantly to MP pollution in aquatic environments [39].

MPs vary in density, color, chemical properties, shape and size, all of which influence their behavior in the environment. As regards chemical composition, 90% of MPs are composed of common polymers such as PE, PP, PS, and PVC [40–42]. Table 2 provides information on products from daily life made of these polymers, along with their recycling details. The morphology of MPs was usually divided into fibers, fragments, films, pellets, foams, and others. Fibers and fragments account for more than 80% of the total MPs [43] and have extensive sources. The fibers are usually generated from washing garments and other textiles or the shedding of textile materials such as synthetic textiles, fishing tools, and woven bags. The fragments mainly come from the fragmentation and degradation of larger plastics in the environment [11]. Plastic mulch films have been identified as a primary source of film-shaped MPs. In fact, the environmental degradation of plastic mulch films makes them a major source of secondary MPs [44]. MP pellets are frequently used in cosmetic scrubbers or plastic production, such as facial cleansers and toothpaste [45]. Additionally, foam plastics primarily originate from fragmented lightweight foam materials for packaging and shipping floats [46]. Due to their higher specific surface area and lower density, foams are considered easily suspended within aquatic systems.

Table 2. Plastic types: chemical structures, densities, products, and recycling information.

Polymer Type	Chemical Structure	Density [g/cm^3]	Products	Recycle Sign	Recyclability
Polyethylene terephthalate (PET/PETE)		1.30–1.40	Soda bottles, water bottles, polyester film, containers for food, jars, fibers for clothing, and even carpets.	♺	Widely recycled
Polyethylene (HDPE)		0.94–0.97	Milk jugs, juice containers, grocery and trash bags, motor oil containers, shampoo and conditioner bottles, soap bottles, detergent containers, bleach containers, and toys.	♺	Widely recycled
Polyvinyl chloride (PVC)		1.15–1.70	Plumbing and sewage pipes, window frames, non-food packaging, cards, electrical cable insulation, flooring, and phonograph records.	♺	Not easily recyclable
Polyethylene (LDPE)		0.917–0.94	Plastic bags, computer components, trays, six-pack rings, milk and juice cartons, packaging for computer hardware, Ziploc frozen food bags.	♺	Recycle at specialist points
Polypropylene (PP)		0.90–0.91	Flip-top bottles, plastic diapers, Tupperware containers, margarine tubs, yogurt containers, prescription bottles, bottle caps, and even chairs.	♺	Widely recycled
Polystyrene (PS)		1.04–1.05	CD and DVD cases, packing peanuts, single-use disposable cutlery, trays, disposable razors, and smoke detector housings.	♺	Not easily recyclable
Polycarbonate (PC)		1.15–1.20	Plastic lenses in eyewear, medical devices, bulletproof glass, automotive components, protective gear, greenhouses, digital disks (CDs, DVDs, and Blu-ray), and exterior lighting fixtures.	♺	Recycle at specialist points
Polylactic acid (PLA)		1.23–1.25	Takeaway storage containers, takeaway cups and utensils, medical applications like implants, rods, and screws, home 3D printing	♺	Recycle at specialist points
Acrylonitrile butadiene styrene (ABS)		1.02–1.21	Lego bricks, computer keyboards, power tool housings, housing for home electrical appliances such as shavers, vacuum cleaners or food processors, automotive bumpers, golf club heads, toys, canoes, 3D printing.	♺	Recycle at specialist points
Polyamide (PA, nylon)		1.01–1.60	Toothbrushes, wear pads, wheels, gloves, guitar strings and pics, tennis racket strings, medical implants, electrical connectors, fishing line, tents, gears.	♺	Recycle at specialist points
Polyurethane (PU/PUT)		1.23–1.35	Flexible foam, rigid foam, coatings, adhesives, sealants and elastomers.	♺	Recycle at specialist points

These plastic particles enter the environment through various pathways, including stormwater and wastewater, with wastewater treatment processes contributing to their partial removal. The small size of MPs allows them to be ingested by a wide range of organisms, from plankton to fish and birds, thus introducing them into the food chain. The

ubiquity of MPs raises concerns due to their potential risks to humans and the environment, necessitating further research to establish regulations and management strategies.

3.2. Transport

MPs originate from a wide range of sources, both land-based and marine. These sources contribute to MP pollution through various pathways, including direct emissions and indirect inputs via rivers, runoff, and atmospheric deposition. Once MPs are released into the environment, their transport and distribution are influenced by a variety of physical, chemical, and biological processes. These include riverine transport, ocean currents, wind, and even the ingestion and excretion by organisms. Most MPs will accumulate in the ocean through river transport and direct discharge.

3.2.1. Riverine Transport

The majority of MP pollution is thought to originate from land sources, including urban, industrial, and agricultural activities. Land-based sources are responsible for approximately 80% of MPs that enter marine environments [47]. Rivers act as major conduits for transporting MPs from land-based sources to marine environments. They collect plastic debris from urban runoff, wastewater effluents, and stormwater systems, carrying them downstream to coastal areas. The concentration of MPs in rivers varies depending on factors such as population density, land use, and proximity to plastic manufacturing facilities. Large rivers, like the Yangtze [48] and Ganges [49], have been identified as major pathways in Asia for MP pollution to the ocean. The presence of MPs was investigated in marine water along the eastern coast of Geoje Island (Republic of Korea), near the Nakdonggang River estuary, during the dry season (May) and rainy season (July) [50]. In May, 0.57 pieces/m^3 of microplastics in the size range above 330 µm and 260–11,410 pieces/m^3 above 50 µm were found. In July, the number increased to 0.64–860 pieces/m^3 and 210–15,560 pieces/m^3, respectively, most likely for the higher river flow.

3.2.2. Ocean Currents

About 71% of the Earth's surface is occupied by oceans, which hold 97% of the Earth's water [51]. The remaining 3% is present as water in ponds, streams, glaciers, ice caps, and as water vapor in the atmosphere [6]. Marine sources of MPs include activities that occur at sea, such as commercial fishing, shipping, and offshore oil and gas operations. Lost or discarded fishing gear, such as nets and lines, can degrade into MPs over time, contributing to the accumulation of plastic particles in the ocean. Oceanic currents play a crucial role in the global transport of MPs [52]. These currents disperse MP particles across vast distances [53], leading to their accumulation in remote regions such as the Arctic and Antarctic [23,54,55], with a recent study suggesting that nanoplastics are the dominant fraction of marine plastic pollution [56]. The distribution of MPs is often linked to ocean gyres, where large amounts of plastic debris converge and form floating "garbage patches," such as the Great Pacific Garbage Patch [57,58]. The difference in density between plastics and seawater causes MPs to show up at various depths in the water, column, from the surface to the deep ocean, where they are ingested by different marine species [59–62]. Plastics with lower density (PE, PP, PS) are ingested more easily by the organisms that inhabit the upper part of the water column, while plastics with higher density (PVC, PET) affect the benthic organisms [63–65]. In addition, they can accumulate organic contaminants from the water, potentially increasing their toxicity.

3.2.3. Atmospheric Transport

MPs have been detected in atmospheric deposition, indicating that wind plays a role in transporting plastic particles over long distances [66]. Once airborne, MPs can travel

thousands of kilometers before settling back onto the Earth's surface. Studies have found MP contamination in remote locations such as the French Pyrenees [67] and the Arctic [68], far from any direct sources of plastic pollution. In addition to being a significant source of direct contamination in plants, thus in food [69], atmospheric transport is likely to be a consistent pathway for MP contamination in both terrestrial and aquatic environments, although research in this area is still in its early stages. In fact, atmospheric–marine exchange has been estimated to 1.2 tons of airborne MPs that are transported from air to the marine environment annually [70]. More research is required to gain a deeper understanding of the mechanisms that control the transport of MPs through the air.

3.2.4. Biological Transport

MPs can also be transported by living organisms. Marine organisms such as fish, seabirds, and marine mammals may ingest MPs, either accidentally or through the food chain [71]. These particles can then be transferred through the food web or excreted into the environment in different locations. MPs have been detected in land-based organisms, such as earthworms [72], which ingest tiny plastic particles present in the soil during feeding activities [73,74]. This suggests that MPs can also be mobilized within terrestrial ecosystems, although the full extent of this pathway remains unclear.

The pervasive presence of MPs in the environment, from the deepest oceans to the highest mountains, presents a significant ecological challenge. Their sources are diverse, ranging from urban areas and industrial processes to marine activities and atmospheric deposition. Once released, MPs can be transported over vast distances by rivers, ocean currents, the wind and even living organisms, ultimately affecting ecosystems around the globe. Further research is needed to fully understand the impacts of MPs on environmental and human health, as well as to develop effective strategies to mitigate their release into the environment.

It is clear that the multiplicity and diversity of microplastic sources, together with the vast scale and complexity of their transport dynamics, represent a significant challenge for both research and mitigation efforts. These factors underscore the imperative for an interdisciplinary, integrated, and harmonized approach, particularly with respect to sampling methodologies and physicochemical analyses.

4. Occurrence in Water Bodies

MPs have emerged as a pervasive pollutant in aquatic ecosystems globally. While early research concentrated on marine environments, growing evidence points to the presence of MPs in freshwater systems, including rivers, lakes, and drinking water sources. The distribution and ecological impacts of MPs in freshwater systems are increasingly concerning due to their potential to harm aquatic life and their implications for human health. This section provides an overview of the current understanding of MP pollution in freshwater systems, with a particular emphasis on its occurrence in drinking water sources.

4.1. Freshwater

Freshwater ecosystems, comprising rivers, streams, lakes, wetlands, reservoirs, glaciers, and icecaps, are of utmost significance, being the chief sources of potable water. They account for just 3% of the water on Earth yet support up to 10% of its species, making them biodiversity hotspots [75]. MPs can enter freshwater systems through various pathways, including surface runoff, atmospheric deposition, and the application of sewage sludge in agriculture [76]. A recent study revealed a significant 1450% increase in MPs in treated soil after just four years of sludge application [77] which could lead to a greater input in land and marine water bodies, through both surface runoff and atmospheric trans-

port of soil dust. The transport of MPs is influenced by hydrodynamic processes, which can facilitate their movement from urban areas to remote aquatic environments [49,78]. In addition, the characteristics of MPs, such as their size and density, play a crucial role in their distribution and accumulation in water bodies [79].

Considerations on Standardization of Sampling and Analysis

It should be noted that the main issue that emerges when examining data from field studies on MP concentrations in aquatic environments lies in the heterogeneity of sampling and analytical procedures. In particular, different studies employed diverse separation methods or nets with varying mesh sizes, resulting in different size ranges or limits of detection (LOD) of the observed particles. Collected water volumes and units of measurement changed significantly, as well. This variability makes direct comparison of results difficult, particularly with regard to early investigations. For instance, in a 2018 review, grouping studies conducted in different locations but using very different sampling protocols, reported MP concentrations were found to vary significantly, ranging from over one million particles per cubic meter to fewer than one particle per 100 cubic meters.

In addition, very recent works [80,81] suggest that the majority of MPs in water are smaller than 10 μm, which is below the detection limit of most methods routinely used in the past.

Nevertheless, some key findings and important trends, such as seasonal variations, can still be identified in the previous literature. As a matter of fact, MP concentrations vary significantly by location even when the same controlled set of monitoring protocols is used. A case study of surface waters in nine waterways in Flanders (Belgium) reported MPs in the size range of 25–5000 μm with concentrations ranging from 0 to 4.8 particles/L [82]. In fact, the abundance of MPs present depends on numerous factors, such as the surface basin, its depth, as well as the wind and tidal conditions that may arise. For instance, smaller MPs are more likely to remain suspended in the water column, while larger particles may settle in sediments, affecting their bioavailability and potential impact on aquatic organisms [83].

In freshwater systems, MPs enter via several pathways. Urban runoff, wastewater effluent, industrial discharges, and atmospheric deposition are the primary routes of entry. Wastewater treatment plants (WWTPs) have been recognized as major pathways for the release of MPs into the environment [84]. Studies have shown that WWTPs can contribute significantly to MP pollution, with treated effluent often containing residual MPs that are not effectively removed during the treatment process [85,86]. Similarly, stormwater runoff from urban areas can transport MPs from roads, tire wear, and other plastic products into rivers and lakes. The increasing use of synthetic fibers in textiles further exacerbates the problem since MP fibers released from domestic washing machines can enter wastewater systems and subsequently be discharged into receiving waters, contributing to the overall MP load in aquatic environments [38]. Conversely, it seems that the total mass of MPs and nanoplastics (NPs) released from plastic articles during mechanical dishwashing is low and minor compared to other known sources of plastic pollution [87].

Due to these diverse sources and pathways, MPs are now present in various freshwater environments around the world. Studies have shown widespread contamination in rivers, lakes, and reservoirs, with concentrations varying based on proximity to urban centers, industrial activities, and the efficiency of local waste management systems. The spatial distribution of MPs in freshwater systems can be influenced by hydrological dynamics, such as flow rates, turbulence, and sedimentation processes. In Europe, the Rhine River was shown to contain high levels of MPs, which were collected using a Manta net with a 300 μm mesh size and identified under a stereomicroscope, with peak concentrations reaching 4960 particles/m^3 in 2015 [88]. A study by Stratmann et al. [89] reported the presence of

MPs in the Seine River in France, with a limit of detection (LOD) of 25 µm. Concentrations reaching up to 600 particles/m^3 and a major particle diameter between 25 µm and 300 µm were assessed. Scherer et al. [90] discovered MP pollution in the Elbe River in Germany, using a mesh size of 150 µm and reporting an average concentration of 5.57 particles/m^3 in the water phase. The abundance of MPs in Antuã River (Portugal) water, collected using a net with a 55 µm mesh size and identified under a stereomicroscope, ranged from 58 to 193 particles/m^3 in March and from 71 to 1265 particles/m^3 in October [91]. Sbarberi et al. [92] reported that 0.9–62.9 particles/m^3 were found by filtration with 100 µm mesh size and using micro Fourier Transform Infrared Microscope (µFT-IR) analysis in Po River tributaries in Northern Italy.

4.2. Drinking Water

The same considerations regarding the lack of standardization and harmonization of protocols, previously noted for freshwater in general, can be extended to the analysis of drinking water. Similarly, examining the findings documented in the literature can provide significant general insights and, more importantly, suggest guidelines for improving future procedures and strategies.

In fact, several studies suggest that drinking water may be an important source of human intake of MPs. It is estimated that Americans can ingest from 39,000 to 52,000 MP particles each year from food, with bottled water potentially contributing an additional 90,000 MPs compared to about 4000 from tap water sources [93]. The implications of MP contamination in drinking water are significant, as they pose direct potential health risks to humans. The ingestion of MPs through drinking water may lead to adverse health effects, although research in this area is still emerging [94–96]. The presence of MPs in drinking water highlights the need for improved water treatment technologies and regulatory measures to mitigate their entry into water supplies. The occurrence of MPs in drinking water has been documented in various studies, revealing their presence in both raw (surface water and groundwater) and treated water sources (tap water and bottled water).

4.2.1. Raw Water

Surface water bodies that serve as sources of drinking water are often contaminated by MPs. Similarly, groundwater, which is traditionally considered to be less susceptible to pollution due to natural filtration processes, has also been found to contain MPs [97,98]. However, experimental data in the existing literature often suffer from the mentioned lack of standardization and incomplete analysis. Specifically, microplastics below the 10 µm threshold are frequently excluded from most studies. For example, a study conducted by Mintenig et al. [99] found low levels of MP particles (>20 µm) using Fourier transform infrared spectroscopy (FTIR) imaging in raw water samples from drinking water reservoirs in Germany, with concentrations ranging from 0 to 7 particles/L. Similarly, a pilot study conducted by Brancaleone et al. [94] found that MPs (>20 µm) were detectable through micro-Raman spectroscopy in Italian groundwater and fountains with a concentration ranging from 2 particles/L to a maximum of 5 particles/L. However, a significantly higher value of 38 ± 8 particles/L (in the range 20–500 µm) was detected using Laser Direct Infrared in an unconfined groundwater aquifer in Victoria, Australia [100] indicating that even seemingly pristine water supplies can be contaminated. Similarly, the study by Pivokonský et al. [101] further corroborated these findings using scanning electron microscopy (SEM), FTIR spectroscopy, and Raman spectroscopy, and demonstrating the presence of MPs (in the range 1–100 µm) in both raw and WWTP-treated drinking water, which raises concerns about the efficacy of current water treatment methods in removing these contaminants.

4.2.2. Treated Drinking Water

Since 2018, an increasing number of scientists investigated tap and bottled water originating from various locations around the globe. However, even in this case, the lack of standardization of methods, sampling volumes, and particle size ranges makes the comparison of different articles difficult, if not inconclusive. Meaningful insights can only be obtained within a single study, for example, regarding different locations of a certain site or different brands of bottled water.

A notable example of the lack of harmonization is the 2021 review by Kirstein et al. [102], which synthesized ten studies on MP pollution in bottled water characterized by different methodologies and reported concentrations ranging from 1.4 to 5.42×10^7 particles/L, with the latter value having been obtained using non-validated quantification methods. The authors concluded that it was unclear whether the observed discrepancies were due to differences between the investigated systems or to variations in quantification limits, analytical precision, or contamination during sample collection and analysis. On the other hand, Altunisik et al. [103] analyzed 150 bottled natural water and mineral water samples from Turkey, consistently using FTIR spectroscopy and stereomicroscopy with a detection limit of 1.2 µm; they found that MPs were present in 86% of the samples. Concentrations of MPs ranged from 2 to 35 particles/L with mineral waters having higher average-size particles and greater concentrations. Li et al. [104] examined 10 popular domestic and international brands of bottled drinking water available in Chinese supermarkets by using direct laser infrared system with a LOD of 10 µm and discovered that the average MP abundance was 72.32 ± 44.64 particles/L. The number of MPs detected in PET bottled water (65.62 ± 44.65 particles/L) and glass bottled water (87.94 ± 46.38 particle/L) was higher than that in tap water (49.67 ± 21.43 particle/L).

A more recent review work by the Joint Research Centre, the European Commission's science and knowledge service, summarized the results of 20 studies performed in drinking water samples of different parts of the world using different detection techniques [105]. The paper showed that the amount of microplastic particles found in drinking water vary between 0.0001 and 440 particles/L, which encompasses a range of about 6 orders of magnitude. The reported particle size ranged from 1 µm to 5 mm, even though most of the studies used filters with cut-off values of 10 µm or more, ruling out information about the presence of smaller MPs. In addition, some studies did not explicitly report the upper limit of size. PE, PET, PS and PP were the prevalent polymers. Interestingly, the numbers of MPs seem to be lower in Europe (0.000–0.6 particles/L) than in America (12–316 particles/L) and Asia (0.7–440 particles/L). As pointed out by the authors, part of this variability could be due to the use of different methods for MPs collection ("container-sampling" or "at-source filtering"), strategies for particle counting, and analyzed water volumes. Differently, automated Raman microspectroscopy with a LOD of 1 µm was used consistently in a very recent study that analyzed ten different brands of PET bottled water and one tap water sample from France [80]. The MP concentrations ranged from 19 to 1154 particles/L across the different brands, with 413 particles/L in municipal tap water from the Toulouse Metropole. Significantly, 98% and 94% of MPs were found to be less than 20 and 10 µm in diameter, respectively, and are smaller than the 20-µm limit indicated by the EU Directive 2020/2184 methodology for consumable water quality. In fact, lower number concentrations were found in ten brands of bottled water in Kerala (India) by using stereomicroscopic and a higher LOD of 100 µm, with values ranging from 3 ± 1 particles/L to 9 ± 1.7 particles/L across all brands [106]. By contrast, an average of 92 particles/L was found using a size detection limit of 1 µm in six water brands available on the Croatian market [107]. A study performed on 11 bottled water brands in Nepal found that the lowest MPs concentration was 107 ± 23 particles/L, while

the highest level was 365 ± 15 particles/L, with the particle size ranging from 6.7 µm to 5 mm [108]. The trend of increasing reported concentrations as the LOD decreases was further confirmed by an investigation of 23 popular Iranian brands of bottled water, carried out using SEM with a LOD of 1 µm [109]. The authors found from 199.8 to 6626.7 particles/L) with 91.3% of detected particles in the size range between 1 and 10 µm. However, another recent study [81] suggests that all these numbers could increase by several orders of magnitude if smaller, submicron particles (nanoplastics) are considered. In fact, as many as $2.4 \pm 1.3 \times 10^5$ particles/L were found in bottled water, about 90% of which were nanoplastics. In particular, the size distribution of polystyrene particles was centered around 100 to 200 nm.

These findings underscore the urgent need for a critical re-evaluation of the definition of the LOD and, by extension, of the criteria currently employed for microplastics classification. Collectively, the available evidence indicates that the field remains at a relatively early stage of development, marked by substantial methodological fragmentation and heterogeneity across studies.

Clearly, as also underlined by a remarkably recent systematic review of 140 articles, the large variability of reported MP pollution indicates the lack of standardized definitions, methods of quantitative identification, and comprehensive regulations for microplastics in bottled water [110]. Such shortcomings significantly hinder the comparability of results and represent a major obstacle to a robust and systematic assessment of the microplastics issue.

In addition, the presence of MPs in treated drinking water suggests that current water treatment technologies may not be fully effective at removing these particles. Conventional water treatment processes, such as coagulation, flocculation, sedimentation, and filtration, can remove larger MPs but may be less effective for smaller particles, especially those smaller than 100 µm [101,107]. Advanced treatment processes, such as ultrafiltration, nanofiltration, and reverse osmosis, have shown higher efficacy in removing MPs, but these technologies are not yet widely implemented in drinking water treatment plants [111].

In conclusion, while the studies reviewed often lack methodological harmonization, making a direct comparison of results challenging, it is evident that MPs are a widespread contaminant in freshwater systems and drinking water, originating from various sources, including wastewater treatment processes, stormwater runoff, and atmospheric deposition. Their occurrence in drinking water raises critical concerns regarding water quality and human health, necessitating further research to understand the potential impacts on public health and efficient strategies for MP removal.

5. Environmental and Human Health Impact

The ecological and human health impacts from MPs may primarily manifest as a chemical risk, originating from the specific constituents inherent in the material. In fact, MPs can contain chemical contaminants of mainly two origins. First, they can already be present in plastic particles such as unreacted raw materials or auxiliary materials due to incomplete polymerization reactions during the manufacturing process [112]. Second, there may be toxic contaminants that are adsorbed on the plastic surface after production, such as organic compounds [persistent organic pollutants (POPs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), phthalates, dichlorodiphenyltrichloroethane (DDT), etc.] [57,113] or heavy metals [114–117], bacteria [118], and viruses [119]. This can increase the danger of contaminants. For instance, it was found that biofilm *Escherichia coli* cells attached to MPs had elevated multidrug resistance [120]. Therefore, MPs can be associated with a complex mixture of contaminants that can create significant chemical and physical risks in the ecosystem. The potential for MP-borne chemicals to be transported

to organisms and through the food chain is an active area of research, as are the potential detrimental effects of MPs on organisms and entire ecosystems.

5.1. Environmental Impact

Research indicates that MPs can interact with a variety of biotas, leading to detrimental effects on aquatic and terrestrial organisms. For instance, studies have shown that MP fibers are prevalent in marine organisms such as mussels and zooplankton, which are critical components of marine food [121–123]. The ingestion of MPs by these organisms can disrupt feeding behaviors and reproductive functions, as evidenced by research on copepods, which demonstrated that polystyrene MPs adversely affect their fecundity and overall health [124]. Additionally, the chronic exposure of terrestrial organisms, such as earthworms, to polystyrene MPs has been shown to have transgenerational effects, indicating that the impacts of MP pollution can extend beyond immediate exposure [72]. A recent study provided clear evidence that exposure to MPs can directly induce severe, organ-wide scar tissue formation, termed "plasticosis", in wild free-living animals, potentially compromising individual health and long-term survival [125].

The mechanisms by which MPs exert their effects on biota are complex and multi-faceted, also due to their possible role as vectors for chemical harmful pollutants [126]. This phenomenon raises concerns about the bioaccumulation of these toxic substances within food webs, potentially leading to significant ecological and health consequences. Furthermore, the internalization of MPs into cells has been observed, suggesting that they may not be as inert as previously assumed [127,128]. This "Trojan horse" effect, where MPs facilitate the entry of harmful substances into biological systems, highlights the need for further investigation into their toxicological profiles [75].

In addition, the persistent nature and resistance to degradation mean that MPs are likely to accumulate in the environment over time, complicating efforts to mitigate their impacts [129]. Current wastewater treatment processes often fail to effectively remove MPs, allowing them to enter natural water bodies and exacerbate pollution levels [130]. This highlights the urgent need for improved waste management strategies and innovative technologies to address MP contamination in aquatic and terrestrial ecosystems.

The life cycle assessment of MPs reveals that their environmental hazards may surpass those associated with mismanaged polymer waste, particularly due to their potential for photodegradation and the subsequent release of volatile organic compounds into the atmosphere [131]. The ecological consequences of MP pollution are profound, affecting not only individual species but also entire ecosystems. For example, the ingestion of MPs by zooplankton can disrupt food web dynamics and nutrient cycling, with potential cascading effects on higher trophic levels [132]. Additionally, MPs can alter soil health and ecosystem functions, as evidenced by their impacts on soil-dwelling organisms and nutrient availability [133].

From Environment to Human Body

The widespread distribution and interaction of MPs with a variety of biotas across various habitats necessitate a holistic understanding of their ecological roles and the interrelationships between MP pollution, ecosystems, and human health. In particular, the environmental matrix acts as the primary contamination vector, serving as the starting point for a complex exposure pathway that bridges ecological integrity and human health. This continuum suggests that human health impacts are inextricably linked to environmental concentration levels, as the ingestion and inhalation of particles from contaminated matrices and food facilitate the systemic entry and accumulation of MPs and plastic-associated toxins in the human body [134,135]. Consequently, understanding the dynamics of this

environmental-to-human transfer is essential for assessing the cumulative toxicological risk posed by the global proliferation of microplastic debris.

5.2. Human Health Impact

Exposure to human beings may occur in three main ways: ingestion, inhalation, and dermal contact with MPs present in products, foodstuffs, and air. Figure 3 shows the three main routes of plastic particles' entry into the human body. Information on the impacts of MPs on humans is limited due to ethical constraints, strict biosecurity measures to handle human samples, and limited detection techniques.

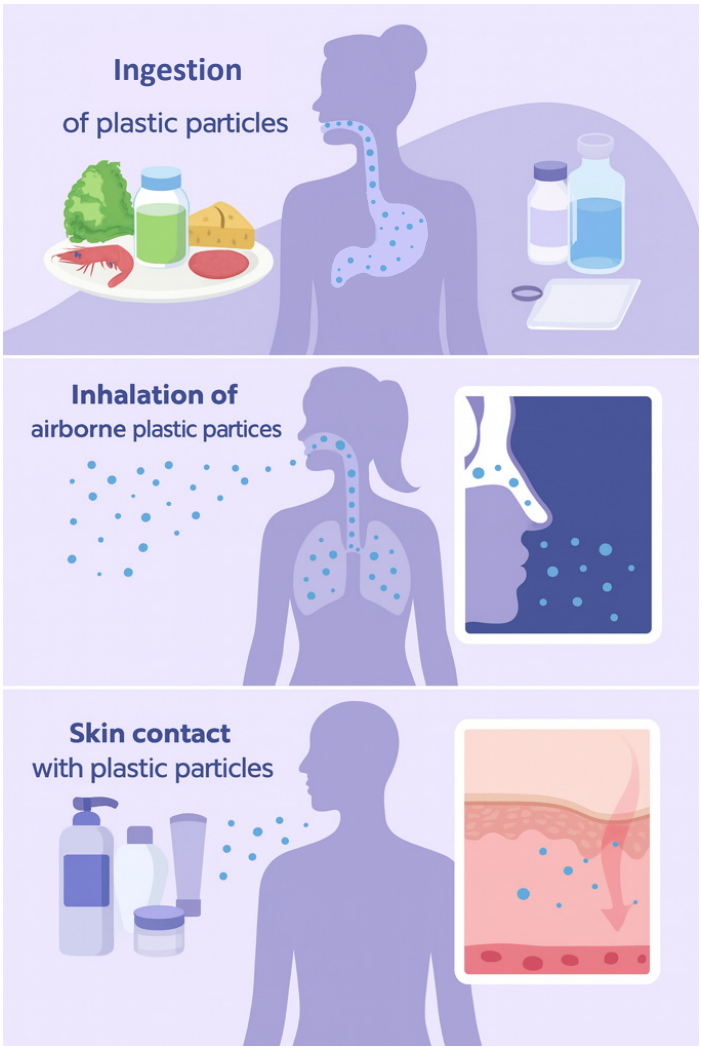


Figure 3. Key routes for micro- and nanoplastics entry into the human body.

5.2.1. Exposure to MPs

Ingestion. Oral ingestion is one of the main ways MPs enter the human body. MPs are widely found in food, beverage, pharmaceutical packaging and everyday products. In addition, through transmission via the food chain, MPs in oceans and rivers may also be ingested by aquatic organisms, such as fish, and then enter the human food chain. In fact, the widely cited study [136] that estimated human ingestion of MPs to a value as high as 5 g (a credit card) weekly has been brought into question by subsequent research [137]. However, recent studies confirm a relevant intake, even though with large variations across different geographic regions, primarily through seafood and drinking water [138]. Dietary exposure to MPs is increasingly recognized, for example in salts [139], sugar [140],

vinegar [141], milk and dairy products [142], bottled water [143], seafood [144], beer [145], honey [146], beverages [147,148], packaged meat [149], packaged food ice-cubes [150] and so on. Catarino et al. [151] predicted that the fiber in the dust fallout on plates during mealtime (13,731–68,415 particles/year/capita) is more important than MPs already present in food. The European Food Safety Authority considers that MPs larger than 150 µm in diameter are unlikely to be absorbed by the human body, while MPs smaller than 1.5 µm can penetrate deep into organs [102,152]. When these foods or drinks containing MPs are ingested by the human body, MP particles may be absorbed through the intestinal epithelial cells and enter the bloodstream. Toxicological data shows that the ingestion of these plastic particles can cause damage to the intestinal, hinder the passage of food or cause consequent reduction of normal food intake, and influence the availability of energy necessary for fundamental life processes [138,153]. They can also affect the immunological system, and cause death, neurotoxicity, and other problems. It should be noticed that significant risks are linked to the fact that the particles ingested may contain toxic contaminants attached to the MPs surface as mentioned before.

Inhalation. Airborne MP particles are also a significant source of human exposure, with a recent study suggesting that we inhale as many as 68,000 microplastic particles daily [154]. These particles may come from industrial emissions, vehicle exhaust, tire wearing, waste incineration, etc., or they may be kicked up by natural factors such as wind and water currents. When the body breathes in air containing MPs, the particles may enter the bloodstream through tissues such as the alveoli [155,156]. In the human body, the inhaled MP fibers (polyester) are taken up by lung tissue and may be related to tumors [157,158]. Research has shown that the MPs inhalation while wearing face masks increased with time during the COVID pandemic [159].

Dermal contact. Skin contact was long considered not the primary way MPs enter the body since dermal exposure to MP > 1 µm is limited by the barrier of the stratum corneum [160,161] and exposure was thought to be restricted to the negligible presence of nanoparticles in cosmetics and personal care products [162]. However, new evidence [160,163,164] suggests that MPs and NPs can trigger cutaneous alterations, elicit inflammatory reactions, interfere with the homeostasis of the skin's physiological functions, contribute to premature aging, and reduce the skin's normal response to damage and lesions. These effects could eventually lead to the proliferation of tumor cells and can be enhanced in damaged skin or mucous membranes (e.g., tattoos, medical implants, etc.), which can be a gateway for MPs to enter [165].

5.2.2. Presence of MPs in Human Specimens

The number of cases of MPs detected in human samples has increased in recent years, and these findings reveal the potential threat of MPs to human health. Here are some examples of specific human samples where MPs have been detected.

Blood samples. In a study published in 2022, a research team at Vrije University Amsterdam in the Netherlands found MP particles in the blood of human volunteers for the first time [166]. They tested blood samples from 22 healthy volunteers and found that 17 of them (77%) had MP particles in their blood, averaging 1.6 micrograms per milliliter of blood. This finding suggests that MPs may have spread throughout all the organs of the human body along with the blood circulation system, posing a great health risk. In a more recent study [167], MPs of 24 polymer types were identified in the blood of 18 volunteers out of 20 (90%). The most abundant compounds were PE (32%), ethylene propylene diene monomer (14%), and ethylene vinyl acetate (12%).

Placenta sample. In a study published in the journal Environment International in 2020, Italian researchers examined the placentas of six healthy pregnant women and detected

MP particles between 5 and 10 microns in four of the placentas [168]. In a study published in 2024, researchers at the University of New Mexico detected MPs in 62 placental samples, with a detection rate of 100% [169]. Very recently, MPs with a size below 10 μm (mean diameter of 4.48 μm) were detected in 14 out of 18 samples of follicular fluid, with an average concentration of 2191 particles/mL [170]. These findings suggest that MPs can circulate through the maternal blood, enter the placenta, cross the placental barrier and enter the fetus, posing a potential threat to the health of the fetus.

Heart and surrounding tissue samples. Researchers from Capital Medical University in China have discovered the presence of MPs in the heart and surrounding tissues [171]. Microplastic particles ranging in diameter from 20 to 469 μm were detected in five different types of tissue collected from the heart, including pericardium, epicardial adipose tissue, pericardial adipose tissue, myocardium, and left atrial appendage. MPs were detected in all types of samples, with the most common type of MP being PET, which accounted for about 77% of the total. This finding further confirms the widespread distribution of MPs in the human body and suggests that MPs may entering the bloodstream can deposit in the body's vital organs.

Stool sample. In 2019, Schwabl et al. [172] reported that all eight human stool samples tested positive for MPs, with an average of 20 MPs per 10 g of human stool with diameters between 50 and 500 microns. A total of nine plastic types were detected, with PP and PET being the most prevalent. This finding shows that MPs reach the human stomach and may be excreted through the digestive system, but they can also linger in the gut and potentially affect the digestive system.

Lung sample. After Dutch scientists detected MPs in the blood [166], British scientists have also found MP particles deep in the lungs of living people for the first time [157]. In detail, 39 MPs were detected within 85% of lung tissue samples with an average of 1.42 ± 1.50 particles/g of tissue. This finding is alarming because it suggests that MPs can enter the body not only through the digestive system but also through the respiratory system and into organs such as the lungs. A more recent investigation [134] detected an average of 14.19 ± 14.57 particles/g of tissue in the range size of 20–100 μm, and with PVC being the dominant polymer.

Nasal flush and sputum samples. Studies have shown that the presence of MPs has also been detected in the nasal rinses and sputum of indoor and outdoor workers such as couriers and office workers [173]. In the nasal lavage fluid of couriers, the predominant MP components were polyamide (PA) and PE, whereas for office staff, the main plastic components were PVC and PA. This indicates that MPs may enter the human respiratory tract through air inhalation and have potential effects on the respiratory system.

Semen samples. Researchers from Shandong Women and Children's Hospital [174] published a study showing that the detection rate of MPs was 100% in the semen samples of 36 subjects, with an average of 2 particles per sample, ranging from 0.72 to 7.02 μm in size. Eight different polymers were identified, with PS (31%) being the most common. In semen samples exposed to PS and PVC MPs, the sperm's ability to pull the thread was significantly reduced, which means that MPs may be harmful to men's reproductive health.

However, it should be noted that recent research suggests a risk of overestimation due to contamination during sample collection, detection, and analysis, pointing to the imperative for rigorous validation of interference factors [175,176].

5.2.3. Disease Related to MPS

The impact of MPs on human health is multifaceted, mainly including the following aspects:

Cancer risk. MPs may act as carriers for the transmission of carcinogens. Many plastic products contain carcinogenic substances, such as phthalates and polyvinyl chlo-

ride [136,177]. When these plastic products are broken down into MPs, these carcinogens may be released and enter the body. Once these carcinogens enter the blood circulation system, they may cause damage to the body's cells and tissues, which in turn increases the risk of cancer [178,179].

Immune system disorder. MPs entering the human body may trigger an abnormal immune system response [180,181]. The immune system is an important line of defense against external pathogens, and its balance is the key to maintaining good health. However, after MPs enter the blood circulation system as a foreign body, they may trigger the autophagy mechanism of immune cells and aggravate the stress response of cells, resulting in over-activation or suppression of the immune system, thus triggering immune system disorders. This disorder not only leads to an increased inflammatory response but also weakens the body's defenses against pathogens and increases the risk of autoimmune diseases and cancer.

Cardiovascular events. Emerging evidence suggests that MPs and NPs can infiltrate the circulatory system, posing a potential threat to cardiovascular integrity. In the cardiovascular system, MPs are known to cause free radical damage and cardiac fibrosis. Specific to atherogenesis, they affect every step by predisposing to dyslipidemia, causing endothelial dysfunction and inflammation, and creating a procoagulant environment. In particular, MPs cause switching of vascular smooth muscle cells phenotype and are shown to accumulate in the plaque and accelerate its growth [182,183]. Recent clinical studies have highlighted a significant correlation between microplastic accumulation and cardiovascular mortality. Specifically, studies have demonstrated that the presence of MPs and NPs within arterial plaques is associated with a markedly higher risk of myocardial infarction, stroke, or all-cause mortality. Longitudinal data indicate that patients with detectable plastic particles in their carotid plaques face a substantially increased risk of these adverse events at a 36-month follow-up, suggesting that vascular contamination represents a critical independent risk factor for cardiovascular health [184].

Reproductive system damage. MPs, and/or additive substances, are believed to have endocrine-disrupting effects that may interfere with the normal function of sex hormones [185]. Sex hormones play a crucial role in regulating the development and function of the reproductive system. However, the chemicals in MPs may mimic or interfere with the action of sex hormones and interfere with the body's endocrine balance. This interference can lead to problems such as abnormal development of the reproductive system, gonadal dysfunction, and reduced fertility. In particular, children and adolescents are easy targets for the effects of MPs on reproductive system function [186]. They are more sensitive to environmental chemicals at important stages of reproductive system development.

Accelerated cell aging. In recent years, studies have shown that the introduction of MPs into the blood can accelerate the cell aging process and cause significant health effects [187]. Cell aging is one of the important mechanisms of biological aging and disease, and the presence of MPs may accelerate the process through oxidative stress and other mechanisms, leading to the decline of body function and disease.

Studies have shown that MPs can cause damage to target organs and cells by reducing cell vitality [188], inducing cell apoptosis [189], generating oxidative stress [190] and inflammation [191,192], activating related signaling pathways [193], and affecting cell metabolism [194]. Some MPs contain harmful chemicals that can disrupt the body's endocrine system, leading to hormonal imbalances [185]. The immune system is unable to clear the synthetic particles, and long-term exposure may lead to chronic inflammation and increased tumor risk [195]. Nonetheless, knowledge of MPs toxicity is still limited and largely influenced by exposure concentration, particle properties, adsorbed contaminants, tissues involved, and individual susceptibility, requiring further research.

6. Detection Methods

Since MP pollution has now turned out to be one of the most critical environmental concerns, the detection of MPs has become a critical area of research due to their pervasive presence in various environmental matrices and their potential impacts on ecosystems and human health. The development of effective detection and identification methodologies is beyond necessary since it helps reveal MP pollution's prevalence, types, and impacts [196].

Current microplastic analysis typically follows a two-phase workflow: physical characterization (morphology and size) and chemical identification to confirm polymer composition [197]. While microscopy is the standard for physical assessment, and spectroscopy or thermal analysis are preferred for chemical validation, certain advanced microscopic methods now offer dual analytical potential. Because no single technique is universal, a multimodal approach, combining high-resolution laboratory standards with rapid screening tools, is essential to enhance the precision and reliability of MP monitoring across diverse environmental contexts.

6.1. Microscopy

Microscopic methods are essential for detecting, quantifying, and characterizing MPs, particularly in terms of their size, shape, and surface morphology. These techniques often complement spectroscopic methods by providing visual identification of MPs particles, and when combined with spectroscopic techniques, they offer a comprehensive analysis of MPs. However, microscopy-based approaches present some common drawbacks. In fact, it may require specific sample preparation depending on the material to examine under the microscope for MPs. For instance, in drinking water, filtration of large volumes may be necessary by using specific filters that are suitable for microscope observation. Below are the microscopic methods used for MP detection, including optical microscopy and electron microscopic methods.

Optical Microscopy. Optical microscopy is widely employed for the preliminary assessment of MPs, providing essential data on size, number concentration, shape, color, and surface morphology [198]. While cost-effective and straightforward, its reliable application is generally limited to particles and fibers larger than 100 µm [198,199]. Advanced techniques, such as stereo/dissecting microscopy, offer three-dimensional visualization for initial sorting, often preceding spectroscopic confirmation [200]. Additionally, polarized light optical microscopy (PLOM) can enhance identification for materials with birefringent properties, effectively characterizing MPs [199,201]. However, the method is prone to false positives/negatives due to its dependence on operator expertise and interference from organic or inorganic matrices [202,203]. Consequently, optical microscopy is primarily utilized as a rapid screening tool rather than a definitive identification method [149,150].

However, it should be noted that the resolution and reliability of optical microscopy can be improved by using digital microscopy, which enables the observation of particles with dimensions down to 1 µm [204].

Fluorescence microscopy. Fluorescence microscopy, particularly when coupled with staining with specific fluorescent dyes, such as Nile Red, is a highly effective method for detecting and quantifying small-scale MPs in complex matrices [205,206]. This approach enhances contrast, facilitating the rapid identification of common polymers like PE, PP, and PS [207]. Recent advancements, including laser confocal fluorescence microscopy, have improved detection sensitivity and the localization of stained MPs in biological studies [205,207]. To mitigate false positives caused by organic matter, researchers have integrated counterstaining techniques [208] and explored alternative dyes, such as Coumarine 6, Rhodamine B, and iDye variants, to broaden the range of detectable polymers and enhance analytical accuracy [209–211].

Fluorescence lifetime imaging microscopy (FLIM). This method identifies MPs by measuring the decay time of fluorescence emission, providing detailed spatial mapping for material differentiation. Compared to traditional methods, FLIM significantly accelerates the analysis of dye-stained particles [212]. Furthermore, when combined with phasor analysis, FLIM enables a fast, sensitive, and label-free identification of various MP types based on their unique fluorescence lifetimes [213].

Confocal laser scanning microscopy (CLSM). improves upon standard fluorescence techniques by providing high-resolution, three-dimensional imaging of microplastics in situ [214]. This approach is instrumental in ecological studies, as it enables the visualization of MPs distribution and interactions within complex environmental matrices and biological tissues [214]. For instance, CLSM has been successfully employed to image fluorescently labeled polystyrene microbeads encapsulated within plant tissues [215].

Hyperspectral imaging (HI) and microscopy enable the identification of MPs and NPs by capturing unique spectral signatures across a wide wavelength range [216]. A major advantage of HI is the simultaneous collection of spatial and spectral data, which significantly reduces the need for extensive sample preparation and tissue digestion [214,217]. For instance, this technique has been successfully applied to identify polymers within fish intestinal tracts and water samples, acting as a rapid precursor to more time-consuming methods like Raman or FTIR spectroscopy [217,218]. Furthermore, dark-field hyperspectral microscopy offers a label-free, non-destructive approach, making it a valuable tool for both environmental monitoring and nanotoxicological studies [219].

Scanning electron microscopy. Utilizes focused electron beams to characterize the surface morphology, texture, and microstructure of microplastics at high resolution. It is particularly effective for examining surface degradation and microbial colonization, which influence the environmental fate of particles [220]. When coupled with energy dispersive X-ray spectroscopy (EDX), SEM helps to provide elemental composition data, enabling the chemical identification of MPs and the assessment of their potential toxicity [221].

Transmission electron microscopy (TEM) enables the characterization of MPs and NPs at the nanometer scale by transmitting an electron beam through ultra-thin sections. This technique provides exceptional resolution for examining internal structures, degradation processes, and interactions with environmental matrices [214]. While not routinely used for general detection, TEM is indispensable for distinguishing polymers from organic matter in complex samples—such as soil—and for analyzing particles too small for conventional optical methods [214,222].

Atomic force microscopy (AFM). AFM is a powerful tool for characterizing MPs. It detects MPs and provides high-resolution imaging by scanning surfaces with a sharp probe that measures surface topography and mechanical properties at the nanoscale. Karpenko et al. [223] studied changes in the topography and mechanical properties of degraded polymer surfaces with AFM. Nanoscale infrared, thermal and mechanical properties of TiO_2-pigmented MPs before and after aging were revealed by using an AFM-IR technique [224]. However, AFM is often limited by its inability to analyze large sample sizes quickly, which is critical for environmental monitoring [216].

Microscopic techniques are essential for MP analysis, providing visual and morphological insights, each offering unique advantages in terms of resolution, specificity, and applicability to different sample types. A summary of microscopic methods is presented in Table 3, which compares these techniques from various points of view.

Table 3. Microscopic methods for MP detection.

Method	Size Detection Limit	Chemical Characterization	Sample Preparation	Cost	Principle	Advantages	Limitation
Stereomicroscopy	100 µm	No	Wet peroxide oxidation, filtering, drying (optionally staining)	Low	Provides a 3D view of larger particles using optical paths.	Fast sorting of large particles by shape and color.	Low resolution, cannot detect small particles or provide chemical ID.
Digital Microscopy	1 µm	No	Wet peroxide oxidation, filtering, drying (optional staining)	Low	Provides a very high sharpness images at high magnification (x6000)	Fast sorting of large particles by shape and color.	Cannot detect small particles or provide chemical ID.
Polarized Light Microscopy (PLM)	50 µm	Partial (crystalline)	Wet peroxide oxidation, drying, mounting on a transparent substrate	Low	Enhances contrast using polarized light to detect birefringence.	Useful for fiber identification.	Requires expertise, limited for small particles.
Fluorescence Microscopy	1 µm (with fluorescence)	Partial (via fluorescent labeling)	Filtration, staining, drying, use of optical filters	Moderate	Detects fluorescence from particles or dyes.	High contrast, detects very small particles.	Requires staining, can produce false positives.
Fluorescence Lifetime Imaging Microscopy (FLIM)	100 nm	Yes (based on fluorescence lifetime)	Staining or naturally fluorescent materials, mounting on quartz substrates	Medium to High	Measures the decay time of fluorescence emitted from excited molecules, providing information on molecular environment and interactions.	High spatial resolution, allows for detection of MPs and analysis of molecular interactions, can provide quantitative data on fluorophores.	Requires fluorescent dyes for non-fluorescent materials, can be complex to interpret, sensitive to environmental factors (pH, temperature).
Confocal Laser Scanning Microscopy (CLSM)	500 nm	Partial (via fluorescent labeling)	Staining, centrifugation, filtering, immersion on glycerin (or similar) between quartz substrates	High	Uses laser scanning to create 3D images.	High-resolution, 3D imaging, useful in biological samples.	Expensive, requires fluorescence or labeling.
Hyperspectral Imaging (HIS)	0.5 mm	Yes (spectral information for each pixel)	Wet peroxide oxidation, drying, sieving, avoid thick layer of MPs	Very High	Collects spatial and spectral data for each pixel in an image.	Simultaneous spatial and chemical identification.	Expensive, requires complex data processing, lower spatial resolution.
Scanning Electron Microscopy (SEM)	1 µm	Partial (with EDX)	Wet peroxide oxidation, drying, conductive coating	High	Scans surface with electrons to create detailed images.	High-resolution surface morphology imaging.	Requires conductive coating, no chemical ID without EDX.
Transmission Electron Microscopy (TEM)	1 nm	No	MPs has to have ultra-thin sections or ultramicrotomy	Very High	Transmits electrons through thin samples to visualize internal structures.	Ultra-high resolution, visualizes internal features.	Expensive, complex preparation, no polymer identification.
Atomic Force Microscopy (AFM)	1 nm	No	Wet peroxide oxidation, ultra flat substrate, sample fixing	High	Scans surfaces to create 3D topographical maps based on atomic forces.	Provides 3D surface detail and nanoplastic analysis.	Slow scanning, small sample area, no chemical ID.

6.2. Spectroscopy

The detection of MPs in diverse environmental matrices (such as water, air, soil, and food) using spectroscopic methods is a rapidly growing field. Spectroscopy provides non-destructive, accurate, and efficient techniques to identify the chemical composition of MPs and differentiate them from other particles or organic matter. Below are the spectroscopic methods used for MP detection in the literature.

Fourier transform infrared spectroscopy. FTIR spectroscopy is a cornerstone for MP identification, providing "molecular fingerprints" based on infrared light absorption. Its effectiveness in characterizing diverse polymer types across surface waters, sediments, and marine environments is well-documented [225,226]. Recent methodologies have extended the range to small MPs, highlighting that excluding this size fraction significantly biases concentration estimates [227]. While sample geometry can occasionally complicate baseline interpretation [228], advanced modalities like micro-FTIR (μ-FTIR) allow for the precise quantification of fibers [229]. Furthermore, Attenuated Total Reflectance (ATR-FTIR) offers enhanced sensitivity for particles as small as 6 μm, simultaneously providing data on both size and chemical composition [230].

Raman spectroscopy. Raman spectroscopy is a leading non-destructive technique for MP identification, providing precise chemical fingerprints based on molecular vibrational states. Recent advancements focus on the standardization of protocols and data quantification to improve global comparability [231]. Innovative applications include the estimation of MP concentrations in aqueous samples via peak-area ratios [232] and the use of micro-Raman (μ-Raman) for micrometer-scale characterization directly on filters [233]. Notably, the integration of standing acoustic waves allows for the identification of particles as small as 4 μm in flowing liquids, bypassing laborious filtration steps [234]. Furthermore, surface-enhanced Raman spectroscopy (SERS) has significantly pushed detection limits down to the nanometer scale [216,235].

Near infrared spectroscopy (NIR). NIR has emerged as a portable and cost-effective complement to FTIR, particularly suited for field-based identification of MPs [236,237]. By analyzing polymer-specific spectral signatures in the NIR range, this technique enables high identification rates even with miniaturized spectrometers (MicroNIR) [238]. Its adaptability for widespread environmental monitoring is further demonstrated by low-cost applications for quantifying MPs in complex matrices like soil [239].

Laser direct infrared spectrometry (LDIR). Utilize a quantum cascade laser (QCL) to rapidly analyze infrared absorption spectra directly on surfaces, minimizing sample preparation. This high-speed technique is particularly effective for identifying and quantifying polymers like PVC, PE, and PP across a wide size range (20–5000 μm), surpassing the throughput of conventional spectroscopic methods [240,241]. Its versatility has been demonstrated in diverse matrices, ranging from Mediterranean marine samples to biological fluids such as sputum [240,242].

Nuclear magnetic resonance spectroscopy (NMR). NMR spectroscopy provides detailed insights into the molecular structure and dynamics of MPs by analyzing the magnetic properties of atomic nuclei. It is uniquely suited for analyzing complex mixtures and identifying chemical additives or leached substances without extensive sample preparation [243]. Recent algorithmic advancements in NMR spectra analysis have further enhanced its ability to evaluate structural properties [244], while its application in biological studies offers a deeper understanding of the interactions between MPs and living systems [245].

Optical photothermal infrared (O-PTIR) spectroscopy. O-PTIR spectroscopy overcomes the diffraction limits of traditional infrared methods by combining optical microscopy with photothermal detection. This approach achieves sub-micrometer lateral resolution, enabling the non-contact identification of MPs and NPs within complex biological tissues and environmental matrices [246]. Recent studies have utilized O-PTIR to quantify MP release from consumer products, such as PET bakeware [247], and to develop standardized detection frameworks that offer high accuracy for particles across a broad size range [248].

Fluorescence spectroscopy. Fluorescence spectroscopy identifies MPs by measuring light emission following excitation, either through intrinsic polymer properties or selective staining. Dyes such as Nile Red and 4-dimethylamino-4′-nitrostilbene (DANS) are widely used to differentiate plastics from organic matter. Notably, DANS varies its emission spectrum based on polymer polarity, enabling material discrimination [206,249,250]. Similarly to Raman spectroscopy, this method is highly effective for "in-flow" analysis. By integrating flow cytometry principles, researchers have developed automated, portable devices for the real-time detection of MPs in water streams, significantly reducing analysis time and operational costs [251–253].

Each spectroscopic method for detecting MPs has its own strengths and limitations. A summary of spectroscopic methods is presented in Table 4, which compares these techniques from various points of view. FTIR and Raman spectroscopy are the most used due to their excellent polymer identification abilities. However, depending on factors like the sample matrix, particle size, and detection limits, alternative techniques such as LIBS, fluorescence spectroscopy, or hyperspectral imaging may offer advantages.

6.3. Thermal Analysis

Thermal analysis methods are essential for the quantification and characterization of MPs based on their thermal degradation patterns and chemical composition [254,255]. However, these methods are inherently destructive and may not be suitable for all environmental matrices. Consequently, they are often complemented by non-destructive spectroscopic approaches (e.g., FTIR and Raman) to enhance analytical reliability and provide a comprehensive understanding of MP distribution and ecological impact [256].

Thermogravimetric analysis (TGA). It quantifies MPs by measuring mass changes during controlled heating, providing insights into their thermal stability and decomposition profiles [257]. When coupled with mass spectrometry (TGA-MS) or FTIR (TGA-FTIR), it allows for the simultaneous identification of specific polymer types through the analysis of released volatile products and spectral fingerprints [258–260]. Furthermore, the integration of pyrolysis with TGA enables the effective quantification of mixed samples (e.g., PE and PET) in complex matrices, offering a robust tool for environmental monitoring and risk assessment [189].

Differential scanning calorimetry (DSC). DSC identifies microplastics by measuring heat flow associated with phase transitions, such as melting and crystallization points, which are characteristic of specific polymer types [261]. This technique has been successfully applied to analyze MPs in river sediments and is frequently used in quality testing to evaluate thermal stability [261,262]. Although DSC is a powerful tool, especially when combined with TGA to correlate thermal degradation with phase changes [263], it remains less common in routine environmental monitoring compared to spectroscopic methods due to its destructive nature and lower throughput.

Pyrolysis gas chromatography-mass spectrometry (Py-GC-MS). Py-GC-MS is a premier technique for MP analysis, combining oxygen-free thermal decomposition (pyrolysis) with gas chromatography and mass spectrometry to identify polymers via their volatile fragments. This method excels in analyzing complex mixtures and quantifying plastics in diverse matrices, including sediments and biological tissues [264,265]. Recent applications include the assessment of MP abundance and chemical additives in edible fish and marine samples [266,267]. While portable Py-MS versions are emerging for rapid monitoring [268], this destructive approach is often complemented by FTIR or Raman spectroscopy to characterize smaller particles that may elude thermal detection [235,269].

As summarized in Table 5, while thermal methods like TGA, DSC, and Py-GC-MS offer unparalleled chemical and stability data, their effectiveness is often balanced by limitations in sample size and the need for rigorous calibration.

Table 4. Spectroscopic methods for MPs detection.

Method	Size Detection Limit	Chemical Information	Sample Preparation	Cost	Principle	Advantages	Limitation
Fourier Transform Infrared Spectroscopy (FTIR)	10 μm	Yes (IR absorption spectra)	Wet peroxide oxidation, filtration, cleaning of substrates	Medium	Measures IR absorption to identify polymer composition via characteristic vibrations.	Non-destructive, identifies most polymers, can analyze mixtures.	Limited spatial resolution, unable to detect very small particles (<10 μm).
Raman Spectroscopy	1 μm	Yes (Raman shift spectra)	Wet peroxide oxidation, filtration and deposition on cleaned substrate	Medium to High	Measures scattered light to provide molecular fingerprint based on vibrational modes.	High spatial resolution, detects small particles, identifies pigments.	Fluorescent samples may interfere, lower throughput compared to FTIR.
Near Infrared (NIR) Spectroscopy	500 μm	Yes (broad molecular information)	Wet peroxide oxidation, filtration and deposition on cleaned substrate	Low to Medium	Analyzes molecular overtones and combinations of vibrations in the near-infrared region.	Fast and non-destructive, good for bulk analysis and polymer differentiation.	Limited sensitivity for small particles, broad spectral bands, not highly specific.
Laser Direct Infrared (LDIR) Spectrometry	10 μm	Yes (IR absorption spectra)	Wet peroxide oxidation, filtration, drying	High	Combines laser and IR spectroscopy for high-throughput polymer identification.	High throughput, automated mapping, good for polymer identification.	Expensive, resolution limited by laser spot size (~10 μm).
Nuclear Magnetic Resonance (NMR) Spectroscopy	None (requires dissolved samples)	Yes (chemical structure)	Requires sample dissolution	Very High	Analyzes the magnetic properties of nuclei to provide detailed structural information.	Very detailed chemical information, differentiates complex polymers.	Requires dissolved or pure samples, not suitable for solid particles.
Optical Photothermal Infrared (O-PTIR) Spectroscopy	500 nm	Yes (IR absorption spectra)	Wet peroxide oxidation, filtration, drying	High	Measures infrared absorption indirectly by detecting photothermal effects.	High spatial resolution, can analyze very small particles (<1 μm).	Expensive, complex instrumentation, lower sensitivity for certain materials.

Table 5. Thermal analysis methods for MPs detection.

Method	Size Detection Limit	Chemical Information	Sample Preparation	Cost	Principle	Advantages	Limitation
Thermogravimetric Analysis (TGA)	1 μm	Yes (mass loss profiles)	Wet peroxide oxidation, density separation, drying	Medium to High	Measures weight changes in a sample as it is heated, providing information on thermal stability and composition.	Simple setup, can analyze small amounts of material, useful for assessing the thermal stability of plastics.	Limited to thermal decomposition, cannot provide specific chemical identities.
Differential Scanning Calorimetry (DSC)	1 μm	Yes (thermal transitions)	Wet peroxide oxidation, dehydration, mass of the sample (5–10 mg)	Medium	Measures heat flow into or out of a sample as it is heated or cooled, providing insights into thermal transitions (melting, crystallization).	Provides specific thermal properties, useful for characterizing polymer behavior during heating.	Limited size range, cannot identify specific polymers directly.
Pyrolysis Gas Chromatography-Mass Spectrometry (Py-GC-MS)	1 μm	Yes (chemical composition)	Wet peroxide oxidation, drying, precise weighing (10–100 μg), requires pyrolysis	High	Involves the thermal decomposition of polymers in an inert atmosphere followed by GC-MS analysis of the resulting gaseous products.	Highly sensitive and specific, provides detailed chemical identification of MPs.	Expensive, requires complex sample preparation, not suitable for quantitative analysis without calibration.

6.4. Other Techniques

Recent advancements in detection methods have focused on enhancing sensitivity, speed, and accuracy. This section discusses various innovative techniques for MP detection, highlighting their principles and applications.

Flow cytometry. Flow cytometry is an emerging strategy for MP and NP detection, offering distinct advantages in high-throughput particle size analysis and quantification within aquatic environments [257]. This method is particularly effective for characterizing the smallest MPs fractions and NPs, which often elude traditional analytical techniques [270]. By integrating enhanced detection protocols and Nile Red staining, flow cytometry enables precise enumeration and differentiation based on physical and chemical properties, significantly improving the accuracy of quantitative toxicity assessments [252].

Microfluidic devices. Microfluidic devices offer a miniaturized and automated approach to MPs analysis, enabling sample pretreatment, enrichment, and separation within microchannels [257]. These platforms achieve high throughput and low reagent consumption by integrating multiple detection modalities, such as fluorescence, mass spectrometry, and optical spectroscopy, the latter particularly effective for the 1–100 μm size range [257,271]. Innovations include droplet-based impedance flow cytometry for real-time monitoring [272] and triboelectric sensors that quantify MPs by measuring electrical charges generated during flow [273]. Furthermore, combining microfluidics with low-cost Nile Red staining provides a portable, continuous identification tool comparable to conventional laboratory methods, facilitating long-term in situ environmental monitoring [274].

Electrochemical analysis. Electrochemical analysis identifies microplastics by measuring electrical responses to applied voltage or current, offering insights into their redox behavior and concentration. Recent advancements include hydrophobic carbon electrosensors enhanced with cerium oxide nanoparticles for detecting PE and PP [275], and electrochemical impedance spectroscopy (EIS) using graphene electrodes for the rapid quantification of PS in water [276]. Additionally, liquid-solid triboelectric nanogenerators (LS-TENG) leverage the triboelectric effect to identify MPs based on the specific voltage signals generated during material interactions [206].

Light scattering analysis. Light scattering methods are highly effective for detecting microplastics (MPs) in transparent matrices, exploiting Rayleigh scattering for sub-wavelength particles and Mie scattering for larger particles (1–100 μm). These techniques differentiate MPs based on size, refractive index, and angular scattering signatures [216,277]. Dynamic light scattering (DLS) provides non-invasive size distribution analysis, while static light scattering (SLS), when combined with statistical tools like principal component analysis (PCA) and linear discriminant analysis (LDA), enables the precise determination of MP concentration and surface characteristics [278]. Together, these methods offer a foundation for developing portable, low-cost optical sensors for real-time water monitoring.

Digital holography (DH). DH is a high-resolution, non-invasive imaging technique that records 3D particle holograms, enabling numerical refocusing and quantitative morphological analysis [279]. When integrated with artificial intelligence (AI), DH effectively distinguishes MPs from organic matter, such as marine diatoms [280]. Recent breakthroughs include zero-shot learning methods that identify novel polymer types not present in initial training datasets [281] and polarization-sensitive imaging, which allows for the angle-independent identification of transparent MPs through complex scattering media [282].

Artificial Intelligence and Machine Learning (ML). AI and ML are transforming MP analysis by enhancing the accuracy, scalability, and automation of traditional detection methods. ML algorithms excel at processing large spectroscopic datasets, using pattern recognition to identify polymers based on their spectral signatures [283,284]. Key innovations include explainable AI for improving FTIR classification through data augmentation [285] and

AI-assisted holographic microscopy for rapid in situ characterization of both MPs and NPs [286]. Furthermore, combining HI with ML allows for the efficient mapping of plastics in complex soil and water matrices [287], while predictive modeling offers critical insights into the environmental distribution and ecological risks of plastic pollution [288].

6.5. Final Remarks

Overall, the detection of MPs involves a diverse group of methodologies, each contributing unique insights into the characterization and quantification. In particular, the summary of the size detection limit of various imaging techniques can be found in Figure 4. In practical applications, the challenges associated with MP detection, such as their small size and diverse morphology, necessitate the use of multiple analytical strategies to ensure accurate identification and quantification. The integration of multiple approaches often enhances the sensitivity, specificity, reliability, and comprehensiveness of MP analysis. Notably, a recent study has highlighted the possibility of overestimation, emphasizing the need for further validation regarding contamination, interference issues, and the standardization of observational methodologies. [175,176]. Furthermore, the development of novel MP detection methods is crucial for addressing the environmental challenges posed by these pollutants. Advancements in automated analysis and sample-preparation techniques are expected to streamline the detection process, making it more efficient and less labor-intensive. Finally, as previously discussed in Chapter 4 and highlighted by Anuar et al. [289], standardized methods for analyzing MPs are essential for global comparisons of MP pollution and its environmental impacts.

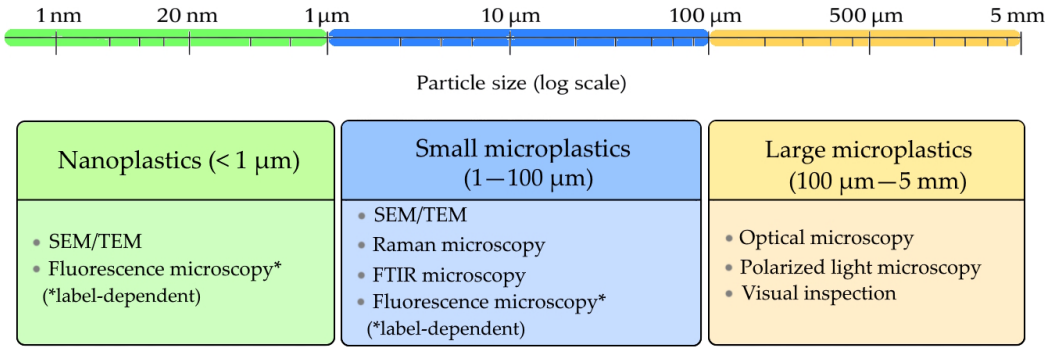


Figure 4. Detectable MP sizes with different imaging techniques.

7. Conclusions and Future Perspectives

The present review clearly demonstrates that MPs are ubiquitously distributed in environmental compartments and are increasingly detected within the human body. These findings highlight that MP pollution is no longer solely an environmental issue but represents a growing concern for human health. Based on the current state of knowledge, several critical aspects emerge:

- Urgent need for methodological standardization.

One of the major limitations in MP research is the lack of standardized sampling and analytical protocols. Harmonization is urgently required with respect to sampled water volumes, units of measurement, size classification, polymer identification, and reporting formats. In particular, the vast majority of studies reported in the literature employ a detection limit exceeding 10 µm. Even the methodology prescribed by EU Directive 2020/2184 for drinking water quality sets a limit of 20 µm. This practice contrasts sharply with recent findings demonstrating that the bulk of microplastics consists of significantly smaller particles, often reaching the sub-micrometric scale. A clear and globally harmonized definition of this parameter, while accounting for the inherent diversity of

various ecosystems, is of paramount importance for establishing future research guidelines. Without standardized methodologies, comparison among studies remains difficult and hampers the development of reliable global assessments.

- Identification of gaps in detection and the most effective quantification methods.

Although numerous techniques are currently employed to sample, identify, and quantify MPs, not all methods offer the same levels of sensitivity, accuracy, or reproducibility. Regarding identification, Raman and FTIR have been used in most of the literature about this field and could be regarded as the gold standard for polymer classification. However, other spectroscopy methods such as fluorescence, MS, and NMR have been proposed for characterizing MPs. Integrating these techniques with optical microscopy and artificial intelligence could be the key to achieving a complete and reliable analysis of MPs. Moreover, the demand for simple, automated, inexpensive, portable systems for on-site inspection should also be considered. Future efforts should aim to critically evaluate existing approaches and define a set of validated, cost-effective, and widely applicable methods for MP detection in environmental and biological matrices.

- Growing evidence of risks to human health.

An increasing body of scientific evidence indicates that MPs can enter the human body through multiple exposure pathways and accumulate in tissues and organs. This raises serious concerns regarding their potential toxicological effects, including inflammation, oxidative stress, and the transport of chemical additives and pathogens. The presence of MPs in human organs underscores the urgency of assessing their short- and long-term health implications.

In conclusion, future research should focus on elucidating the mechanisms of MP toxicity, evaluating chronic exposure effects, and understanding dose–response relationships in humans. Addressing MP pollution requires coordinated efforts across environmental science, toxicology, medicine, and policy-making to develop comprehensive risk assessment and mitigation strategies.

In addition, to effectively mitigate MP-related health risks, proactive measures are needed, including stricter regulations, standardized limits for MPs in products, reduction of single-use plastics, improved waste classification and recycling systems, and increased public awareness. Promoting sustainable and environmentally friendly lifestyles is essential to mitigate MP pollution at its source. Only through standardized scientific approaches, robust regulatory frameworks, and collective societal action can the risks posed by microplastics to both environmental and public health be effectively addressed.

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