



Review

Microplastics in aquatic ecosystems: Detection, source tracing, and sustainable management strategies



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ABSTRACT

Microplastics (MPs) are emerging contaminants characterized by persistence, cross-media transport, and complex pollutant interactions, posing serious ecotoxicological risks to ecosystems and human health. Effective MPs management requires multi-faced, long-term, strategies involving targeted sampling, quantitative detection, and comprehensive risk assessments, all of which entail significant resource investment. Despite advancements in remediation technologies, a holistic governance framework integrating these innovations remains underdeveloped. This review synthesizes current knowledge on MPs, elaborating on their diverse morphologies, degradation pathways, and their role as vectors for toxic substances. State-of-the-art extraction techniques are evaluated in this article, including micropore adsorption using nanocomposites, alongside the incorporation of advanced analytical tools such as spectroscopic methods, electron microscopy, and bioinformatics to augment environmental forensics. This review also underscores the necessity of formulating robust global policies to regulate MPs pollution and discusses the potential of biodegradation and thermal degradation as sustainable solutions for MPs removal. By promoting an interdisciplinary approach, this review advocates for a coordinated global response, integrating environmental science, policy frameworks, and waste management strategies to mitigate the escalating impact of MPs on ecosystems and human well-being.

1. Introduction

Microplastics (MPs), typically defined as plastic particles smaller than 5 micrometers in size, have become ubiquitous in aquatic environment globally (Anderson et al., 2016). Over the past seven decades, the rapid increase in plastic production has led to a staggering rise in plastic waste. A global study estimates that approximately 4.9 billion metric tons of plastic waste were accumulated in landfills or the natural environment between 1950 and 2015, with projections suggesting this figure will reach 12 billion tons by 2050 (Geyer et al., 2017). This widespread plastic accumulation inevitably contributes to the growing

environmental concern surrounding MPs, which are found in oceans, freshwater bodies, soils, and air, representing a significant environmental challenge (Perumpally et al., 2023).

MPs originate from various sources, including the fragmentation of larger plastic debris due to environmental stressors such as UV radiation and mechanical wear, microbeads from personal care products (So et al., 2018), synthetic fibers from textiles, industrial plastic pellets (Gkika et al., 2023; Dayal et al., 2024), roadway runoff from tires and asphalt, and agricultural practices using plastic coverings (He et al., 2022). These particles enter aquatic ecosystems through numerous pathways, including river discharges, wastewater treatment effluents, atmospheric

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deposition, and surface runoff, resulting in widespread dispersion and accumulation in marine and freshwater environments (Kumar et al., 2023; Ansari et al., 2022). The detection of MPs is complicated by their heterogeneity in size, shape, polymer type, and surface characteristics, making specialized analytical techniques essential for accurate identification and quantification (Thompson and Crooks, 2022). Despite the increasing awareness of MP pollution, inconsistencies in data reporting and a lack of standardization in monitoring methodologies hinder comprehensive assessments of MPs' environmental distribution. Inconsistent monitoring networks and varying measurement standards contribute to gaps in global understanding of MP pollution in aquatic ecosystems. Thus, developing a unified approach to MP monitoring and a better understanding of their behavior across different environments is crucial for managing this pervasive issue. Recent studies have highlighted the alarming concentrations of MPs in various aquatic systems. These data reflect significant regional variation in MP abundance and composition, underscoring the need for comprehensive global monitoring efforts (Table 1).

MPs present unique ecological risks due to their small size, large surface area, and persistence in the environment (Campanale et al., 2020). They provide a substrate for microbial colonization, potentially facilitating the transport of pathogens and increasing the risk of biological invasions (Wang et al., 2021). The weight of microorganisms attached to plastic marine debris has been estimated to range from 1000 to 15000 tons (Mincer et al., 2019). Furthermore, MPs can adsorb and transport hazardous pollutants, including heavy metals, persistent organic pollutants (POPs), and pharmaceuticals, amplifying their environmental impact (Lee and Chae, 2021; Ansari et al., 2025). In aquatic organisms, such as plankton, MPs are often mistaken for food, leading to ingestion by species such as plankton, fish, and marine invertebrates. While most MPs are excreted, some remain in the digestive systems of organisms, where they may cause internal damage, oxidative stress, and toxicological effects. As MPs move up the food chain, these toxic effects can be magnified, presenting risks to both marine biodiversity and human health through the consumption of contaminated seafood (Huang et al., 2021).

To address MPs pollution effectively, current mitigation strategies largely focus on post-pollution remediation, including advanced wastewater treatment, physicochemical adsorption, and biodegradation (L et al., 2024; Iyare et al., 2020). However, these measures primarily

target existing pollution, with limited impact on the root causes of MPs proliferation. Environmental forensics, however, offers a proactive approach by identifying and tracing pollution sources, enabling the development of targeted policies to curb plastic waste at its origin. For example, detecting high concentrations of microbeads in cosmetic products could lead to regulatory measures aimed at reducing their use. Furthermore, regulatory frameworks that focus on single-use plastics and encourage the use of biodegradable alternatives can mitigate the long-term environmental burden of MPs (Ambade et al., 2021). As the science of MPs detection evolves, the ability to monitor smaller particles, such as nanoplastics, is becoming increasingly important. While MPs are the current focus of environmental forensics due to their higher abundance and easier characterization, ongoing advancements in analytical techniques will eventually enable the inclusion of nanoplastics in regulatory frameworks (Lv et al., 2022). This progress is vital for ensuring comprehensive policies that address the full spectrum of plastic pollution.

Several regions, including the United States, the European Union, and China, have already implemented regulations targeting MPs. For example, the U.S. introduced the Microbead-Free Waters Act in 2015 to prohibit the use of microbeads in personal care products (Wyer et al., 2020). Similarly, the European Union's 2023 regulation on polymer particles aims to reduce MP pollution by controlling the market entry of products containing plastic particles (Protecting environment and health, 2023). Despite these efforts, regulatory frameworks often face challenges in addressing the full scope of MPs pollution, particularly in terms of biodegradable plastics and products from emerging sources (Table 2). To address these gaps, international cooperation and the establishment of ecologically recyclable standards are necessary to drive more effective global governance of MPs (McDevitt et al., 2017).

This review distinguishes itself from previous studies by emphasizing the role of environmental forensics in tracking and mitigating MPs pollution. By integrating a critical evaluation of existing methods for sampling, extraction, and detection of MPs with recent advancements in their toxicity and environmental interactions, this review aims to inform policy decisions and advance the scientific understanding of MPs in aquatic ecosystems.

Table 1
Concentration and characteristics of MPs in water.

Source	Abundance	Composition	Size	Shape	Ref.
Wei river, China	361 – 1322 items/kg	PE, PVC, PS	31.2 % < 0.5 mm	Fibers (42.0 % – 53.0 %)	(Zhang et al., 2018)
Ganga river, India	99.26 – 409.87 items/kg	PET, PE, PP			(Zhou et al., 2020)
Xisha Islands, China	0 – 2444 items/kg	PP (40.19 %), PS (17.76 %), EVA, (13.08 %) and HDPE (9.35 %)	5.37 – 4011.09 μm	Fragments (58.08 %), films (36.54 %)	(Lin et al., 2024)
Jakarta Bay, Indonesia	185 items/cm ²	PP, PE	300 – 1000 μm	Film (65 %) , fibers (31 %) , fragments (42.9 %)	(Priscilla et al., 2019)
Mediterranean, Italy	1.25/m ²	PE, PP	< 300 μm (26 %) < 500 μm (51 %) > 5 mm (1.4 %)	Fragments (93.2 %), pellets (2.2 %)	(Priscilla et al., 2019)
Thames River, UK	661 items/kg	PET, PP, PS, PVC	1 – 4 mm	Fragments (49.30 %), fibers (47.40 %)	(Wu et al., 2019a)
Caribbean, Colombia	0 – 3.1 items/kg	PP, PE		Fragments, fibers	(Garcés-Ordóñez et al., 2022)
the North Eastern Arabian Sea, India	4400 – 15,300 items/kg	PE, PA, PET	100 – 500 μm	Fibers, fragments, beads, and films	(Gurjar et al., 2023)
the south-west coast of India	617.7 items/kg	PE (24.2 %) , PP (20.4 %) , PS (11.5 %) and PET (11.2 %)	< 250 μm (90 %)	Fibres (54.12 %), fragments (32.19 %), film (13.69 %)	(Nikhil et al., 2024)
the coastal Antarctica	0 – 1.96 items/m ³	PET (23 %), PE (14 %)		Fibres (50 %), fragments (42 %), film (13.69 %)	(Gurumoorthi and Luis, 2023)
Yueqing Bay, China	3.33 – 20 items/kg	PP (43.75 %), PET (6.25 %)	< 500 μm (36.0 %), 500 – 1000 μm (36.0 %)	Fibers (76.0 %), fragments (24.0 %)	(Wang et al., 2024)

Table 2
MPs legislation.

Countries and regions	Year	Subject of regulation	Contents of supervision	Policy benefit	Ref
America	2015	Microsphere	Use in flush-off personal care products is prohibited	Increase the use of biodegradable plastics, reduce the distribution of contaminants in the environment, mitigate their negative effects, develop innovative technologies for the treatment of plastic waste, improve ecosystem health, and raise the public's awareness of environmental protection.	(McDevitt et al., 2017)
Canada	2016	Microsphere	Microbeads are prohibited from being added to toiletries and are considered toxic		(Fischer, 2006)
South Africa	2002	Microsphere	A total ban on plastics less than 30 microns thick and a tax on plastics greater than 20 microns thick		(Dikgang et al., 2012)
China	2019	Microsphere	Ban the use of microbeads in personal care and cosmetics, and ban the use of ultra-thin plastic bags		(Hafnar et al., 2021)
New Zealand	2018	Microsphere	Prohibit plastic beads in personal care products		(Li, 2022)
Thailand	2019	Microsphere	The import, production and sale of cosmetics containing plastic beads are prohibited		(Li, 2022)
Ireland	2020	Microsphere	Ban the use of plastic beads in household and industrial cleaners		(Li, 2022)
France	2017	Microsphere	Prohibit the placing on the market of exfoliating rinsing cosmetics or cleaners containing solid plastic particles		(Li, 2022)
Italy	2020	Microplastic	Prohibit trade in cosmetic rinsing products containing MPs that have an exfoliating or cleansing effect		(Boccia et al., 2024)
European Union	2023	Polymer particles	Strictly control the entry of products containing polymer particles into the market		(Protecting environment and health, 2023)
India	2017	Microsphere	Plastic microbeads are classified as unsafe and cannot be used as an exfoliator or cleaner in rinsed personal care products		(Sambandam et al., 2024)

2. Sampling method of MPs in water

MPs undergo various processes in aquatic environment, including sinking, floating, and accumulating in sediments or being ingested by aquatic organisms. As such, MPs are typically found in water layers, sediments, and biota (Ng and Obbard, 2006). To comprehensively assess the distribution and pollution characteristics of MPs, it is essential to employ a range of sampling techniques and instruments (Fig. 1). These methods must be carefully tailored to account for the heterogeneity of MPs in size, shape, polymer type, and density, as well as the unique environmental factors that influence their distribution (Razeghi et al., 2021).

2.1. Water layer sampling

The water layer is a key reservoir of MPs, with surface runoff and precipitation playing significant roles in their introduction to aquatic environment. Surface water MPs are commonly collected using micro-neuston nets, which are effective for sampling small particles that float near the water surface. Additionally, Manta nets and Bongo nets are widely used for collecting MPs from surface and subsurface waters, respectively, with the latter typically sampling at depths of up to 3 m (Tokai et al., 2021). For larger-scale assessments, studies have suggested sampling volumes greater than 500 L for surface water and 1000 L for drinking water to provide reliable estimates of MP concentrations (Almuhtaram and Andrews, 2022).

The abundance and distribution of MPs in surface waters are influenced by multiple factors, including hydrological conditions such as rainfall and human activities. For example, research in the Paraiba do Sul River Basin showed significantly higher MP concentrations during high-water periods compared to dry periods, highlighting the role of rainfall in mobilizing MPs (Costa et al., 2022). Human activities, particularly tourism, also impact MP distribution, with higher concentrations found in areas with heavy tourist traffic. Therefore, to obtain accurate assessments, it is essential to conduct multi-timepoint and multi-location sampling that accounts for seasonal and environmental

variability.

2.2. Sediment sampling

Sampling MPs in sediments presents unique challenges, as MPs can vary greatly in size, shape, and density. The three primary methods used for sediment sampling are: selective sampling, batch sampling, and volume reduction sampling (Hidalgo-Ruz et al., 2012). Selective sampling is suitable for collecting relatively large MPs (1–5 mm) that are easily distinguished from the surrounding sediment matrix. Batch sampling is a widely used approach in which a bulk sediment sample is collected, and MPs are separated through sieving or flotation methods. Volume reduction sampling, on the other hand, involves progressively reducing the volume of the sediment sample to focus on the portion containing MPs (Yang et al., 2021).

Sampling depths and sediment types also play a crucial role in the recovery of MPs. For beach sediment sampling, it is recommended to collect sediments from the top 5 cm of the surface, allow a 5-hour settling time for MPs, and perform three repeated extractions for optimal recovery (Besley et al., 2017). Understanding the density and size distribution of MPs within sediments is vital for accurately assessing pollution levels, as certain types of MPs (e.g., polyethylene, PP) may be more buoyant, whereas others (e.g., glass beads, heavy polymers) may settle at greater depths (Ehlers et al., 2022; Lu et al., 2024).

2.3. Biota sampling

MPs are not only present in water and sediments but also accumulate in a wide variety of aquatic organisms. These particles can be ingested by plankton, which are subsequently consumed by higher trophic levels, leading to the transfer of MPs through the food chain. This process has been documented in numerous species, including fish, crustaceans, and algae (P and Cr, 2023). A study in Zhoushan, China, found MPs in 22 species of fish and 35 types of crustaceans (Jiang et al., 2023), underscoring the widespread occurrence of MPs across marine food webs.

To monitor MPs in aquatic biota, trawl nets are commonly used to

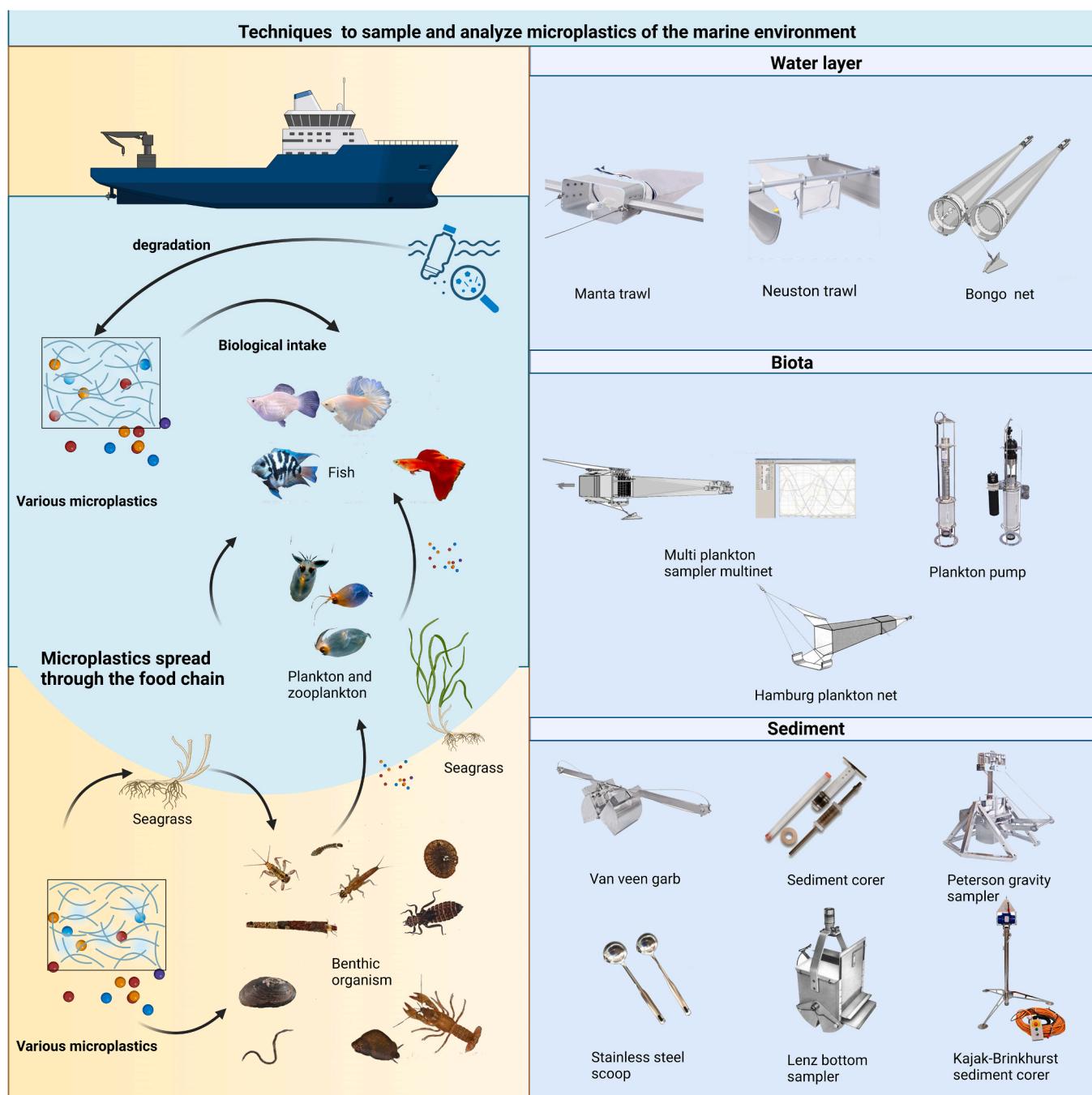


Fig. 1. Sampling of MPs in aquatic ecosystems using different instruments. The MPs in the water layer are mainly sampled using microscale neuston of different sizes; The MPs in the sediment are sampled by different models of mud samplers and can be assisted by spoons, etc; The MPs in animals are captured by trawling nets at different water depths.

sample organisms from varying water depths, capturing species at different trophic levels. In particular, fish are frequently used as model organisms to study MPs pollution due to their diverse habitats across water columns. Sampling fish from aquaculture farms or local fish markets, however, may introduce biases compared to in-situ sampling (Fu et al., 2020). Additionally, algae, which readily sequester MPs through adsorption and physical entanglement (Das et al., 2023), are another important biota for MPs monitoring. Filamentous algae such as *Cladophora* have been found to harbor significant concentrations of MPs, which can be sampled by hand and stored in plastic bags for further analysis (Peller et al., 2021).

2.4. Seasonal and environmental variability in MPs sampling

The collection and analysis of MPs in water layers, sediments, and biota are influenced by environmental factors such as water flow velocity, human activities, and seasonal weather conditions. As a result, single-timepoint sampling is inadequate for accurately assessing MP contamination. To obtain robust and representative data, multiple sampling events across different seasons and environmental conditions are essential (Fig. 2). Seasonal changes in the chemical composition, shape, and load of MPs can significantly impact findings, making long-term monitoring crucial for understanding the dynamics of MP pollution. Variability in climatic patterns and anthropogenic influences

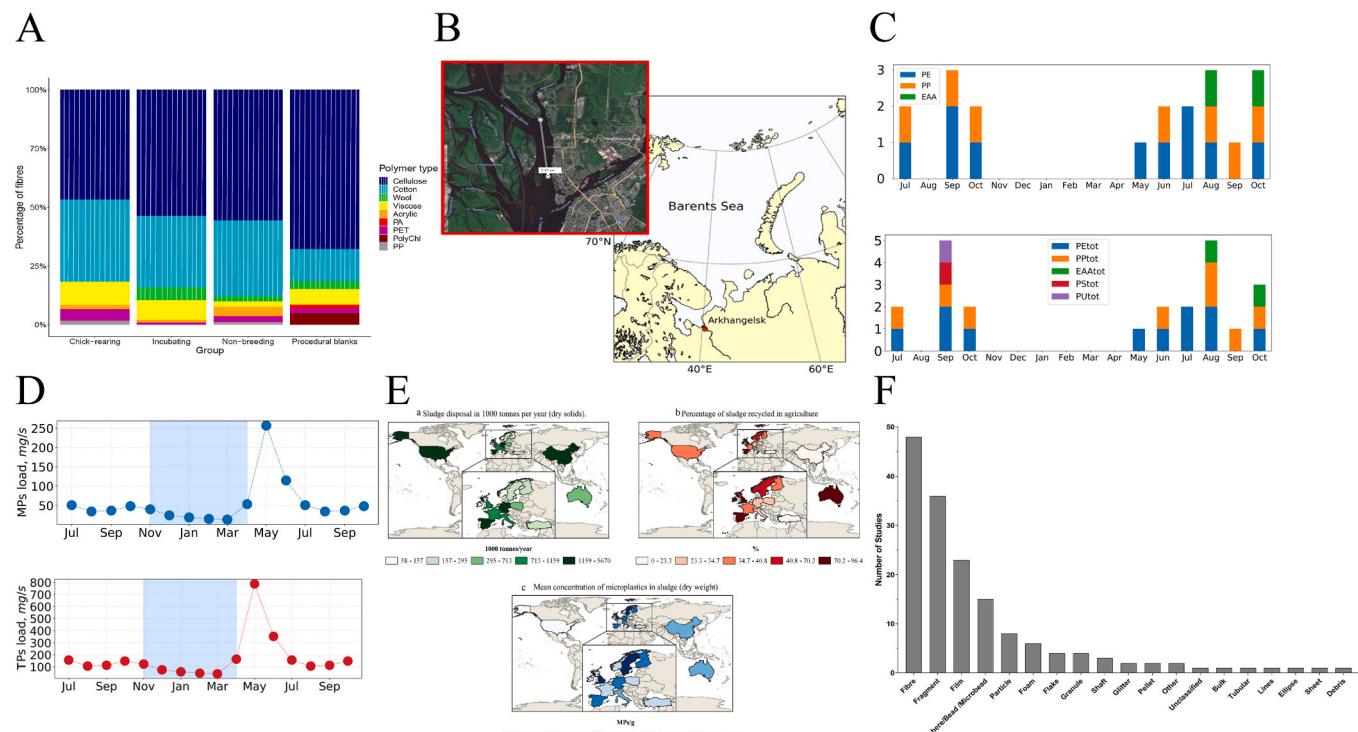


Fig. 2. Seasonal changes in the chemical composition and shape of MPs and MP load in biometabolites: (A) Proportions of microfibres found in King Penguin faecal samples across the different groups: chick-rearing (63 microfibres), incubating (108 microfibres), non-breeding (93 microfibres) birds and procedural blanks (59 microfibres). White hatched categories refer to natural polymer types (Le Guen et al., 2020). (B) Position of a transect where Neuston net sampling was organized. (Surface water samples were taken from the 3 nautical mile transect near the city of Arkhangelsk.) (Zhdanov et al., 2022). (C) Seasonal variability of chemical composition of MPs (top) and a sum of micro- and mesoplastics (bottom) in the Northern Dvina collected with a Neuston net in 2019–2020 (Zhdanov et al., 2022). (D) Seasonal variability of load of MPs (top) and total plastics (bottom) in mg/s calculated with climatic discharges of the Northern Dvina River. Blue colour corresponds to the period when the river is covered with ice (Zhdanov et al., 2022). (E) Distribution of sludge disposal, reuse and microplastic concentrations (Harley-Nyang et al., 2023). (F) Frequency of microplastic shape (Harley-Nyang et al., 2023). (All images above are open access literature).

further complicates the interpretation of MP data, emphasizing the need for comprehensive, multi-timepoint sampling across diverse conditions.

A holistic approach to sampling MPs in aquatic ecosystems must integrate diverse methods to account for MPs' variability across water layers, sediments, and biota. Researchers should factor in water flow, seasonal fluctuations, and human activities when designing sampling protocols. Surface water sampling requires multiple timepoints to capture changes in MP abundance, while sediment sampling must account for particle size, density, and sediment type. Biota sampling should encompass multiple trophic levels to assess the broader ecological impact of MPs. By considering these factors, researchers can achieve a more accurate understanding of the extent and dynamics of MP pollution.

3. MPs treatment and extraction methods

The treatment and extraction of MPs from various aquatic environments require careful consideration of the sample source (water layer, sediment, organism) and the characteristics of the MPs, including size, density, and composition (Zhang et al., 2022). Various techniques, including density separation, chemical digestion, enzymatic degradation, and adsorption-based methods, are employed to isolate MPs for further analysis (Fig. 3). However, traditional extraction methods often present challenges such as incomplete degradation, environmental contamination, and interference from complex sample matrices (Schrank et al., 2022).

3.1. Water layer extraction

Extracting MPs from water bodies, whether oceanic or freshwater, is

particularly challenging due to the large volumes of water involved and the complex nature of the samples. Methods such as density separation (using solutions like NaCl or ZnCl₂), filtration, and magnetic separation are commonly employed. Magnetic recyclable materials, such as Fe₃O₄-PWA/amine nano composites, have shown promise in improving the efficiency of MP extraction from water by adsorbing MPs through ionic interactions and hydrophobic surfaces, with an adsorption rate exceeding 99 % for common polymers like polystyrene and polyethylene terephthalate (PET) (Bhore and Kamble, 2022). This method also benefits from easy post-sampling separation using a magnetic field, simplifying the analysis of MPs in complex water samples.

Another notable development is the use of NaOH digestion for plankton-rich water samples, as demonstrated by Castillo et al., where 1 M NaOH effectively digests plankton without damaging the MPs themselves (Castillo et al., 2016). However, visual identification and isolation of MPs in plankton-heavy environments remain challenging, highlighting the need for more advanced techniques or automation in sample preparation. For extracting MPs from textile wastewater, Fenton reagent (Fe²⁺/H₂O₂) is particularly effective for breaking down organic matter without affecting the structural integrity of textile-derived MPs, while ZnCl₂ is efficient in separating high-density MPs through density separation (Li et al., 2023a). This method is suitable for MPs derived from synthetic fibers like polyester or nylon, which are prevalent in textile industries.

3.2. Sediment extraction

MPs accumulate in sediment over time, particularly in marine and freshwater environments. The extraction process varies depending on sediment type (clastic, chemical, biological, volcanic, or organic), and

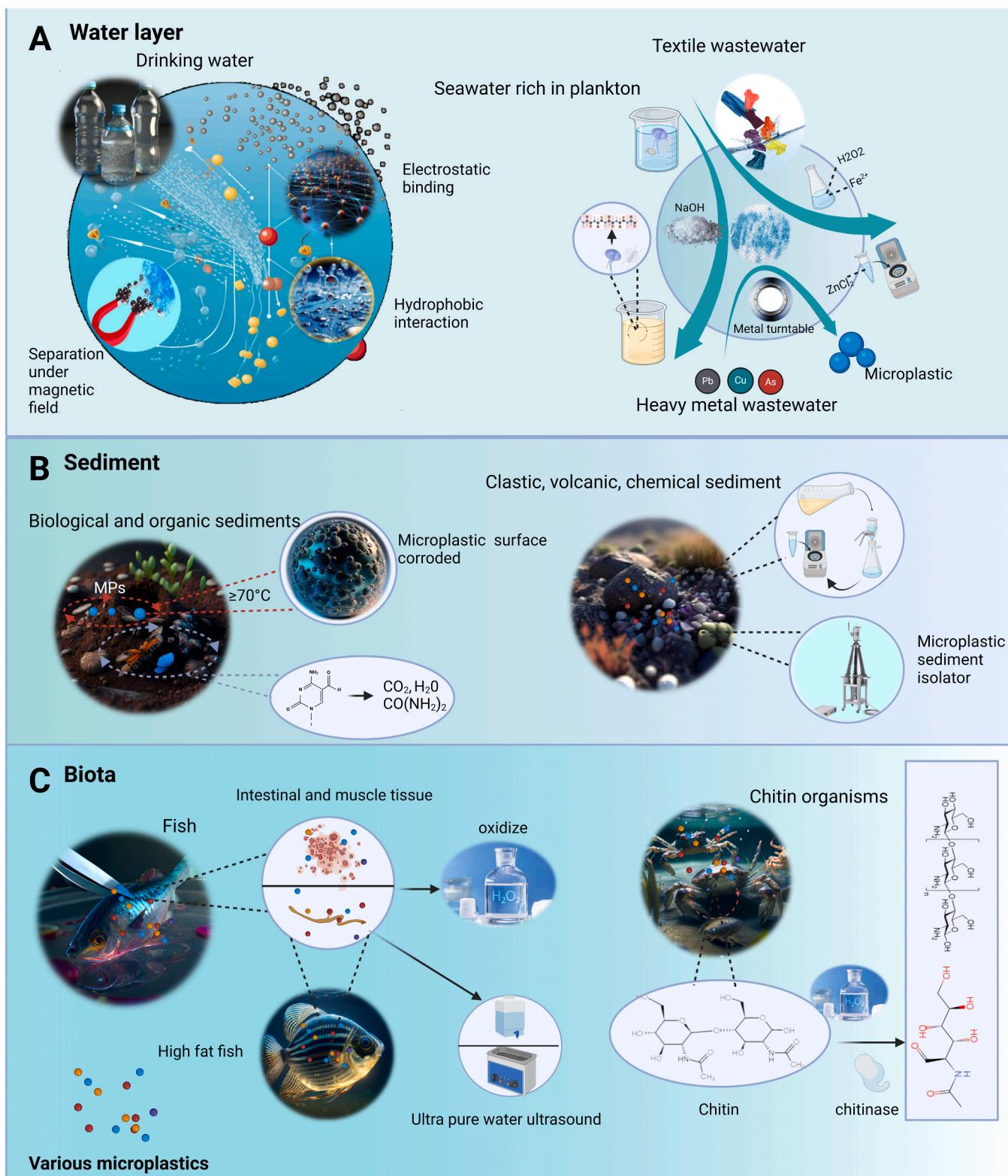


Fig. 3. Method for extracting MPs from water layers (A), sediments (B), and organisms (C). (A) Adsorption of MPs in drinking water through nanomaterials and separation under the action of a magnetic field; Dissolve plankton through 1 M sodium hydroxide; Extraction of MPs in textile wastewater through Fenton reaction; Digestion of organic matter and density separation of zinc chloride; Separation of MPs in heavy metal wastewater through magnetic field. (B) Extracting MPs from biological and organic sediments by removing organic matter through Fenton reaction; Extracting MPs from debris, volcanic, and chemical sediments through density separation and MP sediment isolators. (C) Extracting MPs by digesting the digestive tract and soft tissue of fish, and using ultrapure water ultrasound to extract MPs for high-fat fish; Extracting MPs from chitin organisms through hydrogen peroxide and chitinase lysis.

requires tailored methods to prevent contamination or damage to MPs. Density separation remains the most commonly used method (Zhang et al., 2020a), involving the use of heavy solutions like sodium iodide or sodium bromide (Nuelle et al., 2014). These methods efficiently separate MPs based on their density while minimizing contamination from the surrounding sediment.

For biological and organic sediments, MPs are typically extracted by digesting the organic matter that adheres to their surfaces. Fenton's reaction, an advanced oxidation process, is widely employed to degrade organic matter effectively without compromising the MPs' structure (Tsiring et al., 2022). However, Fenton's reagent can damage sensitive polymers such as PA-6,6 at temperatures above 70 °C, requiring careful temperature control to prevent oxidative degradation (Tagg et al., 2016).

Recent advancements in MP extraction techniques, such as sediment-MP isolators and inverted funnel separators, have improved the efficiency and convenience of isolating small MPs (45–1000 µm) from sediments of varying particle sizes and organic carbon levels (Maja et al., 2023). These devices streamline routine MP extraction and analysis. Additionally, the oleophilic properties of MPs have been leveraged in alternative methods like the oil extraction protocol, which achieves a 96.1 % recovery rate of MPs, including 92.7 % for fibers and 99 % for particles. However, the oil interferes with Fourier-Transform Infrared Spectrometry (FTIR), necessitating a post-extraction cleanup with 90 % ethyl alcohol to eliminate spectral interference (Crichton et al., 2017).

3.3. Extraction from biota

MPs are widely ingested by aquatic organisms, including zooplankton, fish, and marine mammals, where they accumulate through various trophic levels (Scherer et al., 2017). Extraction from biota requires methods that can isolate MPs from tissues such as the digestive tract or soft tissues of organisms. Alkali digestion (e.g., using NaOH) is frequently employed to digest organic tissues, but this can lead to saponification in fatty fish, complicating subsequent analyses. To mitigate this, ultrasonic extraction with ultrapure water has been used to isolate MPs from high-fat organisms, improving extraction efficiency while preserving the MPs' structural integrity (Wagner et al., 2017).

For organisms with chitinous exoskeletons, such as crustaceans, traditional digestion methods (e.g., KOH, HNO₃ and H₂O₂) are ineffective due to the robustness of chitin (Iannilli et al., 2019). Recent studies have demonstrated that a combination of H₂O₂ and chitinase enzymes can successfully break down the exoskeletons without damaging the MPs contained within (Kallenbach et al., 2021). This approach allows for more accurate extraction of MPs from crustaceans, which are significant vectors for MPs in marine food webs.

In addition, marine plants, such as algae and macroalgae, also accumulate MPs. The extraction from these plants is complicated by their tough cell walls (Lahaye, 1991). Cellulase enzymes, such as laccases, are used to break down the cell walls, followed by density-based separation using 96 % ethanol to isolate the MPs (Herrera et al., 2018). However, it remains uncertain whether the use of cellulase enzymes affects the structural integrity of MPs, and further studies are needed to assess this potential issue.

3.4. Emerging techniques in extraction techniques for MPs characterization

The extraction and characterization of MPs from aquatic environments is a complex process that demands a careful selection of methods based on the sample matrix and the specific properties of the MPs. Traditional techniques like density separation and chemical digestion are widely used but face limitations in terms of efficiency and specificity (Turner et al., 2020). Emerging innovations, such as magnetic separation, ultrasonic extraction, and enzyme-assisted methods, are significantly improving the accuracy and recovery rates of MPs, particularly in

complex samples like sediments and biota (Chen et al., 2022). Additionally, advancements in optical tweezers combined with Raman spectroscopy (RS) are revolutionizing the characterization of micro- and nano-sized MPs, with a capacity to precisely manipulate and chemically analyze particles as small as 90 nm (Gillibert et al., 2022). This method, particularly when coupled with effective extraction and concentration protocols, allows for high-precision tracking of MPs in marine environments and enhances our understanding of their fate and distribution. These developments are crucial for advancing environmental forensics and monitoring MPs pollution, which continues to be a growing global concern. Optimizing these emerging techniques for diverse sample environments will be essential for addressing the ecological impacts of MPs and improving mitigation strategies.

4. Methods for detection and analysis of MPs in water

The detection and analysis of MPs in aquatic environments presents a significant challenge due to their small size, diverse shapes, and high mobility. MPs, particularly polyethylene (PE) and polypropylene (PP), are commonly found in water bodies, often in the sub-millimeter size range, making them difficult to detect using traditional methods (Picó and Barceló, 2019). Conventional techniques such as direct visual observation, light microscopy, and electron microscopy are effective for detecting larger MPs (greater than 1 mm) but become increasingly limited for smaller particles, particularly those below 100 µm, which are challenging to detect due to their size and transparency. These traditional methods are labor-intensive and prone to low accuracy, especially when dealing with complex environmental samples that contain diverse particulates. These limitations necessitate the development of advanced analytical techniques capable of detecting MPs as small as 100 nm, and accounting for environmental factors that affect their behavior and interactions with other substances (Lv et al., 2021).

4.1. Chemical detection methods

To overcome the limitations of visual and microscopy-based techniques, chemical detection methods such as thermal analysis and vibration spectroscopy are increasingly employed (Woo et al., 2021). Thermal analysis methods like pyrolysis gas chromatography mass spectroscopy (Pyr-GC-MS) and thermal extraction depletion gas chromatography mass spectroscopy (TED-GC-MS) offer valuable insights into the composition of MPs by detecting the characteristic pyrolysis spectrum of polymers (Yu et al., 2019). While these methods are highly accurate, they require extensive sample pretreatment, and impurities present in the sample can adversely affect the results (Huang et al., 2023).

Vibration spectroscopy, particularly RS and FTIR, offers a more efficient way to identify and quantify MPs in water. FTIR is widely used due to its high sensitivity, rapid analysis, and ability to identify polymers based on their characteristic absorption peaks. It is particularly effective for detecting MPs larger than 20 µm (Käppler et al., 2016). However, FTIR is susceptible to interference from water when analyzing wet samples, which can hinder the detection of MPs in aquatic environments. To overcome this, microscope-assisted FTIR has been developed, allowing for the detection of smaller MPs, though this approach can produce weak signals for small-sized particles, leading to false positives or negatives (Yan et al., 2022).

In addition, Attenuated Total Reflection FTIR (ATR-FTIR) has shown promise for detecting difficult-to-analyze MPs, such as fragments from contact lenses, which are challenging to identify with traditional FTIR due to their thickness and infrared band saturation (Lee et al., 2023). Combining ATR-FTIR with techniques like acoustic trapping can further improve detection sensitivity, particularly for small MPs in complex samples (Freitag et al., 2021).

4.2. RS and variants

RS is another powerful tool for MPs detection in water due to its high resolution, robust resistance to water interference, and non-destructive nature. However, RS is often weak and can be disturbed by fluorescent background noise from inorganic, organic, or colored substances in the sample (Yilmaz et al., 2022). To address these issues, nonlinear RS (N-RS) has been developed, which offers high signal-to-noise ratios and eliminates fluorescence interference, making it ideal for MPs detection in complex aquatic environments (Ye et al., 2022).

An even more advanced technique is Surface-Enhanced RS (SERS), which utilizes metal colloids to enhance the Raman signal, improving the detection sensitivity significantly (Mikac et al., 2023). SERS is particularly effective for detecting MPs in pure water and seawater, where complex marine environments may otherwise hinder detection (Lv et al., 2020). The combination of SERS with FTIR can further enhance the accuracy and speed of MPs detection, enabling rapid environmental monitoring (Mogha and Shin, 2023). As shown in Table 3, the detection and analysis of MPs in water require a combination of traditional and advanced methods, each suited to specific requirements such as particle size, sample complexity, and environmental factors. While traditional methods like microscopy and thermal analysis are useful for larger MPs, emerging techniques such as SERS, N-RS, and FTIR offer enhanced sensitivity and specificity, particularly for smaller MPs. The development of combined techniques, such as microscope-FTIR and SERS-FTIR, holds great promise for improving the detection of MPs in complex aquatic environments, thereby advancing our understanding of MP pollution and its ecological impacts. Continued advancements in these methods are critical for improving the efficiency and accuracy of MPs monitoring and for developing effective mitigation strategies.

5. Quantitative and risk assessment methods for MPs in water bodies

Understanding the spatial and temporal distribution of MPs in aquatic environments is crucial for assessing their environmental impact and guiding mitigation efforts (Talbot and Chang, 2022). MPs are transported from terrestrial sources into aquatic environments via surface runoff, with weather events such as precipitation influencing their movement and concentration in water bodies. Once in the aquatic

environment, MPs are subject to hydrodynamic forces, which affect their accumulation, deposition, and distribution. Factors such as seasonality, population density, geographical features (e.g., slope, elevation), and tidal changes all influence the spatial and temporal distribution of MPs (Qian et al., 2023; Jin et al., 2022; Zhang et al., 2020b).

5.1. Spatial and temporal distribution of MPs in aquatic environments

The distribution of MPs in aquatic environments is influenced by a combination of spatial and temporal factors. Seasonal fluctuations significantly affect MP concentrations (Ambade et al., 2020). During rainy seasons, MPs are often washed from terrestrial sources and sediments into water bodies, increasing concentrations in the water layer (Priya and Arulraj, 2011). In contrast, during dry seasons, lower water flow leads to MPs accumulation in sediments, resulting in higher concentrations in sediments than in surface water (Wu et al., 2020). Tidal changes further complicate this distribution (Li et al., 2023b); high tides tend to transport more MPs to shorelines, concentrating pollution in these areas. However, heavy rains can sometimes dilute MPs concentrations in surface waters, indicating that human activities and spatial factors might play a more significant role than environmental conditions alone (Padha et al., 2022). Population density also plays a crucial role in the spatial distribution of MPs. Areas with higher population densities typically exhibit higher MP concentrations due to human activities such as washing clothes in rivers and the widespread use of personal care products (Liu et al., 2022). The proximity of sewage treatment plants and agricultural lands further influences MP concentrations in water bodies (Ragoobur et al., 2021).

In terms of temporal distribution, MPs concentrations are generally higher in the water column during the wet season and more concentrated in sediments during the dry period (Unnikrishnan et al., 2024). The combination of seasonal variations and human activities leads to increased MP concentrations in coastal sediments and water bodies. While research on the temporal and spatial dynamics of MPs is progressing, much remains to be understood about their sources, distribution, and environmental impacts (Eo et al., 2022). Future studies should adopt a multi-factor and cross-domain approach to comprehensively assess MPs' abundance, sources, and their ecological effects.

Table 3

Methods for detection and analysis of MPs.

Classification	Applicability	Characteristic	Operating principle	Ref.
Direct vision method	Naked eye	Greater than 1 mm	The equipment is simple, but laborious and the accuracy is low	This is achieved through optical magnification and imaging (Saud et al., 2023)
Microscope	Optical microscope Electron microscope	Greater than 100 μm		
Thermal analysis	Pyr-GC-MS TED-GC-MS	Greater than 500μm	Cheap and simple, high accuracy, but require frequent pretreatment, damage to the sample, processing time is long	The pyrolysis products of polymers were compared with the spectral database Pyrolysis, analysis, chromatographic separation and mass spectrometry characterization (Xu et al., 2019; Dümichen et al., 2015; Rodríguez Chialanza et al., 2018)
	DSC		The DSC characteristics of MPs were compared with reference database	
Vibrational spectrum	RS N-RS SERS	1–20 μm	The surface functional group information can be obtained. High resolution; Long measurement time; The fluorescence interferes greatly The scattering spectra with different frequencies of incident light are analyzed	The scattering spectra with different frequencies of incident light are analyzed (Schymanski et al., 2018)
	FTIR	Greater than 20 μm	High sensitivity, simplify the detection process;	Different chemical bond structures will produce different peak patterns, and form a specific map, compared with the database (Wang and Wang, 2018; Ivleva, 2021; Imhof et al., 2012)
	U-FTIR ATR-FTIR	10–20 μm Greater than 500 nm	The sample must be infrared active	
	FPA-FTIR	Greater than 20 μm		

5.2. Ecological risk assessment of MPs

MPs are known to cause a range of toxic effects in aquatic organisms (Lei et al., 2023), including individual MPs toxicity, plastic additive toxicity, and synergistic toxicity (Table 4). Individual MPs, when ingested, can lead to digestive tract obstruction (Yi et al., 2024; Wu et al., 2024), interference with digestion and nutrient absorption, alteration of intestinal microbiota, and impacts on organism growth and reproduction (Jayashree et al., 2013; Mu et al., 2022).

MPs also exhibit synergistic toxicity when adsorbed organic contaminants, such as pharmaceuticals and pesticides, bind to MPs active sites. This increases the overall toxicity to organisms, affecting the food web and potentially leading to antibiotic resistance and other ecological risks. For example, the adsorption of Sulfamethoxazole on MPs surfaces can lead to the spread of antibiotic resistance genes, which poses serious environmental and public health threats (Xu et al., 2018).

However, some research suggests that MPs can have antagonistic effects when interacting with environmental pollutants, reducing the toxicity of certain contaminants, as seen in studies involving the interaction of PS and ciprofloxacin in freshwater organisms (Guo et al., 2021). However, these effects may transform into synergistic ones over time, as demonstrated in a study on the co-exposure toxicity of MPs and Ag ions to *Escherichia coli*, where the antagonistic effect turned synergistic after 48 h (Sun et al., 2020). The antagonistic effects of MPs and environmental co-pollutants are primarily attributed to adsorption, which reduces the chemical damage of pollutants to cells by mitigating stress and lessening the physical damage caused by MPs (Hao et al., 2022). Therefore, understanding the combined toxicological effects of MPs and other contaminants requires studying their interactions and quantifying the stressors' cumulative effects (Batel et al., 2018). This approach will help assess whether the interactions lead to synergistic or antagonistic effects, while also considering mixture toxicity at molecular, cellular, organismal, and population levels, contributing to more comprehensive ecological risk assessments of MPs.

Meanwhile, establishing the threshold concentration of MPs that causes harm to organisms and ecosystems is crucial for ecological risk

assessment. The toxicity of MPs is influenced by factors such as species diversity, particle size, and polymer type. Recent studies suggest that the hazard assessment of MPs may be overestimated when based on raw, unweathered MPs, as the toxicity of weathered MPs is significantly lower (Cui et al., 2024). Therefore, determining accurate threshold values for MPs in aquatic ecosystems is essential for understanding their ecological risks and formulating effective environmental policies.

5.3. Human health risk assessment

MPs also pose potential risks to human health, primarily through ingestion, inhalation, or dermal exposure (Prata et al., 2020). MPs can act as carriers for toxic chemicals, affecting human physiological systems such as the digestive, respiratory, and circulatory systems. Adverse health effects associated with MPs exposure include endocrine disorders, obesity, diabetes, cancer, and cardiovascular diseases (Choi et al., 2023). Studies have detected MPs in human feces, and plasticizers like phthalates in blood and urine, highlighting the direct exposure risks (Sun et al., 2024). The dose-response relationship, based on factors such as particle size, polymer type, and exposure route, is critical in assessing human health risks. For example, exposure to MPs in human adenocarcinoma cells has been found to induce cytotoxicity and immune responses at specific doses, with a minimum doses of 10 µg/mL (5–200 µm) causing cytotoxicity and 20 µg/mL (0.4 µm) triggering an immune response (Danopoulos et al., 2022).

In addition, Kala et al. quantified ingested MPs by converting their quantity to the corresponding mass, revealing that the mass of ingested MPs depends on particle size, shape, polymer type, and size distribution (Senathirajah et al., 2021). This insight is valuable for assessing the health risks associated with MPs and for developing effective policies. Similarly, studying the clinical toxicity of MPs will aid in human health risk assessment. Accurate quantification of MPs and their associated pollutants is crucial for assessing health risks, with research needed to understand exposure levels across different populations, regions, and demographics. This will help prioritize mitigation strategies to minimize exposure and protect public health (Fig. 4).

Table 4
Toxicity of MPs and their co-contaminant mixtures.

Toxicity classification	Model organism	Contaminant	Size	Mechanism	Health outcome	Ref.
Single	Zebrafish	PS; PE	5 µm and 50 µm ; 75 – 100 µm	Intestinal microbiota changes	Glucose and lipid metabolism disorder; neurovirulence; Photosynthesis interference	(Wan et al., 2019; Ding et al., 2022)
	<i>Chlorella pyrenoidosa</i> ; <i>Microcystis flos-aquae</i>	PVC; PP	111 – 216 µm; 64 – 236 µm	Chlorophyll a decreased		(Wu et al., 2019b)
	Scallops; Clams	PE; PET	36.72 ± 24.37 µm; 31.11 ± 14.36µm	ROS	Glycolipid metabolism; tissue damage	(Teng et al., 2024)
	Human infant	PE; PP; PVC		Alteration of intestinal flora	Reproduction toxicity	(Paul et al., 2024)
Antagonism	Strain <i>S. costatum</i>	PVC; Nano-Cu	1 µm; 10 – 30 nm	Adsorption	The growth inhibition on algae decreased	(Zhu et al., 2020)
	<i>Skeletонema costatum</i>	PE; PS; PVC; Triclosan	74 µm; 74 µm; 74 µm and 1 µm	Adsorption	The growth inhibition on algae decreased	(Zhu et al., 2019)
	<i>T. chuii</i>	MPs; Au	~5 nm; 1 – 5 µm	Adsorption	Low concentration MPs reduced the growth inhibition of AuNP on algae	(Davarpanah and Guilhermino, 2019)
Synergistic	Water flea <i>D. magna</i>	PS; Zn	2 µm	Cell permeability increased	Increased food intake, behavioral abnormalities, sex differences, GST sensitivity	(Lee et al., 2021)
	<i>Ruditapes philippinarum</i>	PS; Di-(2-ethylhexyl) phthalate	~1 µm	Combined exposure leads to increased oxidative stress	Decreased feeding, tissue changes	(Zhou et al., 2022)
	<i>Caridina fissarum</i>	PE; Pb(C ₂ H ₃ O ₂) ₂	15 – 25 µm	Bioaccumulation increased	Impaired hepatopancreas health and function	(Gholamhosseini et al., 2024)
Cumulative	<i>Caenorhabditis elegans</i>	PS; Dimethylarsinic acid	1.1 µm	Biological accumulation	Transgenerational toxicity	(Müller et al., 2023)
	Cladoceran <i>D. magna</i>	PS; Phenanthrene	50 nm; 500 nm; 5 µm; 10 µm and 15 µm		Acute toxicity	(Ma et al., 2016)

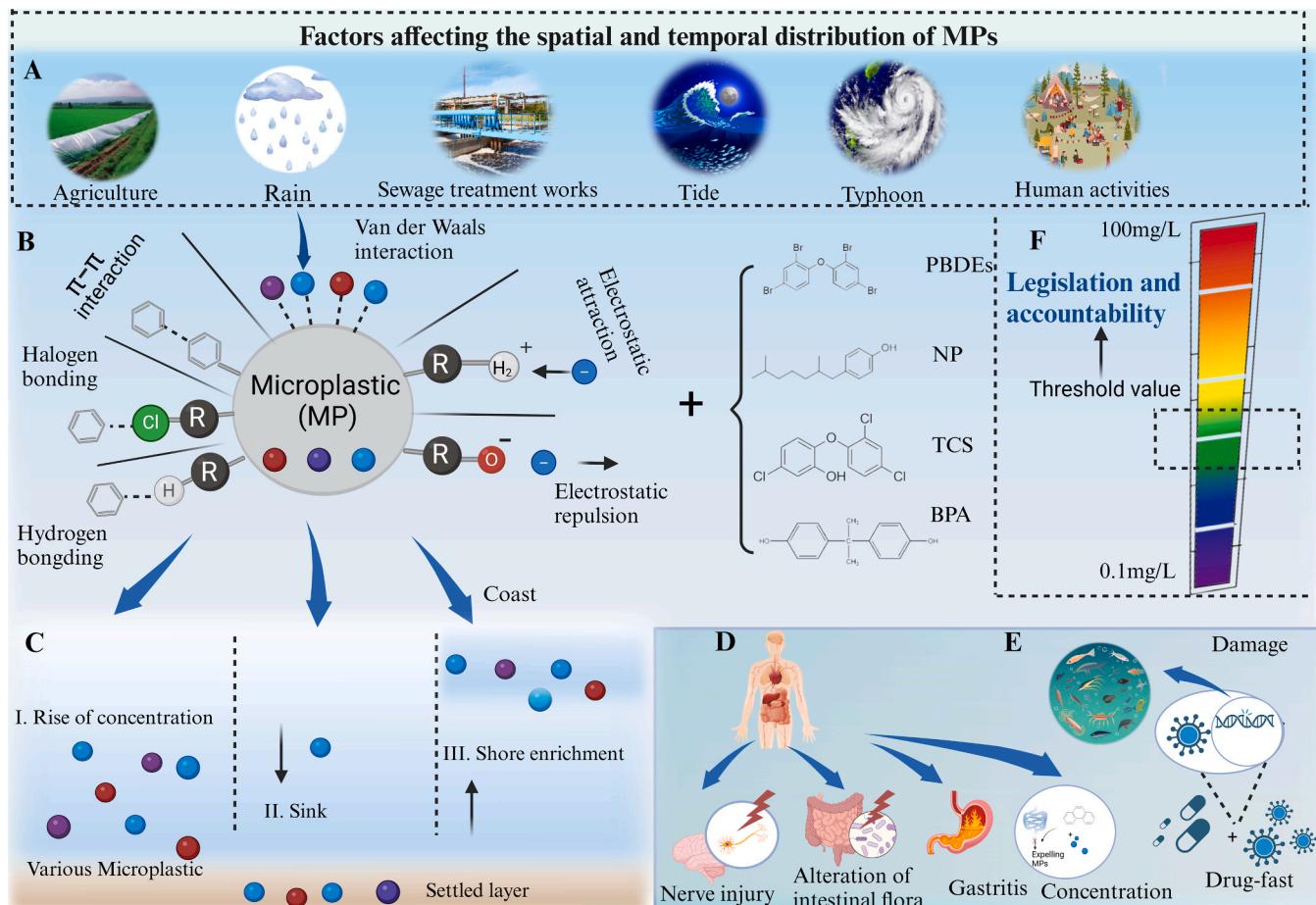


Fig. 4. Spatial and temporal distribution and risk assessment of MPs in water bodies. (A) Factors affecting the spatial and temporal distribution of MPs; (B)(C) The effect of environmental factors and human activities on the distribution of MPs in water and sediment; (D)(E) Health risks posed by MPs and their adsorbed contaminants; (F) Establishing threshold concentrations for effective policy formulation and pollution management.

6. Overcoming obstacles and charting the future course of MPs environmental forensics

MPs have emerged as a significant environmental concern due to their widespread presence in aquatic ecosystems. Their persistence and complex interactions with other pollutants make detection and mitigation challenging. The analysis of MPs requires specialized forensic methods that address the diversity of MPs found in water bodies, including flakes, granules, and fibers. Each type of MP requires distinct approaches for extraction and analysis, which complicates forensic investigations. Additionally, MPs undergo various degradation processes, such as photolysis, oxidation, and hydrolysis, when exposed to natural environments. These processes break down MPs into smaller fragments, and in some cases, nanoscale particles, which not only complicate the forensic matching with spectral libraries but also alter their ability to adsorb POPs over time (Lv et al., 2022).

One challenge in analyzing MPs is their photooxidation, which causes a yellowing effect, hindering the ability to assess their degradation state and fragmentation. To address this, researchers have proposed using the Yellowness Index (YI) as a quantifiable measurement for degradation (Abaroa-Pérez et al., 2022), which results in the use of visual assessments, often leading to inconsistencies. Furthermore, the degradation of MPs through aging and fragmentation, coupled with increased POP adsorption, affects their temporal and spatial distribution in aquatic environments, which in turn complicates environmental forensics.

The adsorption of POPs on MPs varies depending on the plastic type,

its degradation state, and the surrounding environmental conditions. POPs may also accelerate the aging and yellowing of MPs, further complicating the forensic analysis (Andrady, 2017). Thus, a dual approach of both quantitative and qualitative assessments, such as correlating MPs' visual color changes, YI, and FTIR spectra—can offer more accurate insights into their weathering and degradation status.

Despite increasing research into MPs, standardized methods for sampling and analyzing MPs are still lacking, making it difficult to compare results across studies (Yu et al., 2023). Sampling devices and sample methods, such as organic digestion, density separation, and staining, need further development to improve the accuracy of MP sampling, particularly in wastewater, while minimizing false positives from non-plastic particles (Ziajahromi et al., 2017). Moreover, sampling methods need to be versatile enough to account for the heterogeneity of MPs in different environmental matrices.

In addition, one of the biggest challenges in environmental forensic investigations is identifying the source of MPs contamination. Tracing the source is crucial for implementing effective management and mitigation strategies (Kumar and Varghese, 2021). Current forensic techniques mainly focus on the color, size, and classification of MPs, but comprehensive characterization is essential for more accurate identification of sources and origins (Hoguane et al., 2021). Our review advocates for a more detailed approach that incorporates multifactorial analysis to enhance the reference data pool and improve source identification accuracy. Sharing and managing MPs pollution data regionally and internationally can foster better collaboration in tackling MPs pollution and inform the development of more robust environmental

forensics policies (Fig. 5).

The development of effective treatment strategies is equally crucial in addressing the environmental impacts of MPs. One promising avenue is biodegradation, which uses fungi and bacteria to break down MPs, offering a more sustainable solution compared to non-biodegradable methods such as mechanical, chemical, and thermal degradation. Biodegradation progresses in five stages: biofilm formation, microbial colonization, biodisruption, assimilation of carbon sources, and mineralization of plastics into inorganic compounds (Arpia et al., 2021), however, it cannot be denied that these processes require highly

controlled conditions that are difficult to maintain in a heterogeneous environmental matrix and changes in environmental conditions affecting field applications, the increased complexity and cost of different microplastics requiring customized microbial strains, and less efficient emergency mitigation in hot spots such as wastewater discharge areas. Although biodegradation research is still in its infancy, it holds great potential for mitigating MPs pollution without introducing secondary pollutants and in line with the principle of circular economy. At the same time, non-biodegradable treatments also need to be optimized. Bioreactors, for instance, offer a scalable approach to MPs

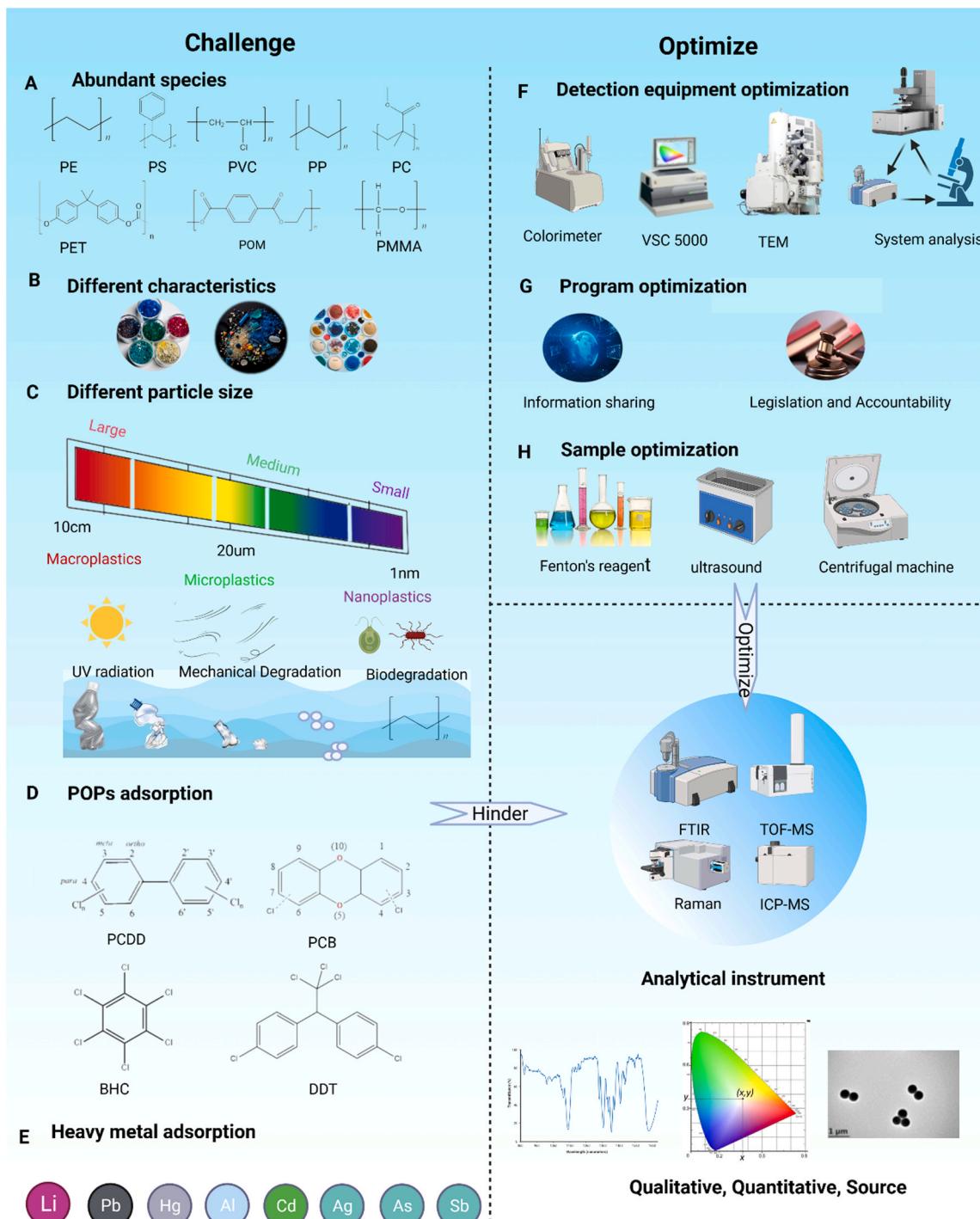


Fig. 5. Challenges and optimization strategies for MPs environmental forensics. (A) (B) The diverse nature of MPs and their interactions; (C) The degradation processes affecting MPs; (D)(E) The complex relationship between MPs and POPs; (F)-(H) Innovations in detection equipment, program optimization, and sample pretreatment for enhanced.

biodegradation, but challenges persist in terms of understanding the microbial conditions required and the variability of MP types (Zeng et al., 2024), although bioreactors provide a scalable framework, their energy demands and slow degradation rate limit their feasibility for immediate remediation in heavily polluted ecosystems. Future research should aim to optimize conditions for large-scale biodegradation while considering the specific characteristics of different polymers and environmental heterogeneity.

In a word, to assess the economic feasibility of microplastic remediation technologies, adsorption, membrane filtration, biodegradation, and advanced oxidation processes (AOPs) are qualitatively compared in terms of initial investment, operational costs, and scalability (Soni et al., 2020). Adsorption is cost-effective for small-scale applications but incurs high long-term material costs. Membrane filtration provides high removal efficiency but requires substantial infrastructure investment and ongoing maintenance due to membrane fouling. Biodegradation offers a sustainable alternative with low material costs; however, its scalability is limited by slow degradation rates and the need for strict environmental controls. AOPs effectively degrade MPs and associated pollutants but are energy-intensive, making them viable mainly for high-priority contamination sites. While precise cost estimates remain challenging due to site-specific variables and technological heterogeneity, this comparative analysis highlights key economic considerations that should guide the selection and optimization of remediation strategies for large-scale applications.

Finally, the ecological and health implications of MPs are multifaceted. While their adverse effects on aquatic life are well documented, comprehensive risk assessments regarding human health remain elusive. While studies suggest that humans may ingest between 0.1 and 5 g of plastic per week through food and water (Catarino et al., 2021), more research is needed to understand the full health risks associated with MPs. Public perceptions of MPs, often driven by fragmented information, can lead to misinformed policies. Rigorous, transparent science communication is essential to contextualize research findings and avoid unnecessary alarm (Catarino et al., 2021). This will aid in developing informed policies that mitigate MPs' environmental and health impacts without causing disproportionate public concern.

7. Conclusion and future prospects

MPs pose a significant environmental threat, particularly in freshwater, where they serve as vectors for harmful pollutants such as heavy metals and POPs. This review provides a more comprehensive understanding of the MPs' distribution sources, and health risks associated with MPs to facilitate thorough risk assessments. Implementing standardized sampling and analytical methods is crucial to ensure the reliability of data for global comparisons and to inform policy decisions.

To effectively combat MP pollution, a multifaceted approach is essential, integrating source prevention, waste management, and remediation technologies. While recent advancements in bioinformatics and environmental forensics have enhanced our ability to detect and characterize MPs, challenges persist in identifying smaller and more degraded particles. Environmental forensics can play a vital role in tracing the origins of MPs, thereby supporting the "polluter pays" principle. Sustainable remediation strategies, including biodegradation and thermal degradation, present promising solutions, yet challenges remain in optimizing microbial processes and selecting effective strains for treatment. Future research should prioritize human health risk assessments and the ecological impacts of MPs, with interdisciplinary collaboration and robust global policy frameworks being critical to mitigating their long-term effects.

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CRediT authorship contribution statement

Sun Da: Conceptualization, Funding acquisition, Writing – review & editing. **Zeng Guoming:** Conceptualization, Funding acquisition, Writing – review & editing. **Wu Baihui:** Writing – original draft, Investigation. **Lei Pengyu:** Writing – original draft, Visualization. **Yu Haiyang:** Writing – original draft, Visualization. **Yi Jia:** Visualization. **He Jiaxuan:** Visualization. **Wu Wei:** Writing – review & editing. **Yang Qinsi:** Conceptualization. **Wang Hanbing:** Visualization.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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