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Editorial

Microplastics in aquatic ecosystems: Sources, distribution, ecological impacts, detection methods, and future perspectives

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ABSTRACT

Microplastics (MPs), generally defined as plastic particles smaller than 5 mm, have emerged as one of the most unescapable pollutants in aquatic ecosystems. Their persistence, widespread distribution, and ability to adsorb toxic contaminants make them a significant environmental concern. Aquatic environments, including freshwater, estuarine, marine, and groundwater systems, act as major sinks and transport pathways for MPs. These particles originate from both main sources, such as industrial manufacturing of pellets and pharmaceuticals, cosmetic microdroplets, and subordinate sources resulting from the fragmentation of larger plastic debris. MPs adversely affect aquatic organisms through ingestion, entanglement, and chemical toxicity, potentially transferring pollutants through food webs to humans. This editorial summarizes the current knowledge of MP sources, transport mechanisms, analytical detection methods, ecological and human health implications, and mitigation strategies. It also highlights emerging research trends and identifies knowledge gaps that require further investigation.

1. Introduction

Plastic production has been increased day by day extensively since the mid-twentieth century, due to its adaptability, toughness, and low manufacturing cost. Global plastic production now exceeds 430 million metric tons per annum (UNEP, 2023). Unfortunately, only a relatively small proportion of discarded plastics is effectively recycled, while significant quantities enter terrestrial and aquatic environments through inadequate waste collection, illegal dumping, stormwater runoff, and mismanaged landfills. Plastics have transformed many industries due to their durability, versatility, and affordability. Insufficient waste management has resulted in widespread plastic contamination to the environment (Geyer et al., 2017). MPs defined as plastic fragments, fibres, beads, films, and pellets measuring less than 5 mm in diameter, represent one of the most concerning forms of plastic pollution (Thompson et al., 2004). It is an important proportion eventually going to the environment because of inadequate management of industrial discharge, and consumer littering. Among plastic pollutants, MPs have attracted considerable scientific attention because of their persistence and widespread occurrence in the environment. MP particles are resistant to biological degradation and may remain in aquatic environments for decades. Rivers transport substantial quantities of MPs from terrestrial sources to oceans, making freshwater ecosystems important pathways rather than merely isolated reservoirs.

MPs have been detected in the Oceans, Rivers, Lakes, Estuaries, Sediments, Groundwater, Sea ice, Atmospheric deposition, and even remote Polar Regions. Their ubiquitous occurrence poses risks to biodiversity, ecosystem functioning, fisheries, and public health.

The propagation of plastic materials has altered modern society by providing inexpensive, lightweight, powerful, and flexible products that have become essential across industrial, agricultural, medical, and domestic sectors. However, the

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extraordinary production and consumption of plastics have generated one of the most pressing environmental challenges of the twenty-first century. Among the various forms of plastic pollution, MPs have emerged as a particularly insidious contaminant due to their microscopic size, persistence, widespread distribution, and capacity to infiltrate virtually every component of aquatic ecosystems. Once considered a localized issue associated primarily with marine debris, MP contamination is now recognized as a global environmental crisis affecting freshwater, estuarine, coastal, and deep-sea environments comparable.

MPs are generally generated as primary MPs for example microbead, deliberately made for industrial or commercial applications. It has been banned in an acknowledgment of the significance of its impact on environmental pollution. However, secondary MPs have the potential to continue to arise from plastics that have already been existed in the nature and it is produced through the disintegration of larger size plastic fragments under the influence of ultraviolet radiation, mechanical abrasion, temperature fluctuations, and biological degradation (Kye et al., 2023). Scientific evidence accumulated over the past decade indicates that MPs are no longer confined to heavily urbanized or industrialized regions. They have become everywhere environmental contaminants detected in drinking water, sediments, aquatic organisms, seafood, agricultural soils, rainfall, and even in the human blood and placental tissues. This extraordinary distribution reflects the immense scale of plastic production, insufficient waste management systems, and the extraordinary environmental persistence of synthetic polymers.

The aquatic environment serves as the ultimate sink for a substantial proportion of global plastic waste. Rivers transport millions of tons of plastic debris annually into the oceans, while wastewater treatment plants, although effective at removing large quantities of suspended particles, remain incapable of completely eliminating microscopic plastic fragments. Consequently, enormous numbers of MP particles are continuously discharged into freshwater and marine ecosystems every day.

The concern surrounding MPs extends beyond their physical presence. These particles possess unique physicochemical characteristics that enable them to adsorb toxic substances counting persistent organic pollutants (POPs), pesticides, antibiotics, heavy metals, and industrial pollutants. Acting as vectors of pollution, MPs may facilitate the transport of hazardous substances through aquatic food webs, thereby increasing ecological and human health risks.

Furthermore, the diversity of plastic polymers complicates environmental assessment. Polyethylene, polypropylene, polyethylene terephthalate, polystyrene, polyvinyl chloride, polyurethane, nylon, and acrylic polymers differ substantially in density, chemical composition, degradation behavior, and ecological interactions. Additives mixing during manufacturing of plasticizers, pigments, stabilizers, antioxidants, flame retardants, and ultraviolet inhibitors—can gradually leach into surrounding waters, introducing additional chemical hazards.

Urbanization, population growth, industrial expansion, and increasing consumer dependence on disposable plastic products have collectively intensified environmental contamination. Single-use plastics, synthetic textiles, fishing gear, packaging materials, cosmetic products, tire wear particles, and industrial abrasives represent major contributors to MP pollution. Washing synthetic clothing releases millions of microscopic fibers into wastewater systems, while abrasion of automobile tyres generate polymer-rich particles that are transported into rivers through stormwater drainage networks.

Agricultural practices also contribute significantly to MP contamination. Plastic mulches, greenhouse coverings, irrigation equipment, sewage sludge applied as fertilizer, and controlled-release polymer-coated fertilizers introduce plastic particles into soils, many of which eventually migrate into nearby water bodies through erosion and runoff. Aquaculture activities, abandoned fishing equipment, and maritime industries further amplify marine plastic pollution.

Climate change may further intensify MP dynamics within aquatic environments. Altered precipitation patterns, flooding events, coastal erosion, glacier melting, and intensified storm activity increase the mobilization and redistribution of plastic debris. Simultaneously, warming temperatures may accelerate plastic fragmentation, generate even greater quantities of secondary MP while modifying their interactions with aquatic organisms.

One of the defining characteristics of MP pollution is its persistence. Unlike many organic pollutants that gradually decompose through biological or chemical processes, most conventional plastics degrade extremely slowly. Instead of mineralizing completely, larger plastics progressively fragment into increasingly smaller particles, ultimately forming of MP that are even more difficult to detect and potentially more biologically active due to their greater surface area and enhanced capacity for cellular uptake.

Particularly vulnerable are filter-feeding organisms such as mussels, oysters, zooplankton, and certain fish species that inadvertently ingest suspended MP particles resembling natural food sources. Once ingested, these particles may accumulate within digestive systems, impair nutrient absorption, reduce feeding efficiency, induce oxidative stress, trigger inflammatory responses, and compromise reproductive success. Such impacts can cascade through food webs, altering predator-prey interactions and ecosystem functioning.

Freshwater ecosystems deserve equal attention despite historically receiving less scientific emphasis than marine environments. Rivers and lakes function not only as transport pathways but also as important reservoirs of MPs contamination. Urban rivers, reservoirs supplying drinking water, wetlands, and groundwater systems increasingly exhibit measurable concentrations of plastic particles, underscoring the pervasive nature of the problem.

From an editorial perspective, the MP crisis illustrates the unintended consequences of unsustainable patterns of production and consumption. Plastic itself is not inherently problematic; rather, the absence of effective waste management, insufficient recycling infrastructure, weak regulatory frameworks, and excessive reliance on disposable products has collectively transformed a valuable material into a persistent environmental pollutant. Addressing this crisis therefore requires systemic solutions that integrate scientific innovation, industrial responsibility, governmental regulation, and public participation.

The growing body of evidence leaves little room for complacency. MP contamination represents not merely an issue of visible pollution but a complex environmental challenge involving chemistry, ecology, toxicology, public health, economics, engineering, and environmental governance. Future policy decisions must take into cognizance the outcomes of contemporary interdisciplinary research which may better help in addressing both the immediate ecological consequences and the long-term sustainability of aquatic ecosystems.

As research continues to uncover new pathways of exposure and increasingly subtle biological effects, the urgency for coordinated international action becomes ever more apparent. Preventing additional plastic emissions, improving waste management infrastructure, promoting circular economy principles, developing biodegradable alternatives, and strengthening environmental legislation are essential components of any comprehensive response. The protection of aquatic ecosystems—and ultimately human well-being—depends upon our collective willingness to recognize MP pollution as a defining environmental challenge of our time. Recent studies indicate that synthetic textile fibers and tyre wear particles constitute substantial fractions of MP entering aquatic environments (Browne et al., 2011; Wagner et al., 2018).

2. Sources of MP in Aquatic Ecosystems

Common sources include plastic bags, fishing nets, bottles, packaging materials, and agricultural plastics. Major sources include: household wastewater contains: laundry fibers, personal care products, cleaning products and synthetic clothing fibers. Wastewater treatment plants remove a substantial fraction of MPs but are not completely efficient. Industrial sources include: plastic manufacturing, textile industries, paint industries, packaging factories and tyre manufacturing. Storm water transports plastic litter from: roads, construction sites, urban drainage systems, and recreational areas. Agriculture contributes through: plastic mulching films, irrigation systems, sewage sludge application and greenhouse plastics. Marine sources include: fishing gear, aquaculture equipment, ship coatings and marine litter.

3. Distribution and transport

MPs are transported through interconnected environmental compartments. In freshwater systems-rivers receive plastics from urban runoff, wastewater, and industrial discharge before transporting them downstream. While estuaries function as transition zones where freshwater mixes with seawater, resulting in sedimentation and accumulation of MPs. In Marine environment-ocean currents distribute MPs globally, leading to accumulation in gyres, coastal regions, and deep-sea sediments. Many MPs settle into sediments because of biofouling and aggregation, where they persist for extended periods.

4. Factors influencing distribution

The environmental fate of MPs depends on: Polymer density, particle size, shape, surface roughness, biofilm formation, salinity, water currents, wind action and temperature. Low-density polymers such as polyethylene and polypropylene generally float, whereas denser polymers tend to sink.

5. Detection and characterization methods

Accurate detection is essential for understanding environmental contamination.

5.1 Sampling and pretreatment

Common sampling techniques are: Neuston nets, Manta trawls, Grab samplers, Sediment corers and Water filtration systems. Pretreatment methods widely involvedinclude: Density separation, Organic matter digestion, Filtration and Centrifugation.

5.2 Identification techniques

Recent advances in analytical technologies have significantly improved the detection and characterization of MPs within an Environmental sample. Spectroscopic techniques such as Fourier-transform Infrared Spectroscopy (FTIR), Pyrolysis–Gas Chromatography–Mass Spectrometry (Py-GC/MS), Raman spectroscopy, Scanning Electron Microscopy (SEM), and thermal extraction methods have enhanced researchers' ability to identify polymer composition, particle morphology, and environmental distribution. Nevertheless, methodological inconsistencies continue to hinder comparisons among studies, highlighting the urgent need for standardized sampling, analytical protocols, and quality assurance procedures. Visual microscopy provides preliminary identification based on particle morphology. FTIR widely used for polymer identification through characteristic infrared spectra. Raman Spectroscopy-offers high spatial resolution and can detect smaller particles. SEM examines particle morphology and surface characteristics. Py-GC/MS provides quantitative polymer composition. Stereo microscopy provides preliminary identification based on shape, color, surface texture and size. However, visual inspection alone often leads to misidentification.

6. Emerging technologies

Recent developments include: Hyper-spectral imaging, machine learning-assisted image analysis, Fluorescence staining using Nile red, automated particle recognition, Microfluidic detection platforms. These technologies improve detection sensitivity while reducing analytical time.

7. Challenges

Despite significant progress, several challenges continue to persist such as lack of standardized sampling protocols, variable size definitions, and limited detection of Nano size plastics, inconsistent reporting units, high analytical costs, contamination during laboratory processing and limited long-term ecological datasets. International harmonization of methodologies remains essential for global assessments.

8. Ecological impacts

The ecological implications of MP contamination are profound because aquatic ecosystems provide essential ecosystem services supporting biodiversity, fisheries, climate regulation, nutrient cycling, water purification, and global food security. MPs have now been documented in every trophic level practically, from microscopic plankton to commercially important fish species, marine mammals, seabirds, and apex predators. Their widespread occurrence raises concerns regarding ecosystem resilience, species conservation, and long-term ecological sustainability. Plankton readily ingests MPs because of their small sizes. Observed effects are included such as reduced feeding decreased growth, lower reproductive success and increased mortality. Fish ingest MPs directly or indirectly through contaminated prey. Fish health impacts includes gastrointestinal blockage, oxidative stress, liver damage, behavioral changes and reduced fertility. Sediment-dwelling organisms such as worms, molluscs, and crustaceans accumulate MPs, affecting nutrient cycling and sediment ecology. Corals ingest MPs, leading to tissue damage, reduced calcification, increased disease susceptibility and impaired growth. According to Ritchie and Roser (2018), marine systems receive approximately 8–12 million tonnes of plastic waste annually. Ocean currents transport MPs over vast distances, leading to accumulation within subtropical gyres, coastal sediments, estuaries, coral reefs, and deep-sea environments (Jambeck et al., 2015). Unexpectedly, MPs have been detected in Arctic and Antarctic sea ice, glaciers, and remote lakes, indicating long-range atmospheric and oceanic transport (Obbard et al., 2014).

8.1 **Chemical Toxicity**

MPs adsorb persistent organic pollutants (POPs), heavy metals, pharmaceuticals, pesticides, and endocrine-disrupting compounds from surrounding waters. After ingestion, these contaminants may desorb within digestive systems, increasing toxicological risks (Rochman et al., 2013). Additionally, plastic additives such as Bisphenol A (BPA), Phthalates and Brominated flame retardants. can leach from plastic particles into biological tissues.

8.2 Microbial colonization

Plastic particles provide surfaces for microbial biofilms collectively termed the "plastisphere." These biofilms may harbor pathogenic bacteria, antibiotic resistance genes, and invasive microorganisms, potentially facilitating their long-distance dispersal (Zettler et al., 2013).

8.3 Food web transfer

MPs undergo trophic transfer from plankton to fish and ultimately to humans through seafood consumption. Although human health implications remain under investigation, evidence suggests potential risks from chronic exposure. Inflammatory responses and metabolic disturbances in numerous aquatic organisms have also been observed.

8.4 Human health implications

Humans are exposed to MPs through the consumption of seafood, drinking water, table salt and inhaling airborne particles. Potential health concerns include inflammation, oxidative stress, endocrine disruption, cellular toxicity and potential long-term chronic effects. Although evidence continues to develop, significant uncertainties continue to remain regarding exposure levels, particle translocation, and chronic health outcomes.

9. Mitigation Strategies

Reducing MP pollution requires integrated approaches: Improved solid waste management, Reduction of single-use plastics, extended producer responsibility, green product design, improved wastewater treatment, public awareness campaigns, International regulatory cooperation and Circular economy practices. Biodegradable polymers and environmentally friendly materials offer promising alternatives but require careful life-cycle assessment.

10. Conclusion and future perspectives

Microplastics (MPs) have become ubiquitous contaminants in aquatic ecosystems worldwide. Their persistence, mobility, and capacity to transport hazardous chemicals pose significant ecological and potential human health risks. While advances in analytical methods have improved detection and characterization, major uncertainties remain regarding long-term ecological consequences and human exposure pathways. Addressing MP pollution requires coordinated efforts involving scientific research, technological innovation, policy interventions, industry participation, and public engagement. Future studies should prioritize standardized methodologies, comprehensive risk assessments, and sustainable strategies to reduce plastic emissions into aquatic environments.
Further future research should be prioritized:

- Development of globally standardized analytical protocols.
- Enhanced detection methods for nano size plastics.
- Long-term ecological monitoring programs to be needed.
- Investigating combined effects with climate change and other pollutants.
- Advanced wastewater treatment technologies. Biodegradable alternatives to conventional plastics.
- Circular economy strategies for plastic waste reduction. Enhanced environmental legislation and international cooperation.
- Citizen science initiatives for monitoring of plastic pollution.
- Comprehensive human health risk assessments.

Declarations competing interests

The authors declare that they have no known competing interests.

Prof. Shikha and Dr. Jiwan Singh Editors in Chief

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