Review Article

Tracking and tackling microplastics: A review of advances in detection, environmental impact, and remediation approaches

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Abstract

Microplastics (MPs) are extremely small plastic debris, less than 5 mm in size, present in the environment. They originate either from primary sources, such as microbeads, or form secondarily through the breakdown of larger discarded plastics, including consumer products and industrial waste. MPs have emerged as pervasive contaminants across marine, freshwater, and terrestrial ecosystems, and are now detected in drinking water, remote environments, and a wide range of aquatic organisms. This review consolidates current knowledge on the environmental fate, biological interactions, and detection methodologies of MPs, with a specific focus on emerging concepts such as plastisphere formation, biofilm development, the Trojan horse effect, and plastiglomerates. MPs act as substrates for microbial colonization, facilitating the spread of antibiotic resistance genes and altering microbial community dynamics. Through the Trojan horse mechanism, these serve as vectors for persistent organic pollutants (POPs), heavy metals, and pathogenic microorganisms, thereby enhancing ecological toxicity. Advanced detection methods including FTIR, Raman spectroscopy, and Py-GC-MS are discussed alongside current mitigation strategies spanning mechanical, chemical, and bioremediation techniques. Despite recent advances, challenges persist in detecting nanoplastics, standardizing methodologies, and implementing scalable remediation approaches. The review underscores the urgent need for interdisciplinary research, regulatory intervention, and public engagement to address the complex and multifaceted impacts of MPs on ecosystem and human health.

Keywords: Aquatic pollution, biofilm, microplastics, nanoplastics, plastiglomerates, plastisphere, Trojan horse effect.

Introduction

Since the onset of mass plastic production in the 1950s, over 8 billion tonnes of plastic have been manufactured globally. Around 50% of this has accumulated in landfills, while only 9% has been recycled. The remainder, much of which has ended up in aquatic environments, undergoes degradation into microplastics (MPs) through abiotic and biotic processes. Microplastics (MPs) are plastic particles that are less than 5 mm in size. They are either intentionally manufactured in microscopic forms such as microbeads used in cosmetics and plastic pellets (also known as nurdles or polymer granules) which serve as raw materials in plastic production or are formed through the degradation of larger plastic debris. Microplastics are highly persistent in the environment and can travel through rivers, infiltrate groundwater, and even contaminate drinking water sources, becoming part of the global water cycle. Their miniature size allows for easy ingestion by aquatic organisms, resulting in potential bioaccumulation and biomagnification through the food chain. Research over the last two decades shows that MPs are all-pervasive in every part of the earth and have been highlighted as a significant environmental contaminant.[1-3] MPs have been reported from marine ecosystems,[4] deep parts of the oceans like the Mariana Trench[5] and freshwater ecosystems.[6,7] The presence of MPs has also been reported in the most remote places of the earth like Himalayan freshwaters[8], deep-sea coral, sea ice and arctic snow. An estimated 82 to 358 trillion plastic particles, weighing between 1.1 and 4.9 million tonnes, are present in just the top foot of seawater, indicating a significant rise in plastic concentrations since the mid-2000s.[9]

Global emissions of microplastics are estimated at 9.6 teragrams (Tg) annually.[10] Studies on the MP concentration in the River Ganga revealed an average MP concentration of 92.85 ± 50.69 particles / m^3, with pollution levels showing a strong correlation with urbanization.[11] Additionally, MPs have been found in groundwater systems, with concentrations ranging from 0.1 to 6,832 particles / litre, raising serious concerns about drinking water safety and ecosystem health.[12] As a result, MP pollution has emerged as a critical global concern. Microplastics enter aquatic environments through multiple pathways, including: (1) wastewater effluents; (2) stormwater runoff; (3) atmospheric deposition, wherein airborne particles settle into water bodies via precipitation; (4) industrial and maritime activities; and (5) riverine transport from inland sources.[13]

Microplastics (MPs) have been detected in a wide array of aquatic organisms, including plankton, invertebrates, fish, and marine mammals. Their impacts manifest at multiple levels as mentioned below.

(1) Physical impacts: Ingestion of MPs can cause internal injuries, gastrointestinal blockages, reduced feeding stimuli,[14] and disruption of reproductive systems.[15]

(2) Chemical impacts: MPs can adsorb and transport toxic substances such as persistent organic pollutants (POPs), heavy metals, and plastic additives like phthalates and bisphenol A.[16] These chemicals may desorb within organisms, acting as endocrine-disrupting compounds (EDCs).[17] In addition, aquatic microbes can colonize MP surfaces and form biofilms, potentially facilitating the spread of antibiotic resistance genes.[18]

(3) Ecosystem-level impacts: MPs can alter physical properties of sediments, such as permeability and porosity, thereby disrupting benthic habitats.[19] They may also reduce light penetration in coral reef ecosystems and introduce pathogenic organisms.[20,21] Accumulated MPs hinder root aeration and soil microbiome composition in mangroves and wetlands.[22] Furthermore, microplastics interfere with key ecosystem processes. They disrupt trophic interactions such as predation and reproduction,[23] ultimately leading to biodiversity loss. Some studies suggest that plastics may also affect carbon cycling by altering the activity of phytoplankton and microbial communities critical to oceanic carbon sequestration.[24] Furthermore, MPs in the atmosphere can directly affect cloud formation, particulate matter formation, and accelerate climate change.[25] These findings underscore the urgent need for comprehensive waste management strategies, improved recycling systems, and further research on the environmental and health impacts of MPs. The existing literature on microplastics (MPs) largely focuses on their presence, types, sources, transport mechanisms, and interactions with other contaminants. This review highlights the catastrophic impacts of MPs in the current context, with particular emphasis on the plastisphere, biofilm formation, the Trojan horse effect, and plastiglomerates. It also provides an overview of the methods used for the identification, analysis, and removal of MPs, and discusses the key challenges involved in mitigating MP contamination in aquatic ecosystems.

Catastrophic effects of MPs in the present scenario

The pervasive presence of plastics in the environment has introduced unique challenges to ecological and biogeochemical systems. Beyond their persistence and physical impact, plastics serve as substrates for microbial colonization, leading to the formation of "plastispheres" that can host pathogenic or invasive microorganisms.[26] These processes facilitate biofilm development which is critical to understanding microbial succession and pollutant dynamics on plastics.[27]

Plastics introduced into aquatic and terrestrial environments are rapidly colonized by microorganisms, initiating the formation of biofilms.[28] These biofilms shield microbial communities from environmental stressors and additionally act as aggregation points for gene transfer, including the spread of antibiotic resistance genes (ARGs).[29] The physicochemical properties of plastic surfaces, including hydrophobicity and surface roughness, influence microbial adhesion and subsequent community structure. This biofilm matrix enhances the stability and persistence of microbial consortia, thereby establishing long-term plastisphere communities.[30]

Bioaccumulation of MPs has resulted in another unique phenomenon - the Trojan horse effect,[31] whereby the biofilms due to their chemical affinities adsorb and transport environmental contaminants including heavy metals, persistent organic pollutants (POPs), and pathogenic microorganisms. These pollutants, often hydrophobic, bind strongly to plastic surfaces and may be ingested by biota, leading to internal exposure once the plastic is assimilated. In this way, plastics act as vectors for toxic agents, bypassing natural barriers and delivering contaminants into biological systems. This effect poses serious implications for food webs and human health. Concurrently, physical interactions between plastics and natural materials result in plastiglomerates, hybrid formations that may further entrench plastic pollutants within geological systems.[32] Plastiglomerates are composite materials formed when molten plastic fuses with natural substrates such as sand, wood, or volcanic rock. First identified on beaches, these formations exemplify the integration of synthetic polymers into natural geological processes. They may serve as long-term reservoirs for the plastisphere and associated contaminants, embedding anthropogenic signatures within the Earth's stratigraphy. The structural stability of plastiglomerates suggests their potential to retain pollutants and support microbial activity over extended timescales. The interconnected phenomena of plastisphere formation, biofilm development, the Trojan horse effect, and plastiglomerate generation underscore the varied influences of plastics in shaping microbial ecology and pollutant dynamics. Understanding these relationships is crucial for risk assessment and the development of mitigation strategies in both marine and terrestrial environments.[32]

Identification and analysis of MPs in water

The accurate detection and analysis of MPs in water are foundational for assessing ecological risk, understanding transport pathways, and developing mitigation strategies. However, due to their microscopic size, diverse polymer composition, and occurrence within complex environmental matrices, MPs pose significant challenges for effective detection and characterization.

Sampling methods for MPs in water

The water samples are typically filtered through membranes of varying pore sizes (0.45 μm–500 μm) to isolate MPs. Surface water sampling is done using Neuston nets (mesh sizes 300–500 μm), to collect floating MPs. In addition to this, grab sampling is done manually by collecting water in containers for laboratory analysis. This method is suitable for smaller water bodies and allows detection of MPs down to 1 μm with appropriate filtration.[33] Alternatively, groundwater samples are collected through pump and purge techniques, and effluent composite samplers from wastewater treatment plants (WWTPs).

Sample processing and pre-treatment

Before analysis, samples must be treated to remove organic and inorganic matter that may interfere with detection. Common pre-treatment steps include (a) oxidation with hydrogen peroxide (H_2O_2) to eliminate organic content; (b) density separation using solutions such as $ZnCl_2$ or NaCl to separate MPs from sediments or suspended solids; (c) enzymatic digestion using enzymes such as proteinase and cellulase for a more environmentally friendly treatment.[34]

Identification and characterization techniques
Stereomicroscopy or optical microscopy is the first step in MP identification, post-sampling. The particles are classified based on shape *viz*., fibres, fragments, beads and colour. This method is subjective and could lead to misidentification of non-plastic materials. After identification, spectroscopic techniques like Fourier-Transform Infrared Spectroscopy (FTIR) and Raman Spectroscopy are used to determine the polymer type. FTIR is widely used to determine polymer type through infrared absorption spectra, and micro-FTIR allows detection of particles down to 10 μm.[35] Conversely, Raman Spectroscopy provides a detailed molecular structure of polymers, and can detect particles <1 μm.[36] MP identification can also be done using Pyrolysis–Gas Chromatography–Mass Spectrometry (Py-GC-MS), where the MPs are thermally decomposed.[37] The gaseous products are then analysed to identify the polymers. Although this method is costly, it is highly accurate and quantitative. In Thermogravimetric Analysis (TGA), weight change is measured with temperature increase and is used to infer polymer composition.[38]

Quantification and reporting
Quantification involves counting the number of particles per volume (e.g., particles/L or particles/m^3). Complementary data such as mass, size distribution, and polymer type should also be reported. Consistent metrics are necessary for cross-study comparisons.

Mitigation strategies

There are several mitigation techniques targeted for environmental cleanup. Conventional mechanical collection using floating booms, nets, and skimmers are presently employed in rivers and coastal areas to collect plastic waste. Collection of MPs using these methods is ambiguous due to lack of data. In recent years, emphasis has been laid on bioremediation of plastics and MPs, using microorganisms as it is considered an environmentally friendly approach when compared with traditional disposal methods. This methodology can be very effective in mitigating many of the issues associated with MPs,[39] but research in this area is still in its nascent phase. The common mitigation strategies (Figure 1) adopted for drinking water, storm water and surface runoff water, and waste water are given below:

Drinking water: Most municipal drinking water treatment plants remove large MPs through sedimentation and filtration, but finer particles may remain, which require advanced filtration strategies. Reverse osmosis, ultrafiltration, and nanofiltration are highly effective in removing sub-MPs.[40] Activated carbon can adsorb plastic additives and associated pollutants. Furthermore, biodegradation of MPs can be done using microbial or enzymatic agents.[1]

Stormwater: Urban runoff is a significant pathway for synthetic fibres to enter water systems. Constructed wetlands, vegetated filter strips and permeable pavements can reduce the transport of MPs into drainage systems. Simultaneously, retention ponds, sedimentation tanks, and filtration systems installed at drainage outlets can intercept MPs before they reach open water.[41]

Waste water: Several mitigation procedures have been developed to address microplastic (MP) contamination, including: (1) Conventional physical filtration in wastewater treatment plants, which removes larger MP particles,[42] (2) Advanced treatment technologies, such as membrane bioreactors (MBRs),[42] which combine biological treatment with membrane filtration to produce high-quality effluent; sand filtration as a subsequent polishing step to further enhance water quality; electrocoagulation and flotation, which aggregate MPs for easier separation; and Advanced Oxidation Processes (AOPs), which use chemical reactions to degrade certain plastic polymers, thereby reducing the formation of secondary MPs,[43] and (3) Sludge management strategies which capitalize on the

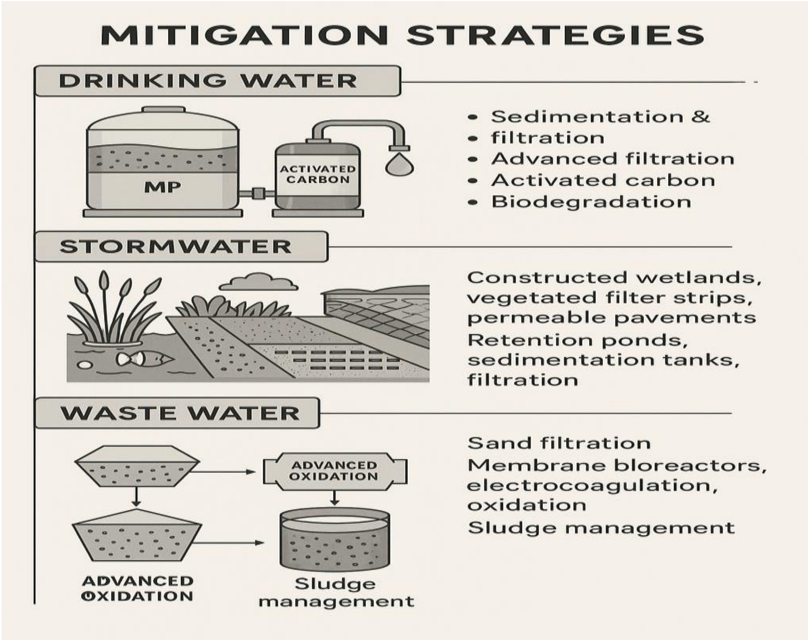

Figure 1: Strategies to mitigate MPs from aquatic systems

accumulation of MPs in sludge during treatment. Safe disposal or treatment of sludge is crucial to prevent environmental re-entry.[44]

Challenges in MP detection and mitigation

Despite awareness of MPs, significant knowledge gaps exist concerning long-term ecological effects of MPs in aquatic ecosystems. Lack of standardization protocols has been identified as the major hurdle in MP detection. Variability in mesh size, filter material, and sample treatment can all lead to inconsistent results.[1] Additionally, MPs smaller than 1 µm (nanoplastics) are below the detection limits of most of the traditional methods. A gap in understanding persists concerning the cumulative and synergistic impacts of MPs. At this moment, development of biodegradable plastic alternatives is a critical requirement. Innovative methods such as nanoparticle tracking analysis (NTA) and field-flow fractionation (FFF) are being explored.[45] Future research must focus on unravelling the long-term ecological and evolutionary consequences of plastic-associated microbial networks and their potential effects on environmental health. Global standards are to be developed for sampling, analysis, and data reporting. It is necessary to combine multiple analytical methods for comprehensive characterization. Furthermore, it is imperative to invest in automation and AI tools to aid in MP particle recognition, and innovate real-time sensing technologies such as portable FTIR/Raman devices and biosensors. Additionally, public awareness, regulatory policies, and industry cooperation are essential to address the root causes of plastic pollution.

Conclusion

Microplastic pollution represents a multifaceted and escalating global environmental challenge, with far-reaching consequences for aquatic ecosystems, biodiversity, and human health. The persistence and mobility of MPs enable them to penetrate remote environments and enter food webs at multiple trophic levels. Their interaction with biota and environmental contaminants is further complicated by the formation of biofilms and plastisphere communities, which enhance microbial survival and contribute to the dissemination of antibiotic resistance genes. The Trojan horse effect exemplifies how MPs act as vectors for heavy metals, persistent organic pollutants (POPs), and pathogens, enabling their bioavailability and internalization by organisms. Concurrently, the formation of plastiglomerates illustrates the physical and geological entrenchment of plastics in Earth's systems, posing long-term ecological risks. Despite advances in detection and analytical methodologies, including FTIR, Raman spectroscopy, and Py-GC-MS, significant challenges remain in the identification of nanoplastics and standardization of quantification protocols. Current mitigation strategies range from mechanical removal and filtration to advanced oxidation processes and emerging bioremediation approaches, which hold significant promise but still require further refinement, integration, and scalability. Addressing the MPs crisis demands a multipronged approach encompassing robust regulatory frameworks, innovative materials research, interdisciplinary scientific investigation, and broad public engagement. Future investigations must emphasize on long-term ecological and evolutionary impacts of MPs, particularly their influence on microbial communities and biogeochemical cycles. Without urgent and coordinated action, the pervasive nature of MPs threatens to redefine ecological baselines and compromise the resilience of aquatic ecosystems for future generations.

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Conflicts of interest
There are no conflicts of interest.

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