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Microplastics as an Emerging Threat to Aquatic Ecosystems: Sources, Impacts, and Mitigation

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ABSTRACT

Plastic pollution has become one of the most important environmental problems worldwide due to the extensive production, consumption, and persistence of plastic materials. Microplastics (MPs), generally defined as plastic particles smaller than 5 mm, have emerged as widespread contaminants in marine, freshwater, coastal, and sedimentary environments. They originate either directly from products or industrial processes, known as primary microplastics, or through the fragmentation and degradation of larger plastic items, known as secondary microplastics. Their small size, persistence, high surface-area-to-volume ratio, and ability to interact with other contaminants make microplastics particularly important emerging pollutants in aquatic ecosystems. Microplastics enter aquatic environments through domestic and industrial wastewater, urban runoff, atmospheric deposition, synthetic textile fibers, tire wear, fishing activities, and the degradation of larger plastic debris. Once released, their transport and environmental fate are influenced by particle size, shape, density, polymer type, weathering, biofilm formation, hydrodynamic conditions, and sediment characteristics. Microplastics have been detected throughout the water column and in sediments, demonstrating that their distribution is not restricted to surface waters. Aquatic organisms ranging from plankton and benthic invertebrates to fish can ingest microplastics directly or indirectly through contaminated food. Microplastic exposure has been associated with oxidative stress, inflammation, impaired growth, altered behavior, reproductive impairment, and physiological disturbances in aquatic organisms. In addition, plastic surfaces can be colonized by microorganisms, forming the aquatic "plastisphere", which may influence microbial communities, nutrient cycling, pathogen dissemination, and antimicrobial resistance]. Although laboratory studies provide substantial evidence of biological effects, ecological risks should be interpreted carefully because experimental concentrations and particle characteristics do not always reflect environmentally realistic conditions. Therefore, standardized monitoring, environmentally relevant experiments, improved waste management, reduction of plastic pollution at its source, and international cooperation are essential. This review evaluates the major sources, environmental fate, biological effects, food-web interactions, ecological consequences, and management strategies associated with microplastics in aquatic ecosystems.

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INTRODUCTION

Plastics have become indispensable materials in modern society because of their low cost, durability, light weight, flexibility, and versatility. They are widely used in packaging, construction, transportation, agriculture, healthcare, textiles, electronics, and numerous other sectors. However, the properties that make plastics economically and technologically valuable also contribute to their persistence after disposal. Once plastic materials enter the environment, they can remain for long periods and undergo physical, chemical, and biological degradation processes that gradually produce smaller particles. Microplastics are generally defined as plastic particles smaller than 5 mm. They are commonly classified into primary and secondary microplastics. Primary microplastics are intentionally manufactured or released at microscopic dimensions, whereas secondary microplastics originate from the fragmentation of larger plastic materials as a result of weathering and environmental degradation (Witczak et al., 2024) [1]. Synthetic textile fibers, industrial plastic pellets, and some consumer products can contribute to primary microplastic pollution, while plastic packaging, bottles, fishing equipment, agricultural plastics, and other plastic debris are important sources of secondary microplastics. Aquatic ecosystems are among the major environmental reservoirs of microplastics. Rivers, lakes, estuaries, coastal waters, and oceans can receive microplastics from both terrestrial and aquatic sources. Freshwater systems are particularly important because they can act as pathways connecting land-based sources with marine environments (Kataria et al., 2024) [2]. Recent research has demonstrated that freshwater environments should not be considered merely temporary transport systems; they can also act as important sinks where microplastics accumulate in water and sediments. Wastewater is another important pathway. Domestic wastewater can contain synthetic textile fibers, plastic fragments, and other microscopic polymer particles. Although wastewater treatment plants can remove substantial proportions of microplastics, complete removal is difficult, particularly for small particles and fibers]. Consequently, wastewater treatment systems can reduce environmental release but cannot necessarily eliminate microplastic pollution. The environmental importance of microplastics is associated with their widespread distribution and their interaction with aquatic organisms. Because of their small size, microplastics can be ingested by organisms at different trophic levels. They can also provide surfaces for microbial colonization and interact with other environmental contaminants (Kataria et al., 2024) [2]. Thus, microplastics should not be regarded simply as small pieces of plastic but as complex environmental stressors capable of interacting with physical, chemical, and biological processes.

1. Sources and Pathways of Microplastics into Aquatic Ecosystems

Microplastics originate from numerous anthropogenic activities. Domestic wastewater, industrial discharge, textile production, tire abrasion, plastic manufacturing, agricultural practices, fishing activities, and inadequate waste management are among the major sources. Synthetic textile fibers represent an important source of microplastic contamination. During washing, mechanical abrasion can release fibers from synthetic clothing into wastewater. These fibers may subsequently reach wastewater treatment plants and, depending on treatment efficiency, may be released into receiving waters. Similarly, tire abrasion associated with road transportation can produce microscopic polymer-containing particles that can be transported by rainfall and urban runoff. Industrial activities can also contribute to microplastic contamination. Plastic pellets used as raw materials can be accidentally released during production, transportation, or handling. Paints, coatings, industrial abrasives, and other polymer-containing materials can additionally contribute to microscopic plastic particles (Mao et al., 2022) [3].

Secondary microplastics are generated through the degradation of larger plastic debris. Ultraviolet radiation promotes photooxidative processes that weaken polymer structures. Mechanical forces such as waves, abrasion by sediment, and water movement can subsequently fragment weathered plastic into smaller particles. Once released into freshwater systems, microplastics can be transported downstream and eventually reach estuaries and marine ecosystems. However, not all particles remain suspended in the water column. Their fate depends on their density, size, shape, surface properties, and interactions with biological and environmental materials (Den et al., 2023) [4]. The formation of biofilms on plastic surfaces can substantially modify the behavior of microplastics. Microorganisms colonizing plastic surfaces may increase particle density and alter their surface characteristics. Consequently, a particle that initially floats near the surface may eventually sink into sediments (Kim et al., 2025) [5].

Another important issue is the lack of complete standardization in microplastic sampling and analysis. Differences in sampling methods, mesh sizes, particle-size limits, polymer identification techniques, and laboratory contamination control can produce substantially different estimates of microplastic abundance. Standardized analytical approaches are therefore necessary to improve comparisons among studies and regions (Sharifinia et al., 2020) [6].

2. Occurrence and Environmental Fate

Microplastics have been detected in rivers, lakes, reservoirs, estuaries, coastal waters, open oceans, and sediments. Their widespread occurrence demonstrates that aquatic environments function simultaneously as transport pathways and environmental sinks. The environmental fate of a microplastic particle is strongly influenced by its physical and chemical properties. Polymer density determines its initial tendency to float or sink, while particle size and shape influence settling velocity and transport. Fibers, fragments, films, and beads can therefore behave differently under the same environmental conditions (Wang et al., 2023) [7]. Sediments are particularly important reservoirs because many microplastics eventually accumulate on or within the sediment layer. Nevertheless, sediment accumulation does not necessarily mean permanent immobilization. Floods, storms, bottom currents, dredging, and other disturbances can resuspend particles and return them to the water column. Weathering also changes the environmental behavior of microplastics. Ultraviolet radiation, oxidation, mechanical abrasion, and biological activity can increase surface roughness and alter chemical properties. These processes may affect the capacity of microplastics to interact with metals, pesticides, persistent organic pollutants, and other environmental chemicals (Abouda et al., 2024) [8]. Microplastics may therefore act as mobile surfaces that interact with environmental contaminants. However, their role as contaminant vectors should not be considered universal. Natural particles such as sediment and organic matter can also strongly adsorb chemical pollutants. Consequently, the ecological significance of contaminant transport by microplastics depends on environmental conditions and particle characteristics. Recent research has also emphasized the dynamic nature of microplastic transport. Weathering can continuously change particle properties, while variations in water flow, temperature, biological activity, and sediment conditions can alter their distribution (Revel et al., 2020) [9]. This dynamic behavior makes the long-term fate of microplastics difficult to predict.

3. Effects of Microplastics on Aquatic Organisms

3.1. Effects on Plankton and Primary Producers

Planktonic organisms are among the first biological groups exposed to microplastics. Microalgae and zooplankton can encounter plastic particles because of their small size and feeding strategies. Microplastics may interfere with feeding behavior and can physically interact with cell surfaces. Exposure to microplastics and nanoplastics has been associated with changes in photosynthetic activity, cellular metabolism, oxidative balance, and growth in aquatic primary producers. Such effects are ecologically important because phytoplankton form the foundation of many aquatic food webs. Changes in phytoplankton productivity can potentially influence the availability of food for zooplankton and higher trophic levels. Therefore, even relatively subtle physiological effects on primary producers may have broader consequences for aquatic ecosystems. Zooplankton can ingest microplastics while feeding. Ingestion may reduce feeding efficiency, alter energy allocation, and affect growth and reproduction. The severity of these effects depends on particle size, shape, polymer type, concentration, and species-specific feeding behavior (Pires et al., 2022) [10].

3.2. Effects on Aquatic Invertebrates

Filter-feeding organisms such as mussels and oysters are particularly relevant to microplastic research because they continuously filter large quantities of water. Consequently, they may encounter microplastics during normal feeding activities. Potential biological effects include physical irritation of digestive tissues, reduced feeding efficiency, oxidative stress, altered immune responses, and changes in energy metabolism. Benthic organisms may also be exposed to microplastics accumulated in sediments. This is important because sediment-associated species can be exposed for prolonged periods and can subsequently transfer particles to predators. The biological consequences may therefore extend beyond individual organisms. If microplastic exposure affects the survival, growth, or reproduction of key invertebrate species, population dynamics and predator-prey relationships may also be affected (Borges et al., 2025) [11].

3.3. Effects on Fish

Fish are among the most extensively studied aquatic organisms in microplastic research because they occupy important positions in food webs and have considerable ecological and economic value. Fish can ingest microplastics directly from the water or indirectly by consuming contaminated prey. Once ingested, particles may accumulate temporarily in the gastrointestinal tract and can potentially influence physiological functions. A major meta-analysis published in Water Research evaluated 3,757 biological endpoints from 85 laboratory studies and found that microplastic exposure significantly inhibited fish growth, survival, and reproductive performance while increasing oxidative damage (Digka et al., 2024) [12]. The study also showed that effects varied according to exposure conditions, microplastic characteristics, and fish life stage. Oxidative stress is one of the most frequently reported mechanisms of microplastic toxicity. Increased production of reactive oxygen species can disturb cellular homeostasis and contribute to lipid, protein, and DNA damage. Elevated levels of oxidative stress biomarkers have been reported in fish exposed to microplastics. Microplastic exposure may also affect fish reproduction. Changes in reproductive performance are particularly important because population-level effects may occur even when individual mortality is relatively low. Reduced reproductive success can influence recruitment and long-term population stability. Behavioral changes have also been reported in exposed fish. Alterations in swimming, feeding, predator avoidance, and other behaviors may influence ecological interactions and survival. However, laboratory results should be interpreted carefully. Some experiments use concentrations substantially higher than those measured in natural environments. In addition, pristine plastic particles used in laboratory experiments may differ from weathered environmental particles. Therefore, environmentally realistic concentrations and aged microplastics should receive greater attention in future studies (Li et al, 2019) [13].

4. Microplastics, Chemical Pollutants, and the Aquatic Plastisphere

Microplastics can interact with microorganisms and chemical contaminants, creating additional dimensions of ecological risk. Plastic surfaces can rapidly become colonized by bacteria, archaea, fungi, algae, and other microorganisms. The microbial community associated with plastic surfaces is commonly referred to as the "plastisphere". The aquatic plastisphere represents a novel ecological niche. Microbial communities developing on plastic surfaces can differ in composition and function from those associated with natural substrates, although the degree of this difference remains an active area of scientific investigation. A recent 2026 review published in Nature Reviews Microbiology emphasized that the aquatic plastisphere may influence microbial community assembly, nutrient cycling, pathogen persistence, and antimicrobial resistance (Zhao et al, 2026) [21]. The potential relationship between microplastics and antimicrobial resistance is particularly important. Biofilms on plastic surfaces may provide favorable conditions for interactions among microorganisms and genetic material. Recent research suggests that plastisphere communities can act as reservoirs or transport environments for antibiotic-resistance genes (Prata et al., 2020) [14]. Microplastics may also adsorb chemical pollutants from surrounding water. Heavy metals, pesticides, and persistent organic pollutants can interact with plastic surfaces depending on their chemical properties and environmental conditions. However, microplastics should not automatically be regarded as the dominant carriers of chemical contaminants. Natural sediment and organic matter can also provide important sorption surfaces. The contribution of microplastics therefore depends on particle properties, environmental concentrations, and the characteristics of competing environmental media. The combination of plastic particles, associated chemicals, and microbial communities makes microplastic pollution particularly complex. Consequently, risk assessments should consider not only the polymer itself but also the biological and chemical processes occurring on its surface (Zhao et al, 2026) [21].

5. Microplastics and Aquatic Food Webs

Microplastics can enter aquatic food webs when organisms ingest particles directly or consume contaminated prey. Planktonic organisms may ingest microplastics and subsequently become prey for fish and other predators. Similarly, benthic organisms may consume particles accumulated in sediments and transfer them to higher trophic level. This process demonstrates that microplastics can undergo trophic transfer. However, trophic transfer should not automatically be equated with biomagnification. Unlike many persistent chemical contaminants, microplastics are physical particles that can be eliminated from organisms through feces and other biological processes. Nevertheless, the movement of microplastics through food webs remains ecologically significant. If exposure alters feeding efficiency, growth, reproduction, or survival at multiple trophic levels, food-web structure and energy transfer may be affected. Microplastics may also influence predator-prey interactions indirectly through behavioral changes. Altered feeding behavior, swimming patterns, predator avoidance, and sensory functions could modify interactions among aquatic species. The consequences may become more important when microplastic exposure occurs simultaneously with other environmental stressors. Aquatic organisms are rarely exposed to a single pollutant under natural conditions. Instead, microplastics may occur together with pesticides, heavy metals, temperature stress, salinity changes, hypoxia, and pathogens. (Rahman et al., 2021) [15]. A 2024 meta-analysis of freshwater fish found that combined microplastic and other stressor responses were often additive or antagonistic rather than consistently synergistic]. This finding demonstrates that combined effects are complex and cannot be assumed to be more severe than individual stressors in every case (Bhardwaj et al., 2024) [20].

6. Microplastics and Ecosystem Functions

The ecological importance of microplastics extends beyond individual organisms. Aquatic ecosystems depend on interconnected processes including primary production, decomposition, nutrient cycling, carbon transport, and energy transfer. Microplastics can interact with microorganisms involved in decomposition and nutrient transformation. Because plastic surfaces provide novel microbial habitats, the composition and activity of microbial communities may be altered. The plastisphere may therefore influence biogeochemical processes. Microbial communities associated with plastic surfaces can participate in carbon transformation and nutrient cycling. These interactions may become increasingly important as plastic abundance continues to increase in aquatic environments. Microplastic pollution can also interact with sediment properties. Particles deposited in sediments may alter physical characteristics and provide new surfaces for microbial colonization. However, the magnitude of these ecosystem-level effects remains uncertain. Long-term field studies are still relatively limited compared with laboratory experiments. Therefore, it is difficult to determine whether changes observed at the cellular or individual level necessarily translate into substantial changes in ecosystem functioning. Future studies should increasingly investigate population- and community-level responses rather than focusing exclusively on individual biomarkers (Chang et al., 2020) [16].

7. Potential Implications for Human Health

Microplastics are also relevant to human health because humans can potentially be exposed through food, drinking water, and other environmental pathways. Fish, shellfish, and other aquatic organisms can contain microplastics, creating a possible connection between aquatic pollution and human exposure. However, the detection of microplastics in food or environmental samples does not by itself demonstrate a specific human health effect. Current evidence concerning the long-term health consequences of environmental microplastic exposure remains incomplete. Potential concerns arise from several characteristics of microplastics. They may contain or interact with plastic additives and environmental contaminants, while their surfaces can support microbial communities. Smaller particles, particularly nanoplastics, may also exhibit different biological behavior because their dimensions allow closer interaction with cells and biological barriers. For this reason, reducing unnecessary environmental exposure represents a reasonable precautionary approach while research continues. Human health assessment also requires better exposure measurements. Reliable estimates of the quantity, size distribution, polymer composition, and biological availability of particles reaching humans are essential for accurate risk assessment (hu et al., 2019) [17].

8. Prevention and Management Strategies

The most effective strategy for addressing microplastic pollution is prevention at the source. Removing microplastics after they have entered rivers, lakes, and oceans is technically difficult and potentially expensive. Consequently, reducing plastic production, consumption, and environmental leakage should be prioritized. Improved waste collection and recycling systems are essential. Single-use plastic products should be reduced where practical, while reusable alternatives and circular-economy strategies should be encouraged. Wastewater treatment represents another important control point. Filtration, membrane technologies, coagulation, sedimentation, and advanced treatment processes can remove substantial quantities of microplastics from wastewater (Jin et al., 2025) [19]. However, particles captured during treatment may accumulate in sewage sludge. Consequently, treatment can sometimes transfer microplastics from water to another waste stream rather than completely eliminating them. Textile-related microfiber pollution can potentially be reduced through improved textile design, washing technologies, and filtration systems. Similarly, controlling urban runoff and tire-derived particles should be considered in strategies aimed at reducing terrestrial inputs to aquatic environments. Nature-based and engineering-based approaches are also being investigated. A systematic review of freshwater management interventions highlighted the importance of combining prevention, monitoring, wastewater treatment, and removal technologies rather than relying on a single intervention (Bhardwaj et al., 2024) [20]. Biodegradable plastics have been proposed as an alternative to conventional plastics. However, biodegradable materials should not be considered an automatic solution to plastic pollution. Their degradation depends strongly on environmental conditions, and incomplete degradation may still result in persistent particles. Therefore, material substitution should be accompanied by reductions in unnecessary plastic consumption, improved product design, appropriate waste management, and environmental monitoring.

9. Current Research Gaps

Despite the rapid growth of microplastic research, several important knowledge gaps remain. First, standardized methods for sampling, identifying, and quantifying microplastics are still needed. Differences in analytical methods can result in substantial variation among studies (Shen et al., 2019) [18]. Second, many laboratory studies use pristine plastic particles that differ considerably from environmentally aged particles. Natural microplastics are often weathered, oxidized, fragmented, and covered with biofilms. Future experiments should therefore increasingly use environmentally realistic particles. Third, nanoplastics remain insufficiently understood. Their smaller dimensions may allow different interactions with cells and tissues, but their environmental concentrations are difficult to measure accurately. Fourth, combined stressors require greater attention. Aquatic organisms are exposed simultaneously to multiple environmental pressures. Microplastics may interact with temperature, salinity, pollutants, pathogens, hypoxia, and other stressors. Importantly, available evidence indicates that combined effects are not necessarily synergistic in all circumstances (Zhao et al., 2026) [21]. Fifth, long-term field studies are essential. Laboratory experiments are valuable for identifying toxicological mechanisms, but population- and ecosystem-level consequences must be evaluated under natural environmental conditions. Finally, the aquatic plastisphere requires further investigation. Recent evidence indicates that plastic-associated microbial communities may have implications for pathogen dissemination and antimicrobial resistance, highlighting the need for a One Health perspective (Sethia et al, 2024) [22].

10. Conclusion

Microplastics have become widespread contaminants in marine and freshwater ecosystems. Their small size, persistence, mobility, and capacity to interact with organisms, microorganisms, sediments, and chemical contaminants make them a complex environmental threat. Aquatic organisms ranging from plankton to fish can ingest microplastics, potentially resulting in oxidative stress, physiological disturbances, behavioral changes, impaired growth, and reproductive effects. Recent meta-analytical evidence provides further support for adverse effects on fish growth, survival, reproduction, and oxidative balance. The ecological importance of microplastics is further increased by their ability to interact with microbial communities. The aquatic plastisphere represents a novel microbial habitat that may influence nutrient cycling, pathogen persistence, and antimicrobial resistance. Nevertheless, important uncertainties remain. Not every microplastic particle has the same environmental behavior or toxicity. Particle size, shape, polymer composition, weathering, concentration, exposure duration, and organism characteristics can all influence biological responses. Furthermore, laboratory experiments do not always reproduce environmentally realistic conditions. Consequently, future research should focus on environmentally relevant concentrations, weathered microplastics, nanoplastics, long-term exposure, multiple-stressor interactions, and standardized analytical methods. Greater emphasis should also be placed on population- and ecosystem-level consequences. Ultimately, microplastic pollution cannot be solved solely by removing particles from contaminated waters. Prevention at the source is essential. Reducing unnecessary plastic consumption, improving waste management, increasing wastewater treatment efficiency, controlling microfiber and tire-derived pollution, promoting circular-economy practices, and strengthening international cooperation are all necessary components of an effective strategy. Microplastics should therefore be considered not simply as small fragments of plastic but as complex environmental stressors capable of interacting with biological, chemical, and physical processes throughout aquatic ecosystems. Effective management will require an interdisciplinary approach combining environmental science, ecotoxicology, engineering, microbiology, public health, and environmental policy.

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