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Microplastics: From Environmental Contamination to Biological Effects in Living Organisms

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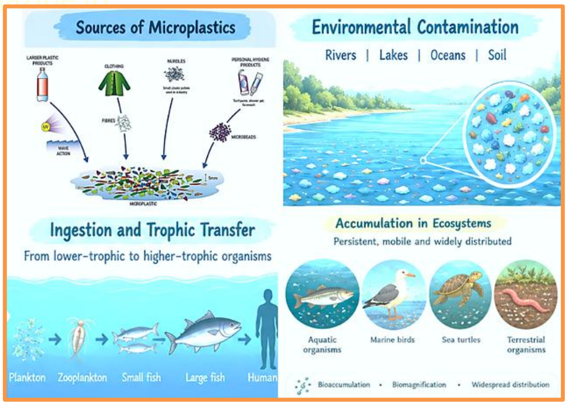
Plastics are synthetic polymeric materials primarily derived from petroleum-based feedstocks and composed of long-chain hydrocarbon molecules, often incorporating various additives to enhance their flexibility, durability, stability, and resistance to degradation. Since their widespread commercialisation in the 1930s, plastics have become indispensable in numerous sectors, including packaging, agriculture, healthcare, fisheries, construction, and consumer products. However, the rapid expansion of plastic production and consumption, together with inadequate waste management practices, has resulted in the accumulation of substantial quantities of plastic waste in terrestrial and aquatic environments. Once released into the environment, larger plastic items undergo weathering processes, including ultraviolet radiation, mechanical abrasion, and biological activity, which progressively weaken the polymer matrix and fragment it into smaller particles, microplastics, and nanoplastics. Their small size and diverse physicochemical characteristics facilitate their transport and dispersal through rivers, lakes, estuaries, coastal waters, and marine ecosystems, allowing them to occur across different environmental compartments. Consequently, the widespread occurrence of microplastics in aquatic organisms, particularly commercially important fish and seafood species, has raised increasing concerns regarding ecosystem health, food safety, and potential human exposure through seafood consumption.

Microplastics



Microplastics (MPs) are defined as "synthetic solid particles or polymeric matrices, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water." It can contain additives and polymeric raw materials (e.g., monomers or oligomers) originating from plastics, as well as chemicals absorbed from the surrounding ambience. Common plastic polymers include polypropylene (PP), polyethylene (PE), Polyvinyl Chloride (PVC), Polystyrene (PS), and Polyacrylates.

Classification of microplastics

Based on the source, microplastics are classified into primary and secondary microplastics.

Primary microplastics

Primary microplastics are plastic particles intentionally manufactured in sizes ranging from **1 µm to 5 mm** and released directly into the environment. They originate from products such as personal care and cosmetic items (e.g., exfoliating scrubs, toothpastes, and face washes), industrial abrasives, medical applications (e.g. dental polishing agents), and drilling fluids used in oil and gas exploration. In addition, synthetic textile fibres released during laundering and accidental spills while manufacturing or transport can also contribute significantly to primary microplastic pollution.

Secondary microplastics

Secondary microplastics are formed through the fragmentation of larger plastic items by **physical, chemical, and biological degradation,** including UV radiation, mechanical abrasion, wave action, and weathering. They mainly arise from improperly managed plastic waste, landfill leakage, recycling losses, plastic mulching in agriculture, synthetic textile fibres, tire wear, synthetic polymer-based paints, plastic-coated paper, and discarded fishing and aquaculture gear. Owing to the continuous breakdown of plastic debris, secondary microplastics are considered to be the most dominant microplastics.

Transport and distribution of Microplastics

Microplastics are transported between the atmosphere, pedosphere, and hydrosphere depending on their size, weight, and density. Lighter and smaller particles are dispersed by wind to remote regions such as glaciers and mountains, whereas denser particles tend to accumulate or become buried in soil. Agricultural plastic mulches and sewage sludge also contribute to the accumulation of microplastics in the soil. Environmental drivers such as runoff, river discharge, wind, ocean currents, tides, and waves, along with human activities including industry, tourism, and transportation, also significantly determine their transport and accumulation. Microplastic distribution also depends on particle density and shape. Although polymers like polyethylene (PE) and polypropylene (PP) are less denser than water, biofouling, adsorption of natural materials, inclusion of inorganic fillers during manufacturing, and fecal pellets increase their density, causing them to settle into sediments. Generally, fibres are more abundant in sediments, whereas microbeads are more common in surface waters.

Microplastics in freshwater ecosystem

Freshwater ecosystems receive microplastics primarily from wastewater discharges, synthetic textiles, personal care products, and industrial activities. In stagnant water bodies such as lakes and ponds, microplastics accumulate more readily due to limited water exchange, while in rivers they are transported downstream and eventually settle in sediments. Microplastic contamination generally decreases with increasing distance from pollution sources. Freshwater organisms are highly exposed to microplastics, particularly near urban and industrial areas. Ingestion of microplastics can cause alterations in feeding behaviour, bioaccumulation in fish and impaired growth and reproduction. Chronic exposure to polyethylene (PE) has also been reported to adversely affect the reproductive performance of freshwater amphipods.

Microplastics in beaches and marine ecosystems

Beaches are reservoirs of highly fragmented plastic debris that transport microplastics back to coastal waters and finally to the open ocean. The concentration of microplastics is usually higher in the upper layer, i.e., the epipelagic layer, than in the lower mesopelagic layer. However, the terrestrial environment also determines the concentration of microplastics, as it harbors industries that can add a huge amount of plastic debris either directly or indirectly into the ocean. Marine ecosystems are major sinks for microplastics, receiving inputs through rivers, surface runoff, and wastewater discharges. Microfibers are the most abundant type of marine microplastic. Their distribution depends on density as low-density particles remain on the sea surface or in the water column, whereas particles denser than seawater settle and accumulate in benthic sediments.

Toxic effects of microplastics shown by trophic transfer

Aquaculture practices can contribute to microplastic (MP) contamination through the degradation of plastic-based materials such as feed packaging, fishing nets, ropes, and pond liners. The fish inhabiting waters receiving urban wastewater effluents often exhibit higher MP burdens, emphasising the influence of anthropogenic activities and inadequate waste management on microplastic pollution in aquatic ecosystems. These microplastics in turn are readily ingested by a wide range of aquatic organisms, particularly non-selective filter feeders such as zooplankton and bivalves, resulting in bioaccumulation and trophic transfer through aquatic food webs. Owing to their resemblance to natural prey, MPs are also consumed by fish, crustaceans, and aquatic birds, with smaller particles exhibiting greater bioavailability and tissue accumulation. In addition to their direct effects, MPs act as carriers of persistent organic pollutants (POPs), heavy metals, and other environmental contaminants owing to their large surface area and hydrophobic nature. Consequently, ingestion of MPs exposes organisms not only to plastic particles but also to sorbed toxic chemicals and associated microbial communities. They also provide substrates for microbial biofilms, collectively known as the *plastisphere*, which consist of pathogenic microorganisms and antibiotic resistance genes (ARGs), facilitating their dissemination in aquatic environments.

Chemicals associated with microplastics may act as endocrine disruptors, causing hormonal imbalance and reproductive impairment, including reduced oocyte quality, sperm motility, and fecundity in oysters. The accumulation of MPs and their associated contaminants impairs feeding efficiency, and induces oxidative stress, inflammation, neurological dysfunction, endocrine disruption, and reproductive toxicity. As MPs fragment into nanoplastics, their enhanced bioavailability enables them to cross biological barriers and accumulate in tissues, potentially exacerbating toxic effects. Beyond individual organisms, MPs alter benthic communities, disrupt microbial assemblages and nutrient cycling, and impair ecosystem functioning. Their widespread detection in aquatic organisms, seafood and other food products highlights their pervasive distribution and underscores their potential ecological and human health risks.

Bioaccumulation and trophic transfer of microplastics in aquatic organisms and its impact on humans

Trophic Level	Microplastic Concentration	Implications for Human Health	References
Primary Consumers (e.g. Zooplankton, Daphnia)	0.56 ± 0.25 items/ individual (zooplankton)	Primary entry point into the food web; early accumulation phase	(Pennati et al., 2022)
Secondary Consumers (e.g., Herring, aquatic snails)	2.74 ± 1.10 items/ individual; up to 1.1 MP/g tissue	Accumulation in commonly consumed fish species	Kandeyaya and Ranatunga, 2024
Tertiary Consumers (e.g., cod, grouper)	4.17 ± 1.20 items/ individual; higher bioaccumulation index	Major route of dietary exposure for humans	(VegaHerrera et al., 2024)
Quaternary Consumers (e.g., whales, dolphins)	Variable; typically, lower levels	Risk of indirect exposure via seafood like tuna, swordfish	(Alava, 2020; Yu et al., 2021)
Estuarine/ Benthic Species (e.g., Crabs, clams)	Crabs: ~15,000 particles/ day; Estuarine fish: variable by site	Ingestion of contaminated species poses gastrointestinal and chronic exposure risk	(Wang et al., 2024)

Effects of microplastics in human beings

Microplastics (MPs) and nanoplastics (NPs) ingested by lower-trophic organisms can be transferred to higher-trophic organisms through predator–prey interactions and food-web processes, facilitating their accumulation and distribution across terrestrial and aquatic ecosystems. Their small size and persistence enable them to interact with a wide range of organisms and potentially cross biological barriers, thereby increasing the likelihood of exposure at different trophic levels. In aquatic ecosystems, MPs and NPs can be ingested by plankton and benthic invertebrates, which subsequently enter the diets of commercially important fishes and ultimately end up in higher trophic organisms, including humans. Increasing evidence of human exposure has further intensified concerns regarding their potential health consequences. MPs have been detected in human blood (Leslie et al., 2022) and various human tissues, raising concerns about their possible effects on immune and enzymatic functions, endocrine regulation, reproductive health, and carcinogenic processes (Koteswararao et al., 2014). Sridhar et al. (2024) reported the presence of MPs in human placental tissues and suggested that their occurrence may be associated with processes involved in the development of preeclampsia. More recently, Nihart et al. (2025) reported substantial quantities of plastic particles, particularly polyethylene, in human brain tissues, with many particles appearing as nanoscale fragments under electron microscopy, indicating that plastic particles may reach and persist within sensitive biological tissues. Beyond their physical presence, MPs and NPs may induce oxidative stress, inflammation, cellular damage, and disturbances in physiological and biochemical processes, while their ability to adsorb and transport environmental contaminants may further increase their potential toxicity. Collectively, the increasing detection of microplastic and nanoplastic particles across organisms and human tissues demonstrates the widespread nature of plastic contamination and underscores their ecological and human-health implications.

Management of microplastic pollution

- Enhancing public awareness, stakeholder participation, and circular economy practices to improve plastic resource efficiency and reduce environmental contamination.
- Strengthening municipal solid waste collection, segregation, and recycling systems to prevent plastic leakage into aquatic ecosystems.
- Developing advanced recycling technologies and chemical depolymerization methods to recover plastics and convert them into reusable raw materials.
- Reforming aquaculture practices by reducing the use of plastic-based feed packaging, nets, ropes, and pond liners, and adopting environmentally sustainable materials.
- Establishing stringent regulations, regular monitoring programs, and effective policy frameworks to control microplastic emissions from industrial, agricultural, urban, and wastewater sources.

Conclusion

Microplastic pollution has emerged as a pervasive environmental challenge driven by the extensive production, consumption, and improper disposal of plastic materials. Their persistence, widespread distribution, and fragmentation into increasingly smaller particles have resulted in contamination of marine, freshwater, and terrestrial ecosystems worldwide. Microplastics are readily ingested by aquatic organisms, facilitating bioaccumulation and trophic transfer while acting as vectors for toxic contaminants and pathogenic microorganisms. Their occurrence in seafood and other food products highlights potential risks to human health, although the long-term consequences remain underreported. Addressing this growing threat requires integrated strategies, including reduced plastic consumption, improved waste management and recycling techniques, development of sustainable alternatives, and continued research to understand the ecological and human health impacts of microplastics.

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