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Review Article

MP Pollution and its Biological Impact on Aquatic Fauna

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ABSTRACT

This review examines the origin, categorization, distribution and biological effects of MPs (MP) on aquatic life. Because of their synthetic polymer makeup, MPs are categorized as primary (manufactured) or secondary (degraded plastics). They enter the ecosystem through atmospheric deposition, wastewater discharge, and urban runoff. MPs have the potential to cause trophic transfer, oxidative stress, physical harm, and endocrine disruption in aquatic organisms. Humans and other higher trophic levels may be impacted by bioaccumulation. This review examines the ecological, histological, and physiological effects of MPs, including impaired ecosystem interactions, decreased nutrition, and reproductive failure, based on recent research. In order to address this urgent environmental issue, the review identifies important research gaps and looks at mitigation techniques like biodegradable substitutes, laws, and better wastewater treatment. It emphasizes the necessity of interdisciplinary approaches and standardized procedures.

INTRODUCTION

The contamination of aquatic ecosystems by microplastics (MPs) has become a significant environmental concern in the Anthropocene (Hale *et al.*, 2020). These particles, composed of synthetic polymers and smaller than 5 mm, can accumulate in water bodies, posing serious risks to aquatic organisms (Frias and Nash, 2019). MPs enter aquatic ecosystems through various channels, exposing organisms to diverse biological stressors (Koelmans *et al.*, 2022). There are two main types of MPs. Primary MPs are made on purpose to be used in cosmetics, personal care products, and industrial abrasives (Jaikumar *et al.*, 2019; Song *et al.*, 2024). Secondary MPs, on the other hand, form when larger plastic debris gradually breaks down through biological activity, mechanical abrasion, and photochemical weathering (Laskar and Kumar, 2019; Lehtiniemi *et al.*, 2018). These particles resist natural biodegradation due to their synthetic polymer composition, which allows them to persist in the environment for extended periods of time and accumulate over several decades across food webs and geochemical cycles (Filella, 2015; Kum *et al.*, 2025). MPs get into water bodies through a mix of human activities and natural movements of water (Rochman, 2018). City runoff, untreated sewage, and particles falling from the air are the main ways they reach rivers and oceans. Most MP pollution comes from land-based sources (Hale *et al.*, 2020; Kay *et al.*, 2018) (Fig. 1).

Some MPs, called secondary MPs, form when plastic waste breaks into smaller pieces. Rivers can carry these pieces into the ocean, where sunlight and waves break them down even more (Kum *et al.*, 2025). These tiny

Abbreviations
DNA, Deoxyribonucleic Acid; IL-1β, Interleukin-1 beta; IL-6, Interleukin-6; MPs, icroplastics; NF-κB, Nuclear Factor kappa-light-chain-enhancer of activated B cells; NLRP3, NLR Family Pyrin Domain Containing 3 (a type of inflammasome); Nrf2-Keap1, Nuclear factor erythroid 2–related factor 2 - Kelch-like ECH-associated protein 1 (a cellular defense pathway); PCBs, Polychlorinated Biphenyls; PET, Polyethylene Terephthalate; PHA, Polyhydroxyalkanoate; PLA, Polylactic Acid; POPs, Persistent Organic Pollutants; PVC, Polyvinyl Chloride; REACH, Registration, Evaluation, Authorisation and Restriction of Chemicals (an EU regulation); StAR, Steroidogenic Acute Regulatory Protein; TNF-α, Tumor Necrosis Factor-alpha; µFTIR, Micro-Fourier Transform Infrared Spectroscopy.

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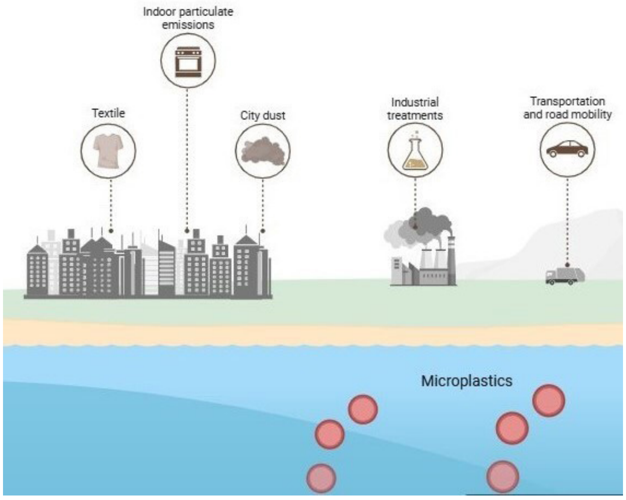

Fig. 1. Sources of MPs. Environmental origins contributing to MP pollution.

plastics are now found in the most remote places, including deep-sea sediments and Arctic ice, showing just how persistent and widespread they are (Ivleva *et al*., 2017). Aquatic animals often ingest MPs, which is one of the main ways these particles enter the food chain (De Sá *et al*., 2018; Jovanović, 2017). Animals of all sizes, from small filter-feeding invertebrates to large predators, can eat MPs by accident. This happens because the particles are tiny (1 µm–5 mm), appear in many shapes like fibers, fragments, and microbeads, and are present throughout aquatic environments (Galafassi *et al*., 2021; Lehtiniemi *et al*., 2018). MPs can harm animals in different ways. Chemicals they carry, such as plasticizers, flame retardants, and pollutants they pick up, can get into tissues and cause mild toxic effects. They can also physically harm the animals, causing blocked intestines, internal scratches, or a false sense of fullness, which can lead to starvation (Bhuyan, 2022). Over time, long-term exposure can weaken immune systems, affect reproduction, and interfere with hormones in fish, mollusks, and crustaceans (Chen *et al*., 2022; Jaikumar *et al*., 2019). Top predators often end up with more MPs because of what they eat. As these plastics move through the food chain, they can build up over time and become more concentrated, which is a serious concern for the health of these animals and the ecosystem (De Sá *et al*., 2018).

MP pollution can change how ecosystems work and how different groups of organisms interact, not just affecting individual species. These effects happen in many ways and can influence the balance of entire aquatic communities (Issac and Kandasubramanian, 2021; Rakib *et al*., 2023). High amounts of MPs in the water can reduce light penetration and make it harder for plants and algae to perform photosynthesis, which may lower overall primary productivity (Sharma and Chatterjee, 2017). MPs can also help spread invasive species, harmful algae, and disease-causing microbes, acting as surfaces and carriers for these organisms (Galafassi *et al*., 2021; Ivleva *et al*., 2017). With climate change and other human pressures potentially making these effects worse, we still do not fully understand the combined impacts of MPs on aquatic ecosystems (Issac and Kandasubramanian, 2021). Plastic production is increasing every year, and as these plastics break down into tiny pieces, they end up in water and ecosystems (Hale *et al*., 2020; Koelmans *et al*., 2022). Plastics are becoming more common in the environment, and tiny pieces of plastic end up in rivers, lakes, and oceans. People are noticing this problem more, but we still do not fully understand how these small plastics affect fish, plants, and even humans over time (Rochman, 2018). To protect the environment, it is important to have reliable ways to find these plastics, study what they do, and figure out the risks (Hidalgo-Ruz *et al*., 2012). Understanding how they affect aquatic life means looking at different areas at once, like pollution, water systems, animal health, and materials science (Ivleva *et al*., 2017; Kum *et al*., 2025). When we look at aquatic animals, it is clear that tiny plastics can cause problems, even if we do not know all the details yet. Paying attention to these effects also shows us where more research is needed and can help guide future studies and ways to manage plastics in the environment (Gola *et al*., 2021; Rakib *et al*., 2023).

CLASSIFICATIONANDCHARACTERISTICS OF MPS

Size, shape, and polymer types

MPs come in many different shapes and sizes, which affects how they move and settle in the environment. The tiniest of these, called nanoplastics, are so small that they are almost invisible and behave more like particles in a colloid, while larger fragments are easier to see (Rodríguez-Seijo and Pereira, 2017). The different sizes of MPs affect basic behaviors like how they sink, how they reflect light, and how they interact with aquatic animals (Kooi and Koelmans, 2019). Their shapes also influence how they behave in the environment. In freshwater systems, fibrous particles are the most common, mainly coming from textile shedding and laundry wastewater, and they often have long, thin shapes (Ali *et al*., 2024). In contrast, marine habitats tend to have more irregularly shaped particles because larger plastic debris breaks down over time (Shim *et al*., 2018). Laboratory studies with model organisms have shown that the shape of MP particles can strongly influence how animals feed and how efficiently they ingest these particles (Lehtiniemi *et al*., 2018). Looking at the types of plastics helps us understand where pollution comes from. Polyethylene and polypropylene are seen almost everywhere, probably because so much of these plastics is made for packaging (Gündoğdu, 2022). When we look closer at different regions, polystyrene shows up more near cities and coasts than in the open ocean (Digka *et al*., 2018).

Chemical properties and bioavailability

MPs are made up of complex chemical mixtures and can pick up contaminants in several ways. During production, manufacturers often add substances like flame retardants, which help prevent fires, and plasticizers, which make the plastic more flexible (Beiras *et al*., 2021). Once in the environment, factors like water conditions and the type of plastic influence how quickly these chemicals are released into aquatic habitats (Yu *et al*., 2024). MPs can pick up contaminants because of the way their surfaces interact with the environment. As these particles stay in water, they attract and hold hydrophobic chemicals from nearby sources, which makes them even better at gathering pollutants (Wang *et al*., 2021). This is particularly important for persistent organic pollutants, which tend to stick strongly to plastics (Tang *et al*., 2022). When aquatic animals come into contact with these plastics, the chemicals can interfere with their hormones and harm reproduction, posing serious risks to their health (Chen *et al*., 2019). MPs last a long time in the environment because their plastic backbones are man-made and do not break down easily. Complete mineralization is still very uncommon in aquatic environments, even if photodegradation and mechanical weathering gradually break up particles (Xiong *et al*., 2022). Instead of eliminating them, this results in constant size reduction, which over time produces particles that are more bioavailable (Maddison *et al*., 2023). Across trophic levels, bioavailability patterns show a definite size dependence. From filter feeders to visual predators, a variety of creatures can more easily consume smaller particles (Botterell *et al*., 2019). By changing their physical and chemical cues to resemble natural food sources, surface alterations brought about by biofilm growth greatly improve particle ingestion (Kalčíková, 2023).

OCCURRENCE AND DISTRIBUTION OF MPs IN AQUATIC ECOSYSTEMS

According to (Xiong *et al*., 2022), MPs are found in freshwater habitats all over the world, and their distribution patterns are greatly impacted by both human activity and natural hydrology. In linked water systems, aquaculture activities dramatically increase MP concentrations by three to five times when compared to natural circumstances (Xiong *et al*., 2022). Lakes have distinctive accumulation zones that are influenced by their hydrodynamic properties and water retention periods (D'Avignon *et al*., 2022), whereas rivers have noticeable MP hotspots close to cities and wastewater outfalls (He *et al*., 2020). How MPs settle in water depends on layers in the water and seasonal changes (Gunaalan *et al*., 2024). In the sediments at the bottom, biofilms can trap more MPs, increasing retention by about 38–42%, especially where the sediment has a lot of organic matter (Wang *et al*., 2022). Coastal areas act as final collection points for MPs. They are important zones where plastics from land meet the ocean (Strafella *et al*., 2021).

Near cities, the amount of MPs in coastal waters can be four to seven times higher than in less developed areas. This is closely linked to how much the coast has been built up (Jang *et al*., 2020). The water column has layers where MPs settle differently, depending on the type of plastic and the growth of biofilms (Choy *et al*., 2019). While sediments along coasts store many MPs, the accumulation of floating plastics in open ocean gyres is affected by organic matter in the water and the movement of surface currents (Shim *et al*., 2018).

Sediments act as long-term storage areas for MPs. How the particles settle depends on water movement and the characteristics of the plastics themselves (Bellasi *et al*., 2020). In rivers, the amount of MPs is closely linked to organic matter, which suggests that similar processes control their deposition (He *et al*., 2020). Most particles eventually move downstream, but strong water flows can temporarily lift them back into the water (Xia *et al*., 2021). The growth of biofilms at the boundary between sediment and water can move MPs between different layers. At the same time, the water surface remains very dynamic because of animal activity and wind (Pasquier *et al*., 2023; Wang *et al*., 2022). To measure MP concentrations accurately, careful sampling is needed to account for these changing conditions (Razeghi *et al*., 2021).

Freshwater and marine systems have different patterns of MP pollution. Rivers are key pathways, carrying plastics from land to the ocean (Luo *et al*., 2019). In Asia, rivers contribute about 86% of the world's plastic inputs to the seas, which is a very large share (Tang *et al*., 2023). Differences in MP types between regions are linked to local waste management, industrial activity, and water conditions (Jiang, 2018). In tropical areas, strong sunlight can break down plastics more quickly (Atugoda *et al*., 2020). Using standardized methods is still important to make sure measurements are accurate across different environments (Li *et al*., 2021).

INGESTION AND BIOACCUMULATION OF MPs IN AQUATIC FAUNA

Ingestion of MPs by fish

Fish can take in MPs in different ways, depending on what they eat and where they live (Jovanović, 2017). Some plastics look or move like the fish's normal food. Visual predators, such as bass (*Micropterus salmoides*) and perch (*Perca fluviatilis*), may eat these plastics on purpose (Lusher *et al*., 2020). Microbes can grow on plastic surfaces and produce chemical signals that make the plastics seem even more like food, which increases the chance of fish eating them by mistake (De Vries *et al*., 2020).

MPs can also enter fish by accident during normal feeding or when water flows over their gills. This is called passive ingestion (Sacco *et al*., 2024). Fish that live near cities or areas with wastewater discharge usually have more MPs in their bodies compared to fish that live farther out in open waters (Wootton *et al*., 2021). The distribution of polymers reflects global output, with polyethylene accounting for 42%, polypropylene for 31%, and PET for 18% (Wootton *et al*., 2021). Nanoplastics (less than 1 µm) have been found in hepatic tissues using sophisticated detection techniques as Raman microscopy and µFTIR spectroscopy, suggesting a systemic dispersion outside of the digestive tract (Jovanović, 2017). Figure 2 illustrates the exposure of fish to MPs through gills and gut ingestion.

MP uptake in amphibians

Because amphibians have complex biphasic life cycles, they are especially susceptible to MP pollution (Boyero *et al*., 2020). During filter-feeding, aquatic larval stages consume particles; tadpoles exhibit a preference for consuming 80-200 µm MPs that correspond to their gape size and feeding current velocities (Burgos-Aceves *et al*., 2022). Both larvae and adults' porous integument promotes dermal uptake, especially for nanoplastics that are able to cross cutaneous barriers (Szkudlarek *et al*., 2024). According to research on chronic exposure, MPs build up in digestive tracts and interfere with hormones to cause metamorphic processes to be disrupted (Rahman *et al*., 2024). Superoxide dismutase and catalase activity, two indicators of oxidative stress, sharply rise after exposure, suggesting cellular harm from plastic additives and adsorbed pollutants (Burgos-Aceves *et al*., 2022). Due to their comparatively sluggish metabolic clearance rates, several species of adult frogs store MPs for lengthy periods of time, and they continue to acquire them through their diet and the environment (Hou and Rao, 2022). As shown in Figure 2, tadpoles experience endocrine disruption due to MP accumulation.

MP ingestion in mollusks and crustaceans

Because of their extensive range and effective filter-feeding processes, bivalve mollusks are useful bioindicators for MP contamination (Ding *et al*., 2022). Large amounts of water are processed by mussels (*Mytilus* spp.) and oysters (*Crassostrea* spp.), which passively concentrate MPs that are then stored in digestive glands (Wang *et al*., 2021). Within hour of ingestion, MPs smaller than 100 µm can penetrate intestinal epithelial barriers and enter circulatory systems, according to particle translocation studies (Ding *et al*., 2022). MPs physically occupy the space of the digestive canal, these exposure paths frequently result in misleading satiation signals and poor food absorption (Prata *et al*., 2023). Different species have significantly different depuration rates, some bivalves remove over 90% of particles in 72 h, while others hold onto MPs for weeks (Wang *et al*., 2021). Figure 2 further illustrates MP retention in mollusks digestive tissues and impaired digestion in crustaceans.

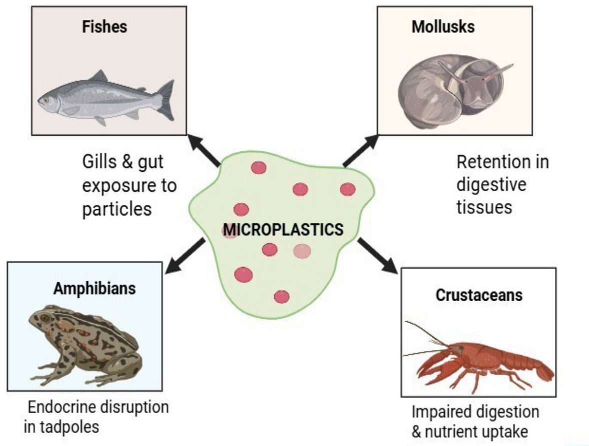

Fig. 2. Ingestion by aquatic fauna. Pathways of MP uptake in aquatic organisms.

Bioaccumulation and trophic transfer

MPs distribute differentially across tissues and organ systems according to particle characteristics and organism physiology (Miller *et al*., 2020). Chemical additives including plasticizers and stabilizers leach from MPs under physiological conditions, with release rates accelerated by gut acidity and enzymatic activity (Franzellitti *et al*., 2019). Retention times vary phylogenetically, reflecting fundamental differences in digestive system morphology and metabolic rates (Li *et al*., 2021). Bivalves generally retain MPs longer than fish due to more efficient particle sequestration in digestive glands (Hou and Rao, 2022).

Predator-prey relationships allow MPs to spread across food webs (Au *et al*., 2017). Particles introduced by primary consumers cause higher trophic species to biomagnify (McHale and Sheehan, 2024). The adsorptive properties of MPs enhance their role as vectors for hydrophobic contaminants, creating complex exposure scenarios that vary across ecosystem types (Au *et al*., 2017). Through species that live in sediment, benthic channels demonstrate effective transmission (O'Connor *et al*., 2022). The highest trophic retention rates are found in fibers (McHale and Sheehan, 2024). Transfer is very effective in deep-sea food webs (O'Connor *et al*., 2022). These processes may have cascading effects on ecosystem structure and function through impacts on keystone species and trophic interactions (McHale and Sheehan, 2024).

PHYSIOLOGICAL AND HISTOPATHOLOGICAL EFFECTS OF MPS IN AQUATIC FAUNA

Tissue-specific pathologies and systemic effects

When aquatic creatures are subjected to MPs, their branchial systems gradually deteriorate (Xing *et al*., 2023). Gill filaments exhibit epithelial lifting at first, which eventually progresses to full lamellar fusion. Both chemical irritation from leached plastic additives and physical abrasion from particle surfaces cause this structural degradation (Wang *et al*., 2022). In response, the respiratory epithelium secretes large amounts of mucus, usually two to three times the normal amount (Bhagat *et al*., 2020). This results in notable diffusion barriers that reduce the effectiveness of oxygen intake. Chloride cells exhibit substantial ciliary damage and mitochondrial enlargement, according to ultrastructural investigations (Zhang *et al*., 2024). Important osmoregulatory processes are interfered with by these alterations.

Damage to intestinal tissues shows a clear development. In situations involving prolonged exposure, this starts with microvilli shortening and progresses to total villous atrophy (Rakib *et al*., 2023). Tight connection protein structure between enterocytes gradually degrades. This results in elevated intestinal permeability and possible systemic absorption of poisons (Subaramaniyam *et al*., 2023). Histological analyses reveal a significant infiltration of leukocytes in the lamina propria. Phagocytosed MP particles are seen in many macrophages (Jeyavani *et al*., 2023). Hepatic disease presents as a series of metabolic abnormalities that change during the course of exposure (Patra *et al*., 2022). In situations involving extended exposure, initial steatosis develops into lobular inflammation and, ultimately, periportal fibrosis. Hepatocytes show megamitochondria production and a progressive build-up of lipofuscin granules, persistent oxidative stress is indicated by both (Pirsaheb *et al*., 2020). The hepatic stellate cell population gets activated, They become myofibroblasts, which spread extracellular matrix components all across the liver parenchyma (Hu *et al*., 2023).

Molecular stress pathways and cellular dysfunction

When mitochondrial electron transport chains are disrupted, the oxidative cascade starts. Significant amounts of superoxide radicals are produced as a result (Osman *et al*., 2023). Large-scale lipid peroxidation chain events are started by these reactive oxygen species. They specifically target cellular membrane polyunsaturated fatty acids (Jewett *et al*., 2022). Reactive aldehydes are created as a result, including malondialdehyde and 4-hydroxynonenal. These produce long-lasting protein adducts that impair the integrity of the cytoskeleton and prevent essential enzymes from functioning (Bilal *et al*., 2023).

Phase II detoxification enzymes are coordinately upregulated in cellular antioxidant responses, the Nrf2-Keap1 signaling pathway is responsible for this (Sussarellu *et al*., 2016). But these defenses are eventually overpowered by long-term exposure to MPs (Uguen *et al*., 2025). As a result, the thioredoxin system eventually collapses due to significant glutathione depletion. Eight-oxoguanine lesions and strand breaks are signs of oxidative damage to DNA, they are especially concentrated in tissues that are metabolically active (Prinz and Korez, 2020).

Pattern recognition receptors are activated to start inflammatory reactions, these consist of the NLRP3 inflammasome complex and Toll-like receptors (Egbeocha *et al*., 2018). NF-κB is translocated to the nucleus by subsequent signaling cascades (Mason *et al*., 2022). Pro-inflammatory cytokines such TNF-α, IL-6, and IL-1β are significantly released as a result (Mason *et al*., 2022). Different macrophage activation characteristics are caused by persistent inflammation, it also results in widespread fibroblast proliferation (Gola *et al*., 2021). Tissue fibrosis is caused by these factors taken together.

Reproductive and developmental toxicity

Multiple parallel processes lead to endocrine dysregulation. These consist of inhibition of aromatase, competitive receptor binding, and suppression of several steroidogenic enzymes (Corinaldesi *et al*., 2021). There is a change in the pulsatility of gonadotropin-releasing hormones in the hypothalamic-pituitary axis (Lusher *et al*., 2020). As a result, gonadotropin secretion patterns are disrupted. Numerous metabolic processes are compromised in steroidogenesis, these include 17β-hydroxysteroid dehydrogenase activity and StAR-mediated cholesterol transfer (Cera and Scalici, 2021).

Accelerated atresia rates are seen in ovarian follicles. Alongside this, there is aberrant zona pellucida development and decreased vitellogenin uptake (Kaloyianni *et al.*, 2021). Numerous pathological alterations are indicative of testicular injury, these include impaired blood-testis barrier integrity, Sertoli cell vacuolization, and germ cell death (Hou and Rao, 2022). Asynchronous development patterns are common in spermatogenic phases, the frequency of aberrant sperm morphology has increased (Honda and Suzuki, 2020). Transgenerational effects result from germ cell epigenetic reprogramming, many generations are affected by these (Yin *et al.*, 2022). Stable alterations in DNA methylation at imprinted sites are among the consequences . Additionally, histone modification patterns are continuously changing and small RNA profiles undergo significant changes (Xie *et al.*, 2021). These epigenetic changes significantly change the course of an offspring's development, even when there is no direct exposure to MPs, this still happens.

Organismal and ecosystem impacts of MPs

MPs use a variety of stress pathways to significantly limit population persistence and organismal growth. During crucial growth times, intestinal blockage and poor nutrition absorption cause developmental bottlenecks in larval stages (Uy and Johnson, 2022). Reduced size-at-age results from disruption of skeletal development and protein metabolism, which changes juvenile growth trajectories (De Sá *et al.*, 2018). Resources from somatic development are diverted when cellular stress responses trigger energetically expensive detoxification pathways (Wright *et al.*, 2013). Climate change intensifies these physiological effects by raising metabolic rates and MP toxicity (Prokić *et al.*, 2019). Through a combination of physical and biological mechanisms, MP contamination causes systemic alterations in the way aquatic ecosystems function. As bioturbation rates decrease, benthic-pelagic connection is disrupted, impacting nutrient transport across sediment-water interfaces (Mason *et al.*, 2022). Reduced filter-feeder activity modifies particulate organic matter export and changes carbon cycling (Wright *et al.*, 2013).

When coupled with additional stressors like eutrophication and climate change, these functional alterations may cause regime shifts in the status of the ecosystem (Du *et al.*, 2021). According to long-term monitoring, these consequences are getting worse as the amount of MP pollution in the world keeps rising (Issac and Kandasubramanian, 2021). Because MPs disrupt both optical and chemical threat assessment systems, prey species exhibit weakened antipredator responses (Savoca *et al.*, 2021).

MPS AND CHEMICAL POLLUTANTS IN AQUATIC ECOSYSTEMS

Adsorption dynamics of heavy metals and persistent organic pollutants

MP surfaces display substantial adsorption capacities for both heavy metals and persistent organic pollutants (POPs) due to their hydrophobic qualities and high surface area-to-volume ratios (Bayo *et al.*, 2018). The way MPs attract contaminants depends on the type of plastic. Polyethylene and polypropylene tend to attract nonpolar pollutants, such as polychlorinated biphenyls (PCBs), more strongly. Polyvinyl chloride (PVC), on the other hand, picks up more heavy metals, like lead and cadmium (Zhu *et al.*, 2023). Environmental factors, such as pH, salt levels, and dissolved organic matter, also affect how well contaminants stick to plastics. For example, lower pH can make metals attach more easily to the plastic surface (Liu *et al.*, 2021). Over time, MPs change due to sunlight and mechanical wear. This aging process makes their surfaces more porous and adds oxygen-containing groups, which help them bind more contaminants (Brennecke *et al.*, 2016). Because of this, MPs can carry pollutants from rivers to the sea, acting as transporters in estuarine ecosystems (Bakir *et al.*, 2014). Microbes can grow on plastic surfaces, and this changes how chemicals stick to the plastics. The sticky substances made by the microbes, called extracellular polymers, help some pollutants attach more easily (Gilewski *et al.*, 2025).

Combined toxic effects on aquatic animals

When fish and other aquatic animals eat MPs carrying pollutants, the effects can be worse than with either the plastic or chemicals alone. These combined exposures can harm their health in several ways. Because of their altered speciation and extended retention in digestive systems, heavy metals linked to MPs exhibit higher toxicity (Chen *et al.*, 2023). MPs hinder organisms capacity to digest co-occurring chemical pollutants by interfering with detoxification enzymes such cytochrome P450 at the cellular level (Avio *et al.*, 2015). By producing reactive oxygen species, the presence of MPs intensifies oxidative stress reactions to contaminants, increasing lipid peroxidation and DNA damage (Vo and Pham, 2021). Larval fish display developmental defects and lower survival rates, indicating that early life stages are especially sensitive to these combined exposures (Botterell *et al.*, 2019). When the reported toxicity surpasses the sum of the effects of the individual components, the combined effects frequently exhibit non-additive patterns (Marchant *et al.*, 2022). These interactions differ between species, with benthic invertebrates and filter-feeding organisms responding most strongly to MP-chemical combinations (Scherer *et al*., 2017).

Ecological consequences of MP-mediated contaminant transport

Through special transport mechanisms, MPs change the temporal and geographical distribution of contaminants in aquatic environments. Many plastics are buoyant, which makes it easier for absorbed pollutants to travel horizontally over large distances across ecosystem boundaries (Gateuille and Naffrechoux, 2022). Pollutants are transferred from surface waters to benthic sediments through vertical transport, which happens when biofouled particles lose their buoyancy (Haque and Fan, 2023). By creating novel exposure pathways through ingestion and direct touch, MPs alter established contamination pathways in freshwater systems (Lambert and Wagner, 2018). Since MPs avoid conventional sedimentation processes and keep pollutants in biologically active zones, marine habitats undergo altered pollutant cycling (Amelia *et al*., 2021). In contaminated locations, the contaminant load carried by MPs frequently accounts for a sizable portion of the overall pollutant burden (Rodrigues *et al*., 2019).

When MPs move through an ecosystem, they can change which animals and plants live there. The species that can handle pollution survive, while others may disappear (Rakib *et al*., 2023). Sometimes, MP levels rise suddenly because of seasonal changes. These spikes can make it harder for the ecosystem to bounce back after being disturbed (Lambert and Wagner, 2018).

HUMAN HEALTH IMPLICATIONS VIA AQUATIC FOOD CHAINS

Trophic transfer and bioaccumulation dynamics

Zooplankton and small filter-feeding animals play a key role in bringing MPs into the ocean food chain because they eat almost anything in the water (Miller *et al*., 2020). Plastics can attract harmful chemicals from the water, creating mixtures of pollutants that can build up as they move through the food chain (Carbery *et al*., 2018). Studies show that meat-eating fish tend to have more MPs in their bodies than plant-eating fish (McIlwraith *et al*., 2021). Some shellfish, like mussels and oysters, filter water directly and remove MPs very efficiently (Van Raamsdonk *et al*., 2020). Bioaccumulation patterns vary significantly among aquatic habitats due to ecosystem-specific characteristics such as hydrology, sedimentation rates, and community structure (O'Connor *et al*., 2022). Understanding the flow of MPs through food webs has improved due to recent developments in stable isotope analysis, which have shown surprising paths such as detrital feeding routes (Li *et al*., 2023).

Seafood contamination and human exposure pathways

MP contamination is very ubiquitous in commercial seafood, according to market surveys; contamination levels in farmed and wild-caught seafood are similar (Fig. 3, Smith *et al*., 2018). Bivalves have the highest particle concentrations due to their filter-feeding ecology and extensive whole-body consumption; oysters have far greater levels of MPs than do crustaceans or finfish (Ding *et al*., 2022). Seafood from urbanized estuaries has higher particle loads, indicating that coastal proximity is a significant factor of pollution levels, according to geographic study (Danopoulos *et al*., 2020).

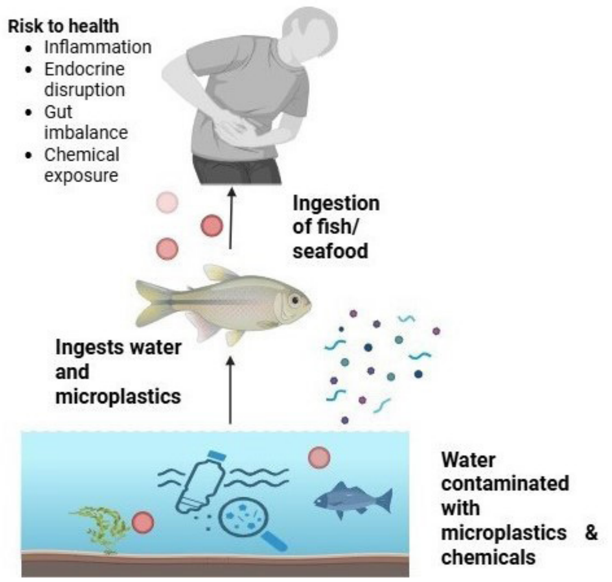

Fig. 3. Human health implications. Risks from seafood consumption contaminated with MPs.

Multiple paths of seafood intake expose humans, but raw or little processed goods are more dangerous since there is less particle removal during preparation (Garrido *et al*., 2020). MPs digestive bioavailability differs depending on the kind of polymer; bigger polystyrene particles have less intestinal absorption capacity than polyethylene and polypropylene (Unuofin and Igwaran, 2023). High-temperature preparations increase the leaching of plastic additives while perhaps lowering particle burdens, demonstrating how cooking techniques affect the transfer of contaminants (Vital *et al*., 2021).

Health risk assessment and research priorities

Chronic exposure to MPs may have negative health effects, such as inflammatory reactions and cellular damage processes, according to toxicological research (Alberghini *et al*., 2022). Particulate plastics and adsorbed pollutants may interfere with endocrine function, which might have a negative impact on reproductive and developmental health outcomes (Santonicola *et al*., 2023). Although there are currently few human research, there is growing evidence that MPs may change the makeup of the gut microbiota and the function of the intestinal barrier (Hantoro *et al*., 2019). Understanding long-term, low-dose exposure effects and possible synergistic interactions with other environmental stressors remains a critical research need (De-la-Torre, 2020). Standardizing testing procedures for nanoplastics and creating biomarkers for evaluating human exposure are two methodological problems (Ricciardi *et al*., 2021).

In order to stop MPs from entering aquatic environments, risk management techniques are placing a greater emphasis on source reduction and enhanced wastewater treatment (Bellasi *et al*., 2020).

CURRENT MITIGATION STRATEGIES FOR MP POLLUTION

Wastewater treatment upgrades and removal technologies

The removal efficiency of conventional wastewater treatment plants vary; basic treatment stages remove 50–98% of particles through physical settling processes, with an average removal of ~80% across systems (Talvitie *et al*., 2017). By fusing physical filtration methods with biological degradation, advanced tertiary treatments like as membrane bioreactors and fast sand filtration attain removal rates of 95–99% (Bayo *et al*., 2020). Membrane technologies are especially promising; using size-exclusion principles, ultrafiltration devices can efficiently capture particles as small as 10 nm (Yang *et al*., 2021). By causing particle aggregation through charge neutralization, emerging electrochemical techniques improve removal efficiency and make it simpler to separate from wastewater streams (Corpuz *et al*., 2024). Adaptive treatment techniques are necessary due to seasonal differences in MP burdens; studies have shown that sophisticated systems work consistently under varying influent circumstances (Iordachescu *et al*., 2024). Alum and ferric chloride-based natural coagulation techniques have the potential to be economical ways to remove MPs in environments with limited resources (Reza *et al*., 2023).

Public awareness campaigns and policy frameworks

The general public's awareness of MP pollution is still uneven, with coastal towns showing higher levels of awareness than inland ones (Omoyajowo *et al*., 2022). To improve risk perception, effective communication tactics include visual examples of MP deposition in common seafood items (Henderson and Green, 2020). Programs for environmental education at the university level greatly increase understanding of the causes of MPs and ways to prevent them (Janoušková *et al*., 2020). The European Union has implemented extensive restrictions on primary MPs in cosmetics through REACH rules, however there are significant differences in international policy responses (Lam *et al*., 2018). Localized restrictions on single-use plastics are becoming more common in developing countries, however their implementation is difficult because of inadequate waste management infrastructure (Usman *et al*., 2022). In order to encourage the reduction of plastic trash at the source, new legislative strategies center on extended producer responsibility programs (Munhoz *et al*., 2022).

Biodegradable alternatives and sustainable materials

While retaining the material qualities required for packaging applications, bioplastics made of polylactic acid (PLA) and polyhydroxyalkanoate (PHA) show encouraging degradation patterns in marine settings (Acharjee *et al*., 2023). The production of biodegradable MPs during partial degradation and their possible ecological effects, however, continue to raise concerns (Wang *et al*., 2022). Biopolymers made from agricultural waste provide sustainable substitutes, cellulose-based materials exhibit the most potential for products with limited lifespans (Samer *et al*., 2022). Because some bioplastics demand large energy inputs and agricultural land for feedstock production, life cycle studies show complex tradeoffs (Atiwesh *et al*., 2021). The broad use of biodegradable substitutes in some applications is now hampered by performance limits in mechanical strength and moisture barrier qualities (Cruz *et al*., 2022). Ongoing material science innovations focus on improving the marine degradation rates of bioplastics while maintaining functional durability during product use (Ali *et al*., 2023). Regulatory frameworks must evolve to distinguish between truly compostable materials and conventional plastics marketed as biodegradable without proper certification (Prata *et al*., 2019).

RESEARCH GAPS AND FUTURE DIRECTIONS IN MP STUDIES

Knowledge gaps

Understanding of long-term ecological effects is limited by the paucity of longitudinal studies investigating the effects of chronic, multigenerational MP exposure in current research (Issac and Kandasubramanian, 2021). The majority of lab investigations use brief exposures that last a few weeks to months, but field research never lasts longer than one cycle every year. Comprehensive evaluation of ecosystem-level consequences and transgenerational effects is hampered by this temporal constraint (Rakib *et al*., 2023; Vo and Pham, 2021). Regarding population resilience and the possibility of recovery after extended exposure to MPs, there are still important knowledge gaps (Li *et al*., 2021). Current studies have significant taxonomic and regional biases. Despite their ecological sensitivity, tropical freshwater systems and polar marine settings are still significantly underrepresented in studies, which disproportionately concentrate on economically valuable species and temperate coastal ecosystems (Harris *et al*., 2021; Stanton *et al*., 2020). In studies on MPs, most attention goes to fish and marine mammals. Small animals, like insects and shellfish, are often ignored (Varg *et al*., 2022). Even creatures living on the ocean floor or in deep-sea habitats are rarely studied, even though MPs are present there (Nawaz *et al*., 2025).

Standardization needs

Scientists around the world agree that we need consistent ways to collect, process, and analyze MPs (Al-Azzawi *et al*., 2020). Right now, different labs use very different methods, such as how they digest samples, filter particles, or identify plastics with spectroscopy. These differences make it hard to compare studies or combine data (Sharma *et al*., 2024). To improve this, researchers suggest standardizing how we classify MP sizes, creating reference materials, and thinking about how environmental conditions affect measurements (Sharma *et al*., 2024). Special care is also needed when processing tissues, because some techniques can change the properties of MPs (Hermsen *et al*., 2018). Many experts recommend using multiple analytical methods but staying flexible so that each study can meet its own specific goals (Mitrano *et al*., 2023).

CONCLUSION

MP pollution is now one of the biggest environmental problems, affecting waters from the ocean surface down to deep-sea sediments. This review shows that different aquatic animals can suffer from ecological disruption, stress on their bodies, and even damage at the cellular level because of these tiny plastics. Eating seafood can also pose risks to humans, as harmful substances carried by MPs can move up the food chain and build up over time.Particularly in delicate arctic and deep-sea ecosystems, there are still significant knowledge gaps about long-term, intergenerational implications. Worldwide efforts to analyze and mitigate are hampered by the absence of standardized detection techniques. Innovation in biodegradable materials, strict international legal frameworks, and modern wastewater treatment must be integrated in a way never seen before in order to provide effective solutions. The magnitude of this problem necessitates quick, coordinated response from the public, business, and scientific sectors. Source reduction, better waste management, and consistent research investment are necessary to preserve aquatic biodiversity and provide food security. Despite the seriousness of the problem, this assessment confirms that the spread of MP contamination can be stopped by scientifically based remedies and a coordinated worldwide reaction. The time for serious action is now, as our window for meaningful involvement is closing.

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