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Review Article

Microplastics: The Unseen and Unavoidable Threat to Aquatic Environment and its Public Health Implications

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Abstract

Microplastics are pervasive contaminants in the ecosystems and have become a major concern for ecosystem integrity and public health. The rapid expansion of industrial activities, coupled with inadequate waste management and widespread plastic usage, has resulted in a substantial increase in microplastic pollution. Particles smaller than 150 μm penetrate the food chain, thereby leading to their accumulation and potential induction of adverse toxicological effects, including acute toxicity, chronic health impacts, carcinogenesis, developmental abnormalities and genotoxicity. Addressing this issue necessitates a sustainable framework focused on the reduction, reuse and recycling of plastic waste or using alternative materials in place of plastics to mitigate environmental microplastic burdens. However, despite increasing recognition of the problem, effective management strategies remain limited and this review provides an insight into the origin, source, effects and mitigation measures against the unseen and unavoidable menace of microplastic pollution in our dear environment. In parallel, the present work examines the potential for transforming plastic waste into value-added products, thereby offering a promising avenue to reduce environmental plastic accumulation while delivering sustainable societal benefits.

Key words: Microplastic, aquatic, environment, public health, carcinogenesis, toxicology

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INTRODUCTION

Microplastics are artificially produced solid particles consisting of polymer-based matrices, occurring in either uniform or irregular morphologies¹. Microplastics are commonly defined as plastic particles smaller than 5 mm in diameter. Their widespread presence in the environment arises from two major sources: The first comprising primary microplastics that are engineered to exist within this specified size range and secondary microplastics, formed through the physicochemical degradation or mechanical breakdown of larger plastic debris^{2,3}. Microplastics may enter aquaculture ecosystems via many pathways. Microplastics are polymer-based materials with uniform or irregular morphologies, particle sizes ranging from 1 μm to 5 mm, from primary manufacturing or secondary fragments and are characterised by their insolubility in water. They pose threats to human health and the environment because they have the ability to emit harmful substances into the air, water and food supplies⁴.

Microplastics enter natural ecosystems through diverse sources such as textiles, cosmetics, food packaging, construction and renovation materials and industrial processes, thereby contributing to environmental pollution. The designation 'microplastics' serves to distinguish these minute particles from larger plastic debris and they are broadly classified into two categories⁴ which include primary and secondary microplastics exhibit environmental persistence and are detected at elevated concentrations, especially in marine and other aquatic ecosystems; there, they constitute a major source of water pollution. An estimated 35% of oceanic microplastics originate from textiles, primarily through the release of acrylic, nylon and polyester fibers during laundering processes. In addition to aquatic systems, Microplastics are also deposited and accumulated in atmospheric and land-based environments⁵, Airborne microplastics have been identified across diverse indoor and outdoor environments, as well as in the broader atmosphere. Owing to the extremely slow degradation of plastics, often persisting for several hundred to thousands of years, microplastics exhibit a high inclination for ingestion and bioaccumulation, resulting in their incorporation and persistence within the bodies and tissues of a wide range of organisms⁵. Toxicants originating from marine environments and terrestrial runoff can undergo biomagnification through the food chain biomagnification of contaminants through trophic transfer within the food chain⁶. In terrestrial ecosystems, microplastics have been demonstrated to compromise soil ecosystem functionality⁶. As of 2023, the environmental pathways and transport dynamics of

microplastics remain only partially understood. Surface ocean surveys likely underestimate their abundance, as deep-sea sediment analyses in China have detected plastic particles within depositional layers that predate the onset of large-scale plastic production⁶. Microplastics are expected to undergo further fragmentation into nanoplastics through mechanical abrasion, chemical weathering and biological degradation, including digestive processes in animals. Nanoplastics, defined as particles smaller than 1 μm (1000 nm), represent a subset of microplastics that are not visually discernible to the naked eye⁷. Nanoplastics, owing to their nanoscale dimensions and heightened physicochemical reactivity, can traverse biological barriers, accumulate in animals and engage with cellular components, so presenting considerable and largely unexamined threats to ecosystem integrity and human health⁷. Despite increasing evidence of microplastic pollution, there is still a lack of understanding of their transport dynamics, accumulation patterns and toxicological impacts, particularly in terrestrial systems as opposed to aquatic ecosystems. This study aims to investigate the occurrence, distribution and environmental impact of microplastics in aquatic systems and to evaluate their potential implications for public health⁷.

Classification of microplastics: Microplastic fibres have been found in marine settings. In 2004, Professor Richard Thompson, a Marine Biologist at the University of Plymouth in the United Kingdom, coined the term "Microplastics"⁸. Microplastics are now widely distributed across diverse environmental compartments. In 2014, global ocean surveys estimated between 15 and 51 trillion microplastic particles, with a total mass ranging from 93,000 to 236,000 metric tonnes. Plastic breaks down into tiny pieces called microplastics or even nanoplastics when exposed to sunshine, wind, waves and other environmental conditions⁸.

Primary microplastics: Primary microplastics are deliberately manufactured plastic particles designed for specific applications. They are widely utilized in cosmetics, facial cleansers and air-blasting technologies and in rare cases have been employed in medicine as drug delivery vectors. Personal care formulations, including facial scrubs and exfoliating cleansers, increasingly utilize microplastic 'scrubbers' in place of traditional natural abrasives, including oats, pumice and powdered nut shells⁹. Primary microplastics have also been engineered for use in air-blasting applications, where microplastic particles composed of melamine, acrylic, or polyester are propelled against engines, boat hulls and machinery to facilitate the removal of rust and paint⁹. These

microplastic scrubbers, which are repeatedly employed until their size and abrasive capacity diminish, are frequently contaminated with heavy metals, including chromium, lead and cadmium. Despite corporate commitments to reduce microbead production, certain bioplastic microbeads, particularly those incorporated into cosmetics, remain persistent within environmental matrices due to their prolonged decomposition cycles⁹.

Secondary microplastics: Secondary microplastics are minute plastic fragments generated through mechanical wear and physicochemical degradation of larger plastic materials, occurring across marine and terrestrial environments¹⁰. Plastic waste undergoes progressive structural weakening through physical, biological and photochemical processes, particularly sunlight-induced photo-oxidation, ultimately producing particles undetectable to the eye. This progressive breakdown of larger plastics into smaller fragments is known as fragmentation¹⁰. Microplastics are believed to potentially disintegrate into smaller particles, yet in 2017, the smallest microplastic particle detected in oceanic samples was approximately 1.6 micrometres (6.3×10^{-5} in) in diameter. The occurrence of irregularly shaped microplastics indicates that fragmentation is a primary cause. Studies have shown that biodegradable polymers may produce greater quantities of microplastics than non-biodegradable polymers in both marine and freshwater environments¹⁰. Microplastic fibers are also released as by-products of the abrasion and laundering of synthetic textiles. Similarly, tires with a partial composition of synthetic styrene-butadiene rubber degrade during use, generating fine plastic and rubber particles that accumulate as dust¹¹. Plastic pellets with sizes ranging from 2.0 to 5.0 mm are commonly used as raw materials in plastic manufacturing, entering ecosystems primarily through accidental spillages and related release events. A 2015 review by the Norwegian Environment Agency suggested that these sources could be classified as primary microplastics when their release results directly from human activities at the point of initial material use, with the rate of release depending on the level of material and product use rather than from subsequent environmental fragmentation¹¹.

Nanoplastics: Nanoplastics are defined as particles measuring less than 1 μm (1000 nm) or fewer than 100 nm in size, depending on the specific definition employed. Speculations regarding nanoplastics in the environment vary from their classification as a transient result of microplastic fragmentation to their identification as an imperceptible environmental hazard with potentially

elevated and persistently increasing concentrations¹². Nanoplastics have been detected within the North Atlantic Subtropical Gyre and recent advances in analytical techniques such as atomic force microscopy-infrared spectroscopy (AFM-IR), nanoscale Fourier-transform infrared spectroscopy (nano-FTIR) and Raman spectroscopy integrated with optical tweezers (Raman Tweezers) provide promising approaches for future quantification of nanoplastics in environmental samples¹³.

Nanoplastic pollution poses a complex challenge, necessitating detailed investigation of their nanoscale properties and interactions with biomolecules, fundamentally, using methods offering enhanced spatial and temporal precision. These particles are increasingly acknowledged as significant threats to both environmental integrity and human health¹³. Owing to their nanoscale dimensions, nanoplastics are capable of crossing cellular membranes and altering cellular functions¹³. Their lipophilic nature facilitates interactions with lipid bilayers, with modeling studies suggesting that nanoplastics composed of polyethylene can integrate into the hydrophobic domain of these membranes. Nanoplastics have been shown to traverse the epithelial barriers in fish and bioaccumulate within multiple organs, including the pancreas, gallbladder and brain¹⁴. Evidence also suggests that they can interfere with bone cell function, potentially contributing to abnormal bone formation. Current knowledge on the detrimental biological effects of nanoplastics on organisms, including humans, remains limited. In *Danio rerio* (zebrafish), exposure to polystyrene-based nanoplastics has been shown to trigger stress response pathways, resulting in alterations in glucose and cortisol levels, which are likely associated with behavioral changes under stress conditions¹⁴. Nanoplastics are capable of adsorbing hazardous chemical pollutants, including antibiotics, thereby promoting their preferential interaction with antibiotic-resistant bacterial strains. This interaction facilitates simultaneous dispersion of antibiotic-resistant bacteria and nanoplastics through the soil via the bacterivorous nematode *Caenorhabditis elegans*¹⁵.

Exposure pathways: Airborne microplastics have been reported in diverse indoor and outdoor environments and are capable of long-range transport via atmospheric wind currents. A 2017 investigation reported that indoor airborne microfiber concentrations ranged from 1.0 to 60.0 fibers per cubic meter and approximately 33% were identified as microplastics¹⁶. A separate study investigating street dust in Tehran identified 2,649 microplastic particles across ten samples, exhibiting concentrations between

83 and 605 particles (± 10) per 30 g of dust. Microplastics and microfibers have been detected in atmospherically pure air at high-altitude regions and in snow samples far from their sources. As with freshwater and soil environments, additional research is required to comprehensively elucidate the impacts and environmental significance of airborne microplastics¹⁶.

Water: A growing concern in marine ecosystems is the prevalence of microplastic, which refer to plastic particles with diameters of less than 5 mm. These are frequently incorporated into cosmetic and personal hygiene formulations, including facial cleansers, hand soaps and other exfoliating formulations¹⁶. These microbeads pose substantial ecological risks to marine organisms, primarily filter-feeding species, which can readily ingest them and experience adverse health effects¹⁶. Following the use of such products, microplastics can bypass water filtration systems and enter marine environments, as their small size often allows them to evade detection by primary treatment screens in wastewater facilities. Microplastics pose a significant problem due to their diminutive size, which complicates cleanup efforts. Consequently, individuals can mitigate their impact by opting for products that utilise environmentally friendly exfoliants. Owing to the widespread global utilization of plastics, microplastics have proliferated in the marine ecosystem¹⁶. The occurrence of microplastics has been reported in various compartments of the marine environment, including sandy beaches, water columns, surface waters and deep-sea sediments. They coexist with various marine debris, including soil particles and dead organic matter (shells and tissues) dispersed by wind or transported into the ocean through riverine inputs¹⁶.

Ice cores: Plastic pollution has been reported in both surface waters and sediments of the Antarctic region and within Arctic Sea ice. In 2009, microplastics were first identified in the Antarctic Sea ice, based on analyses of an ice core retrieved from East Antarctica containing 96 particles representing 14 distinct polymer types. The large sizes of the particles identified in Antarctic Sea ice suggest the influence of a proximal contamination source¹⁶.

Freshwater: Microplastics have been extensively identified in global aquatic ecosystems. The earliest documented assessment of microplastic contamination within freshwater ecosystems, conducted in 2011, identified an average abundance of 37.8 particles per square metre within sediment samples collected from Lake Huron. Subsequent research has

documented the presence of microplastics across all of the Great Lakes, showing mean concentrations of approximately 43,000 particles/km²¹⁶. A three-year investigation in Canada reported an average microplastic concentration of 193,420 particles/km² kilometer in Lake Winnipeg. The microplastics identified were neither microbeads nor micro-pellets; instead, the majority consisted of fibres formed through the degradation of synthetic textiles and larger plastic materials, as well as via atmospheric deposition¹⁶. The highest recorded concentration of microplastics was detected in the freshwater system of the Rhine River, reaching 4,000 particles per kilogram¹⁶.

Watersheds: Researchers at Western Carolina University, Highlands Biological Station and Virginia Tech reported the occurrence of microplastics within the Richland Creek watershed in Western North Carolina. Ninety percent of the microplastics were fibres, primarily resulting from apparel, urban runoff and air deposition¹⁶.

Soil: Substantial accumulation of microplastics is expected in global soils; however, research on terrestrial microplastic pollution remains limited compared to aquatic systems. In wetland ecosystems, microplastic concentrations have been shown to inversely correlate with stem density and plant cover¹⁷. Fibrous secondary microplastics released from washing machines are hypothesised to enter soils, since wastewater treatment plants are incapable of completely removing all microplastic fibres. Geophagous soil organisms, including earthworms, mites and collembolans, can contribute to soil microplastic accumulation by mechanically and biologically fragmenting ingested plastic waste into secondary microplastics during digestion¹⁷. Additional research is, however, required. Concrete data establishes a connection between the utilisation of biological waste materials and the presence of synthetic fibres in the soil; nonetheless, the majority of studies on plastics in soil primarily document their existence without addressing their origin or quantity. Experimental studies on land-applied wastewater sludges (biosolids) containing fibres have shown that measurable quantities of fibres can still be recovered several years following application¹⁷.

Salt and seafood: Studies have shown that microplastic concentrations are considerably higher in sea salts than in rock or well salts, lake largely due to oceanic pollution, whereas contamination in rock and well salts is primarily introduced during processing steps such as collection, wind drying and

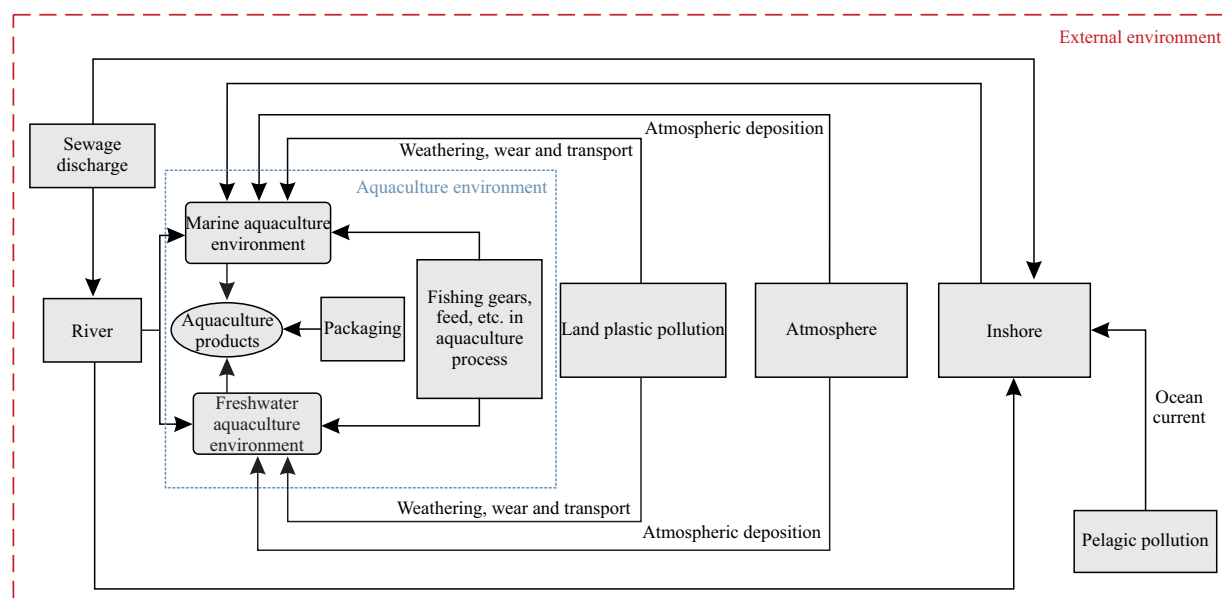


Fig. 1: Ways of Microplastics Introduced into Aquaculture Environments and Aquaculture Products¹⁹

packaging¹⁷. Research estimates that individuals who consume seafood may take in close to 11,000 microplastic particles annually¹⁷. In 2019, a study quantified microplastic contamination in common consumables, detecting 440 particles per kilogram of sugar, 110 particles per kilogram of salt and 94 particles per litre of bottled water¹⁷.

Composition of microplastics: Microplastics exhibits considerable heterogeneity. A 2023 study examining multiple fish taxa reported that approximately 80% of the microplastics identified were thread-like, primarily consisting of polyamide (10%), polyethylene (25%) and polyester (20%). The majority of particles were blue (27%) or black (61%)¹⁸. Microplastics comprise two distinct categories of compounds. “The first category consists of additives and fundamental polymeric materials, including monomers and oligomers¹⁸. By design, chemical additives are incorporated during the plastic manufacturing process to confer properties such as colour and transparency, while also enhancing product performance by increasing resistance to degradation from ozone, humidity, temperature fluctuations, microbial activity and light radiation, as well as improving mechanical, thermal and electrical stability. Microplastics embody additives including chemically inert or reinforcing filler materials, dyes, ultraviolet stabilizers, plasticizers, Fire retardant, antioxidants and lubricants, whereas another category of chemicals consists of compounds adsorbed from the external environment¹⁸.

Sources and origin of microplastics: Microplastic contamination is prevalent throughout global aquaculture systems and their derived products, exerting significant impacts on both. Microplastic sources in aquaculture are classified as external, derived from rivers, marine environments, terrestrial runoff and atmospheric deposition and internal, arising from aquaculture practices such as the Deterioration of fishing equipment and the feeding and packaging of cultured products. Figure 1 illustrates the mechanisms by which microplastics penetrate aquaculture ecosystems.

Riverine microplastics originate from wastewater treatment plants, industrial effluents, agricultural activities and various human practices, among others¹⁹. Textile wastewater constitutes the main source of fibrous microplastics among industrial effluents in rivers. Microplastics were detected in effluent released from a textile industrial zone in Shaoxing City, China, adversely affecting the local freshwater ecosystem. Microplastic concentrations in nearby open waters ranged from 2.1 to 71.0 units per litre, while sediment samples contained between 16.7 and 1,323.3 units per kilogram¹⁹. Wastewater generated by the food processing, packaging and automotive industries also contains measurable quantities of microplastics. Anthropogenic activities serve as a primary contributor to microplastic emissions in the environment, with everyday products such as cosmetics, toothpaste and shampoo serving as common sources. Routine laundering of synthetic fibre garments in daily life represents a significant source of microplastic release. Data show that Polyester fleece

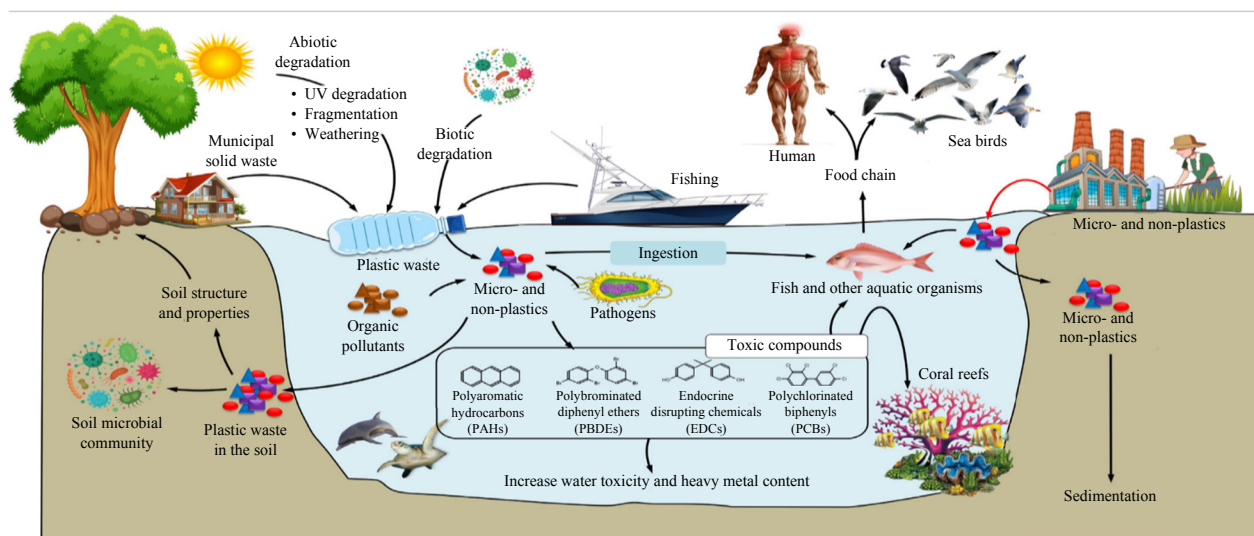


Fig. 2: Source and life cycle of Microplastics in the aquatic environment and their extended impact on humans, animals and plants²⁰

fabrics discharge an average of 7,360 fibres per square metre per litre during a single washing cycle, while garments made of nylon, acrylic and other synthetic fibres also discharge varying amounts of microplastics during laundering¹⁹. Microplastics seep into rivers through residential sewage, while both industrial and domestic wastewater contribute to non-point source riverine pollution via direct discharges from adjacent areas.

Within aquaculture systems, microplastics originate from the degradation of plastic fishing gear and from packaging and feeding activities. The reliance on plastic-based fishing gear inevitably results in microplastic release into the aquaculture environment. Prolonged exposure and mechanical abrasion of floats, fishing ropes, nets, floats and other plastic materials employed in cage and raft aquaculture contribute to the generation of microplastics. Ultraviolet (UV)-induced catalytic degradation further accelerates microplastic generation¹⁹. Research conducted on marine-based aquaculture in Weihai, China, reported microplastic concentrations of 11.49 particles/m in mariculture zones, markedly exceeding the 1.57 particles/m recorded in wild marine environment¹⁹. These microplastics are believed to result from the degradation of foam buoys, net and fishing ropes used in aquaculture systems. The prolonged exposure of plastic enclosures to radiation emitted by the sun, combined with mechanical stress from the activity of crabs and crayfish, facilitates their fragmentation into microplastics¹⁹. Boring isopods can fragment Styrofoam floats used beneath cultivation piers, thereby releasing considerable

quantities of plastic micropollutants¹⁹. Foam oyster rafts contribute to microplastic generation through mechanical stress induced by hydrodynamic activity and progressive weathering¹⁹. In Chilean salmon farming, feed bags, ropes and buoyant polymer materials used during production discharge microplastics into the ambient mariculture ecosystem¹⁹.

Shrimp and fish meals, predominantly sourced from wild-caught shrimp and fish, serve as high-protein feed components in aquaculture¹². Microplastics are commonly detected in aquafeeds, Hanachi *et al.*¹⁹ reported the occurrence of microplastics in four types of fish meal, with concentrations positively correlated to microplastic levels observed in farmed carp. Microplastics were detected at concentrations of 10.7 n/100 g in shrimp meal and 5.4 n/100 g in fish meal samples across 5 nations. Packaging represents the final stage preceding the departure of aquaculture products from the production site, with plastic trays, Styrofoam boxes and durable plastic containers, widely employed for this purpose¹⁹.

Effects of microplastics on the aquatic resources:

Microplastics have been detected in several aquaculture resources, including fish, mussels, shrimp and crabs. Microplastics elicit multiple toxicological effects in aquaculture species, including oxidative stress, behavioral alterations, impaired development and reduced reproductive capacity, ultimately reducing the economic viability of aquaculture²⁰. Studies suggest that plastic debris can disrupt the metabolic

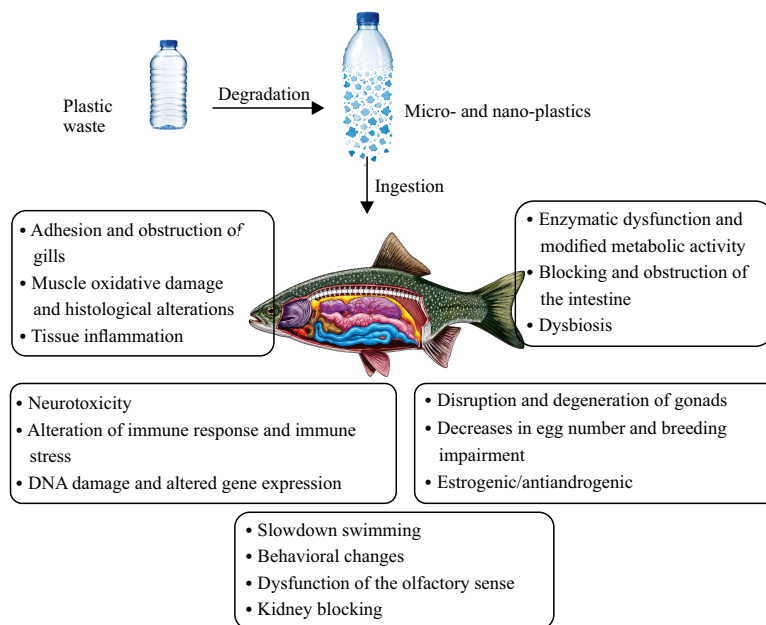


Fig. 3: Accumulation of microplastics in aquatic environments²³

homeostasis of fish, stimulate the generation of reactive oxygen species (ROS) and thereby elicit oxidative stress responses. Excessive generation of reactive oxygen species (ROS) can disrupt cholesterol homeostasis and impair the activity of key enzymes involved in lipid metabolism in fish²⁰. The impact of microplastics on humans, animals and plants are detailed in Fig. 2.

Evidence from experimental studies demonstrates that polyethylene terephthalate (PET) and polyvinyl chloride (PVC) microplastics ranging from 40-150 µm are capable of inducing oxidative cellular damage in sea bass and sea bream²⁰. Bulkier microplastic particles are typically retained within perineural tissues, vasculature and the conjunctiva, where their accumulation may impair cognitive function. Fragment above 500 nm in size may elicit an immunological response, alter fish metabolism and gut microbiota, ultimately resulting in neurophysiological impairment²¹. Microplastic exposure can impair cardiac and gill function; For instance, 51 nm polystyrene (PS) microplastics have been demonstrated to induce oxidative stress in zebrafish, leading to a decreased heart rate²¹. Simultaneously Karami *et al.*²² demonstrated that exposure to 60 µm microplastics results in tissue damage to the gills of the African sharp-tooth catfish (*Clarias gariepinus*). Microplastics are capable of adversely affecting non-fish aquaculture species. Microplastics may induce an inflammatory reaction in the digestive tract of mussels²². Similarly, microplastics have been shown to compromise lysosomal membrane integrity in phagocytic cells of sea

urchins, thereby activating apoptotic signaling pathways. Exposure to triclosan and microplastics elevated oxidative stress biomarkers in mussels (*Perna canaliculus*), notably superoxide dismutase (SOD) activity and lipid peroxidation levels. Microplastics can potentiate sertraline-induced immunotoxicity in *Tegillarca granosa*²².

Accumulation of microplastics in aquatic organisms:

Microplastic buildup in several cultured water systems²³. Microplastics have the potential to bioaccumulate in aquaculture species, with commercial bivalves from fisheries markets exhibiting concentrations of 4.3 to 57.2 microplastic particles per individual. Worldwide aquaculture output, serving as a key source of human protein, expanded from roughly 1 mL tonnes in 1950 to 112 mL tonnes by 2017 (FAO, 2017). Given the large-scale nature of aquaculture, microplastic contamination of aquaculture resources is expected to exert profound and widespread effects, with bioaccumulation representing a key process in the microplastic life cycle (Fig. 3). The process typically initiates with the release of primary or secondary microplastics into terrestrial and aquatic ecosystems, after which they are transported into aquatic systems. Consequently, microplastics infiltrate aquatic food webs and progressively accumulate within organismal tissues through bioaccumulative processes. Upon ingestion by zooplankton, small fish, larger fish and other aquatic organisms, microplastics sequentially transfer and magnify across successive trophic levels²³.

The ingestion of these pollutants has been shown to provoke detrimental physiological effects in aquatic organisms, including species such as mussels, fish and sea turtles, in which these effects can impair both immune and digestive system functions, eventually leading to their death²³. Microplastics may threaten human health by entering the food chain via the ingestion of fish and other aquatic organisms contaminated with microplastics. Human neuronal cells are vulnerable to harmful effects from microplastics²³. Microplastics may adsorb antibiotics and other toxic substances because to their extensive surface area. This further intensifies the issue of microplastic pollution. Moreover, the environmental circulation of microplastics is sustained through their excretion by organisms and their release into ecosystems via both treated and untreated wastewater effluents²³.

Synergistic impacts of microplastics and co-occurring pollutants: Microplastics have negatively impacted the environment and living species, including people. The toxicity of microplastics presents a continual and enduring threat to organisms in the ecosystem. Microplastics have been shown to adversely affect procreativity in mammals as well as aquatic organisms, with lethal effects manifesting when exposure exceeds specific threshold concentrations. Microplastics exposure has been demonstrated to compromise hatching success and suppress larval development²⁴. Administering MP may elicit aberrant animal behavior by obstructing the gastrointestinal system. The research conducted by Hwang *et al.*²⁵ examined the impact of microplastics on red tilapia.

Microplastics have been detected at higher concentrations in fish tissues, with the liver being particularly affected relative to other organs. Microplastics have been reported to bioaccumulate and disperse across the gills, musculature and gastrointestinal tract. Studies have associated microplastic ingestion in marine organisms with oxidative stress, cytotoxicity, gastrointestinal physiological alterations, growth inhibition, immune suppression and changes in gene expression²⁵. Marine creatures' gastrointestinal tract physiology may be adversely modified by MPs. Mature zebrafish may experience intestinal microbiota dysbiosis, disrupted enterocyte proliferation and villus rupture. *Danio rerio* (zebrafish) exposed to microplastics for 21 days exhibited intestinal microbiota imbalance, marked by disruptions in normal metabolic processes²⁵.

The detrimental impacts of microplastics on marine organisms are extensively documented²⁶. Furthermore, research has reported the presence of microplastics in clinical samples obtained from humans; including meconium, feces, colectomy specimens and placental tissues. Aquatic organisms have been observed to ingest a variety of polymer types, including polyethylene (PE), polypropylene (PP), polyester and nylon²⁷. Moreover, microplastics impose substantial toxicological effects on animals through diverse exposure pathways, including dermal, subcutaneous, intraperitoneal, oral and intravenous routes. The introduction of microplastics through direct or indirect pathways can elicit multiple biological effects, with direct exposure referring to conditions in which organisms come into immediate contact with the particles²⁷.

Ecotoxicity of microplastics: Ecological interception involves the deployment of large aquatic plants to slow water flow, thereby capturing contaminants and contributing to the enhancement of water quality. Mangroves constitute a type of aquatic vegetation frequently utilized for ecological interception. Waterborne pollutants can be taken up and retained by mangrove vegetation and the underlying soils through integrated biological, chemical and physical processes²⁸. Mangroves contribute to sustaining ecological balance in aquaculture systems and mitigating pollution in shrimp farming systems. Barbier *et al.*²⁸ emphasized the ecological role of mangroves as nursery and breeding grounds that contribute to sustaining offshore aquaculture²⁸ and also assessed the viability of establishing low-cost seahorse aquaculture in mangrove estuaries and identified considerable potential. Mangroves have the ability to alleviate microplastic contamination in aquaculture. A study reported that both the concentration of microplastics and the proportion of fibrous microplastics were significantly higher along the mangrove margins compared with adjacent areas. Microplastics concentrations in surface waters of mangroves ranged from 620 to 13,100 particles per cubic meter, whereas sediment concentrations varied between 142 and 488 particles per kilogram. Research has shown that increased mangrove plant density enhances the efficiency of microplastic interception²⁹.

Furthermore, mangroves have a specific degrading impact on microplastics. Kathiresan²⁹ reported that polyethylene plastics in mangrove soils exhibited biodegradation rates of 3.77 and 4.21% over a nine-month period. *Bacillus sp.* and *Rhodococcus sp.* from mangrove sediments to breakdown polypropylene microplastics at 6.4 and 4.0% after 40 days. In a mangrove habitat. Polystyrene

and polyethylene terephthalate microplastic degradation. After 90 days in a natural mangrove habitat, polystyrene, polyethylene and terephthalate degraded 19 and 16.4%, respectively²⁹. Furthermore, the degradation rate of polyethylene terephthalate microplastics rose to 18% upon the introduction of engineered microbial strains. Reed demonstrated a microplastic interception effect in freshwater aquatic plants, similar to that of mangroves²⁹.

Reeds are a crucial component of fishpond ecosystems, providing homes and food supplies for aquatic creatures while influencing physical conditions and elemental cycles. Reeds exhibit a specific adsorption capacity for microplastics. Li *et al.*³⁰ reported that microplastics primarily accumulate along the margins of reed beds, where dense vegetation promotes their retention via leaves, roots and biofilms attached to reed surfaces. A study by Senathirajah *et al.*³¹ reported an average microplastic concentration of 511.2 ± 295.0 items per kilogram in reed farm sediments, exceeding the levels detected in nearby waterways. Consequently, due to its ecological conservation value and economic gains, ecological trapping serves as a viable strategy for mitigating microplastic contamination in aquaculture systems. Nonetheless, the presence of appropriate aquatic flora may be absent in some aquaculture zones owing to the variability of the aquaculture environment, hence limiting the use of this strategy based on local conditions³¹.

Toxicity due to chemical and physical properties of microplastics:

Microplastics may migrate across trophic levels, moving from herbivorous organisms to their carnivorous predators, indicating their accumulation and amplification throughout the food chain³². Aquaculture products represent a substantial pathway for human exposure to microplastic contamination. Microplastics have been detected in more than 80% of commercially significant fish species³². The ingestion of aquaculture products has been demonstrated as a potential pathway through which microplastics can be transferred into the human body. Health risk assessments indicate that the levels of microplastics in commercially important species from Fuzhou and Xiamen exceed the established hazard threshold. Assessment of microplastic contamination in bivalves from Daya Bay using the Polymer Hazard Index (PHI) indicated potential risks corresponding to levels II-II. Humans are estimated to ingest approximately 3.3×10^2 to 3×10^3 microplastic particles annually via fish consumption and approximately 2.6×10^3 to 1.6×10^4 particles per year through the consumption of shellfish³². Consumption of aquaculture products contaminated with microplastics may presents a potential pathway for adverse health impacts in humans³².

Microplastics are highly resistant to chemical degradation and, once ingested, can escape mechanical elimination; their persistence in biological systems and the magnitude of exposure are major determinants of their potential risk. Mummaleti *et al.*³² reported that microplastics interact with lipid droplets and digestive lipases within the digestive system, thereby elucidating two pathways through which they interfere with digestion and nutrient absorption. (i) By adsorbing lipase molecules, microplastics decrease enzymatic activity through modifications of the enzyme's secondary structure and disruption of its essential open conformation; and (ii) By forming large lipid-microplastic hetero-aggregates, microplastics reduce the bioavailability of lipid droplets, a process driven by their pronounced hydrophobicity³³.

Located in the ileum, the distal portion of the small intestine, Peyer's patches serve as critical sites for the uptake and translocation of particles. Research has shown that non-degradable particles, including Titanium Dioxide (TiO₂) and aluminosilicate, can accumulate extensively within the basal phagocytes of Peyer's patches³⁴. As non-degradable particles, they are similarly likely to accumulate within this region, displacing the absorption pathways of endogenous particles and consequently impairing immune surveillance and sensory functions, which may ultimately compromise human immunity. Additionally, Ingestion of 5-110 µm PVC particles in dogs resulted in cerebral softening, focal micronecroses and formation of scar tissue in the brain. Microplastics can be transported to thoracic lymph nodes via macrophage-mediated uptake and then disseminated to secondary target organs via systemic circulation, including the liver, kidneys, spleen, heart and brain, where they may cause varied degrees of clinical and functional impairment³⁴. Microplastics such as polystyrene (PS), polypropylene (PP), polyurethane (PU) and polyethylene (PE) have been found in human placental tissues and meconium 111, indicating that they may offer health hazards to developing foetuses³⁴.

Certain chemical constituents of microplastics have been established to exert considerable toxic effects on the human body. These include compounds associated with reproductive toxicity (e.g., BPA and DEHP), mutagenicity (e.g., benzene and phenol) and carcinogenicity (e.g., butadiene and vinyl chloride³⁴). Microplastics may accumulate various environmental pollutants, including hydrophobic organic compounds (HOCs) and heavy metals such as chromium, cadmium, nickel, lead and zinc. *In vitro* studies have demonstrated that chromium adsorbed onto microplastics exhibits higher release rates within the human digestive

system than in aquatic environments, with the gastric phase showing the greatest bioavailability of both Cr (VI) and Cr (III)³⁴. This suggests that the conditions within the human body promote the release of pollutants adsorbed onto microplastics, consequently amplifying the health risks posed by their ingestion³⁴.

Fishing gears as a source of microplastics contamination:

Diverse fishing apparatuses are significant contributors to microplastic contamination within aquaculture systems (Food and Agriculture Organization of the United Nations, 2018). Consequently, using environmentally friendly materials for the production of this fishing equipment aims to mitigate microplastic contamination in aquaculture. Skirtun *et al.*³⁴ claimed that large-scale aquaculture operations in Scotland and the Netherlands are replacing traditional plastic fishing gear with biodegradable alternatives, such as biodegradable socks used in off-bottom mussel production. Furthermore, Deroiné *et al.*³⁵ created a new generation of strong and biodegradable monofilaments to minimise microplastic pollution in aquaculture environments. It is vital to realise that degradable plastics provide a risk of microplastic contamination; nonetheless, their impact on aquaculture resources is negligible.

Avio *et al.*³⁶ reported that an eight-day exposure to bio-based biodegradable poly(L-lactide) microplastics at a concentration of 100 µg/L did not result in appreciable oxidative stress, neurotoxic, or immunotoxic effects in blue mussels. However, exposure of *Mytilus edulis* and *Mytilus galloprovincialis* to polystyrene microbeads (32 µg/L) resulted in decreased catalase and lipid peroxidase activities, concomitant with elevated glutathione S-transferase and superoxide dismutase activities in the digestive glands. Nonetheless, biodegradable microplastics continue to affect the lipid composition of mussels³⁷. This suggests that using non-plastic aquaculture techniques and facilities may be preferable to employing analogous plastic resources³⁷.

In addition to reducing the reliance on conventional plastic fishing gear in aquaculture, there is a need to strengthen the management and stewardship of existing plastic resources within the industry. Potential strategies encompass improving the structural design and material composition of existing fishing gear. In the Shetland Islands, traditional mussel pegs have been replaced by continuous longlines or looped line systems, a modification that reduces gear loss in mussel farming and consequently lowers the potential release of microplastics from these materials into the aquatic environment³⁷. The implementation of plastic waste management in aquaculture is essential, as personnel at

aquaculture facilities routinely utilize various consumer plastic products, such as protective clothing, rubber gloves, beverage and food packaging materials³⁷. When consumer plastic products are improperly disposed of, they may enter aquaculture environments, leading to microplastic contamination within the system³⁷. The reutilization and recycling of fishing gear represent crucial strategies in sustainable aquaculture management. Outdated fishing gear can be effectively recycled and repurposed to mitigate microplastic pollution in aquaculture systems, reduce overall plastic waste generation, promote economic efficiency and reinforce the environmental stewardship of aquaculture practitioners³⁷.

MITIGATION METHODS AGAINST MICROPLASTICS POLLUTION

Physical methods: Microplastics have emerged as a substantial environmental issue owing to their pervasive distribution throughout several ecosystems. In response to this problem, many physical removal techniques have been devised to alleviate the environmental effects of microplastics³⁷. These strategies seek to eliminate microplastics from many sources, including aquatic environments, soil and the atmosphere. This section examined several physical removal approaches that have shown efficacy in addressing microplastic contamination³⁷.

Filtration systems: Filtration devices are often used to eliminate microplastics from aquatic environments. These devices operate by directing water through a succession of filters with varying pore dimensions, efficiently capturing microplastic particles³⁷. The filters may consist of many materials, including mesh screens, membranes, or activated carbon. The selection of filter material is contingent upon the dimensions and classification of the microplastics being addressed³⁷. An example of a filtering system is the use of mesh screens in wastewater treatment facilities. These screens are designed to intercept bigger microplastic particles, therefore inhibiting their entry into rivers and seas. Furthermore, sophisticated filtering methods, like ultrafiltration and nanofiltration, may be used to eliminate smaller microplastics that may bypass standard filters³⁷.

Sedimentation and settling basins: Sedimentation and settling tanks are often used in water treatment plants to eliminate suspended particles, such as microplastics. These tanks operate on the idea of gravity, enabling microplastic particles to accumulate at the bottom while clean water is

extracted from the top³⁸. In these tanks, water is allowed to flow gradually, allowing sufficient time for the microplastics to precipitate. The accumulated microplastics may then be extracted and appropriately discarded, thereby averting their reintroduction into the environment. Sedimentation and settling tanks are notably efficient in eliminating bigger microplastics and may be used with other physical removal techniques for improved efficacy³⁸.

RECOMMENDATIONS

- The management of microplastic contamination is a complex challenge that requires a multidimensional approach encompassing active participation from the public, industrial sectors, regulatory authorities and international organizations. Microplastics, defined as plastic fragments measuring less than 5 mm in diameter, pose substantial threats to aquatic biomes, wildlife and potentially human health. Effective strategies for addressing microplastic contamination include, first and foremost, decreasing the production and consumption of plastics, will minimize their environmental release
- Transformation of plastic residues into economically valuable commodities is largely dependent on the source and composition of the plastic material. A major challenge lies in effectively segregating plastic waste according to its origin. For example, plastic waste contaminated with elements such as nitrogen, sulfur, halogens, or other combustible compounds can pose significant risks during combustion-based fuel production. Consequently, the implementation of appropriate chemical pretreatment strategies is essential to minimize these hazards and mitigate the environmental impact of microplastics
- Microplastics represent a critical environmental challenge that necessitates effective mitigation strategies to minimize their ecological impacts. Although substantial research has focused on elucidating the sources, pathways and environmental fate of microplastics, the potential for converting these particles into valuable byproducts remains largely underexplored
- Synthetic textiles, such as polyester, represent a major source of microplastic pollution; therefore, the adoption of eco-friendly and sustainable clothing composed of natural fibers such as cotton, silk, wool and hemp should be prioritized to reduce microplastic release into the environment

- Although all materials generate some level of microfibers, those derived from natural fibers, such as cotton, generally remain larger than those from synthetic sources. This is because cotton fibers often intertwine and form larger lint aggregates, which are less likely to be dispersed into the environment
- Clothing undergoes substantial mechanical stress during washing and drying, leading to the release of microfibers from various fabric types. However, microplastics originating from synthetic materials such as Polyester polymers are especially concerning due to their long-term persistence and associated ecological risk

CONCLUSION

The extensive use of plastic materials has posed a threat to the environment in several aspects. Anthropogenic activities release microplastics into riverine and coastal systems, constituting the primary external source of microplastic contamination in aquaculture environments. Furthermore, terrestrial waste weathering, oceanic microplastic contamination, air transport and several anthropogenic activities, all contribute microplastics to the environment. Aquaculture fishing gear represents the major internal contributor to microplastic contamination in aquatic ecosystems, although feed and packaging also contribute to the accumulation of microplastics in this setting. Microplastics contamination in the aquatic environment will lead to its degradation, disrupt the material and energy cycles and adversely impact the benefits derived from aquaculture resources. Microplastics subsequently can build up in the water bodies, leading to increased environmental hazards that may induce oxidative stress in aquaculture species, alter their behavior, impede development and reproduction and perhaps result in mortality. As a result, aquaculture profitability is reduced, while the ingestion of microplastics through aquaculture-derived foods poses potential multifaceted risks to human health.

Though, numerous countries have implemented effective strategies to mitigate microplastic pollution, including the ecological interception of microplastics, the reduction or substitution of plastic fishing gear and the purification of aquaculture resources. To enhance the regulation of microplastic pollution, prospective technologies, including remote sensing and portable analytical devices, should be employed to advance and refine microplastic detection systems within the environment. Simultaneously, stakeholders

must consider the legislative regulations governing the environment and the permissible levels of microplastics in aquatic resources, ensuring the execution of environmental protection measures in compliance with established regulatory standards.

Accumulation of microplastics within ecosystems has emerged as an undeniable threat to biota, likely stemming from inadequate waste management practices. However, if policymakers fail to implement adequate and stringent regulatory measures, this will result in severe adverse consequences for marine life, environmental sustainability and human health. Microplastic pollution can be mitigated to some extent through the reduction of plastic consumption and the promotion of plastic reuse practices.

SIGNIFICANCE STATEMENT

Microplastic pollution therefore, represents a growing and largely invisible threat to environmental sustainability, aquatic resources and human health. This study is significant because it synthesizes current knowledge on the sources, pathways, bioaccumulation and toxicological impacts of microplastics across ecosystems, while highlighting their ability to infiltrate food chains and induce adverse biological effects. By emphasizing both environmental and public health implications, the work underscores the urgency for improved waste management, sustainable material alternatives and innovative mitigation strategies. Furthermore, its exploration of converting plastic waste into value-added products offers a practical pathway toward reducing pollution and promoting a circular economy, making it a valuable contribution to ongoing efforts to address global plastic contamination.

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