

Tracing the Journey of Microplastics from Aquatic Ecosystems to Seafood

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Abstract

Microplastic pollution has become an important environmental issue due to the widespread occurrence, persistence, and biological accessibility of small plastic particles in aquatic ecosystems. Fish and other seafood organisms are of particular concern because they may come into contact with microplastics at different stages of their life cycle. These particles can be taken up directly from contaminated water and sediments or indirectly through the consumption of contaminated food. Microplastics have been reported in numerous marine and freshwater organisms, including commercially valuable fish, crustaceans, and bivalves. Their detection in gastrointestinal tracts and, in some cases, edible tissues has raised concerns about seafood safety and quality, ecosystem health, and the possibility of human exposure through seafood consumption. The effects of microplastic ingestion on aquatic organisms are not uniform and can vary according to several characteristics of the particles, including their size, shape, polymer type, concentration, and the chemicals or microorganisms associated with their surfaces. Ingested microplastics may interfere with normal digestive processes and can potentially contribute to oxidative stress, inflammation, changes in feeding behaviour, and other physiological disturbances. Moreover, plastic particles can act as carriers or surfaces for environmental contaminants such as persistent organic pollutants, heavy metals, and microorganisms. These interactions may influence the availability, transport, and exposure of aquatic organisms to such contaminants. The movement of microplastics through aquatic food webs is also complex. Unlike certain persistent chemical pollutants, microplastics do not necessarily undergo progressive biomagnification at each successive trophic level. However, feeding relationships can provide opportunities for microplastics and their associated contaminants to move between organisms and reach higher-level consumers. As seafood forms an important component of the human diet, consumption of contaminated fish and other seafood represents one possible route of human exposure to microplastics. However, the actual level of dietary exposure and the extent to which such exposure poses a health risk to humans are still being investigated.

This review examines the major sources and distribution of microplastics in aquatic environments, their occurrence in fish and other seafood, mechanisms of uptake, biological effects, movement through food webs, and potential implications for human health. It also considers important methodological challenges in microplastic research and identifies areas where further investigation is needed to improve understanding of seafood-associated microplastic exposure and its broader environmental and health consequences.

Keywords: microplastics, fish contamination, seafood safety, aquatic food chain, trophic transfer, plastic pollution, human exposure.

Introduction

Plastic pollution has become a pervasive environmental problem in marine, estuarine and freshwater ecosystems. The widespread use, persistence and durability of synthetic polymers have resulted in the accumulation of plastic debris in aquatic environments, where larger plastic items can undergo fragmentation through physical, chemical and biological processes. These processes generate progressively smaller plastic particles, collectively referred to as microplastics (GESAMP, 2015; Cole et al., 2011). Although definitions have varied among studies, microplastics are commonly described as plastic particles smaller than 5 mm (GESAMP, 2015; NOAA, 2019). Nanoplastics represent an even smaller size fraction and are generally considered separately because their size, surface properties, environmental behaviour, analytical detection and biological interactions can differ from those of larger microplastics (EFSA CONTAM Panel, 2016; GESAMP, 2016).

Aquatic environments receive plastic materials from numerous sources, including domestic and municipal waste, industrial activities, wastewater discharges, stormwater runoff, atmospheric transport, fishing and aquaculture operations, and other maritime activities (Cole et al., 2011; GESAMP, 2015; Lebreton et al., 2017). Rivers are important pathways for transporting land-derived plastic debris towards coastal and marine environments, while direct inputs associated with fishing, shipping and aquaculture also contribute to plastic pollution in marine waters (Lebreton et al., 2017). Consequently, microplastics have been documented in a range of environmental compartments, including surface waters, the water column, sediments, beaches and aquatic organisms across geographically diverse regions (GESAMP, 2016; Wang et al., 2019).

Fish and seafood organisms occupy an important position in discussions concerning microplastic pollution because they can encounter plastic particles throughout their life cycle and may ingest them directly from the surrounding water or sediments and indirectly through contaminated food or prey (Wang et al., 2019; Wang et al., 2020). The occurrence of microplastics in fish has been documented in both marine and freshwater environments, although the extent of exposure and its biological significance can vary considerably among species, habitats, feeding strategies and environmental conditions (Wang et al., 2020). Filter-feeding organisms such as mussels and oysters are of particular interest because they process substantial quantities of suspended material during feeding and can consequently encounter and retain microplastic particles present in the surrounding water (Ward et al., 2019; Wootton et al., 2022). Crustaceans and other benthic organisms may also encounter microplastics associated with or deposited in sediments (Wang et al., 2019). These interactions provide several potential pathways through which microplastics can enter and move through aquatic food webs (Huang et al., 2021).

The detection of microplastics in seafood has generated two interconnected areas of scientific concern. The first relates to ecological effects, including possible effects on feeding, growth, reproduction, metabolism, oxidative balance, immune responses and other physiological processes in aquatic organisms (Wang et al., 2019; Wang et al., 2020). Experimental studies have reported biological responses following microplastic exposure; however, the environmental relevance of some laboratory-based findings remains an important consideration because experimental concentrations and particle characteristics do not always correspond to conditions encountered in natural ecosystems (Wang et al., 2020). The second concern relates to food safety and human exposure, particularly through the consumption of contaminated seafood. Microplastics have been detected in commercially important fish, crustaceans and mollusks, and systematic reviews have confirmed their occurrence across several seafood groups (EFSA CONTAM Panel, 2016; Kutralam-Muniasamy et al., 2020). Nevertheless, the

presence of microplastics in an edible organism should not automatically be interpreted as evidence of a corresponding human-health hazard. Human exposure and potential risk depend on factors including the quantity and characteristics of particles consumed, their distribution within edible and non-edible tissues, food-processing and preparation practices, gastrointestinal fate, potential absorption and the toxicological properties of the particles and associated chemicals (EFSA CONTAM Panel, 2016; Kuttralam-Muniasamy et al., 2020).

Therefore, a critical review of the available evidence is required to distinguish well-established observations from hypotheses and assumptions and to identify important gaps in current knowledge. Particular attention is needed to differences in sampling and analytical methods, particle size and polymer type, tissue distribution, exposure concentrations and the environmental relevance of experimental studies. Such an evidence-based approach is essential for evaluating the ecological significance of microplastic contamination in aquatic organisms and for assessing the extent to which seafood consumption may contribute to human exposure (GESAMP, 2016; Kuttralam-Muniasamy et al., 2020).

Literature Review

Sources and Formation of Microplastics in Aquatic Ecosystems

Microplastics can be broadly divided into primary and secondary microplastics according to their origin. Primary microplastics are manufactured at microscopic dimensions or enter the environment as small particles. Examples include industrial plastic pellets, particles used in certain industrial applications and fibres released from synthetic textiles (Wu et al., 2023; Talukdar et al., 2024). Wastewater treatment systems can retain a considerable proportion of microplastics; however, some particles, particularly small fibres, may pass through treatment processes and subsequently enter receiving waters, making wastewater an important pathway for microplastic contamination of aquatic ecosystems (Talukdar et al., 2024).

Secondary microplastics originate from the fragmentation and weathering of larger plastic objects. Fishing nets, ropes, packaging materials, bottles, containers, agricultural plastics and other plastic debris can progressively break down through ultraviolet radiation, temperature fluctuations, mechanical abrasion, oxidation and hydrodynamic forces. These processes alter the physical and chemical characteristics of plastic materials and generate progressively smaller particles (Wu et al., 2023; Microplastics in freshwater systems, 2024). The resulting fragments may become widely dispersed within aquatic environments. In aquatic ecosystems, microplastic abundance and distribution are influenced by hydrodynamics, sediment characteristics, proximity to urban and industrial areas, wastewater and runoff inputs, and local patterns of plastic use (Owowenu et al., 2023; Jiang et al., 2024). Rivers and estuaries are important transport and transformation zones connecting terrestrial environments with coastal and marine ecosystems. River discharge, surface runoff and drainage can transport land-derived plastic particles downstream, although retention and redistribution within river systems can substantially modify the quantity and characteristics of microplastics eventually reaching the sea (Zhang et al., 2024). Estuarine and coastal environments can further act as zones of microplastic retention, deposition, resuspension and redistribution, depending on tides, turbulence, salinity, sediment interactions and particle characteristics (Jiang et al., 2024). Coastal regions may receive substantial inputs associated with urban activities, fisheries, aquaculture, tourism and land-based runoff, although

the relative contribution of individual sources varies considerably among locations (Belioka and Achilias, 2024; Jiang et al., 2024).

The physical characteristics of microplastics are also important in determining their environmental fate. Particles may occur as fragments, fibres, films, foams or pellets, and their density varies according to polymer type, additives, degree of weathering and physical structure. These characteristics influence particle buoyancy, settling, suspension and resuspension within aquatic environments (Owowenu et al., 2023; Microplastics in freshwater systems, 2024). In coastal waters, microplastic transport is additionally influenced by particle size, shape and density, together with hydrodynamic processes such as currents, tides, turbulence and vertical mixing (Jiang et al., 2024). Biofilm formation and interactions with organic or mineral particles can further modify particle density and settling behaviour, potentially shifting microplastics between the water column and sediments.

Occurrence of Microplastics in Fish and Seafood

Microplastics have been documented in numerous species of marine and freshwater fish. Studies have also reported their occurrence in commercially important seafood organisms, including bivalves, crustaceans and cephalopods. Recent systematic reviews indicate that microplastic occurrence in seafood is widespread but highly variable among taxa and geographical regions. Differences in species, feeding behaviour, habitat, environmental contamination and analytical procedures contribute substantially to the variability reported between studies (Woh et al., 2024; Pacyna-Kuchta & Jungnickel, 2025).

In fish, microplastics are frequently reported from the gastrointestinal tract (GIT). This is biologically plausible because the digestive tract is a major site of exposure following ingestion of contaminated water, sediment or prey. A recent review specifically examining micro- and nanoplastics in fish GITs identified the gastrointestinal tract as an important interface between environmental exposure, biological effects and potential entry of plastic particles into food webs (Khan et al., 2025). Detection in edible muscle and other tissues has also been reported in some studies, although the occurrence of particles outside the digestive tract is less consistently documented and remains an important area of investigation. Recent reviews have emphasized that evidence for tissue translocation and the implications of microplastics detected in edible tissues require careful interpretation because results can vary with particle characteristics, species and analytical methodology (Jangid et al., 2025; Khan et al., 2025).

The occurrence of microplastics in seafood should therefore be interpreted according to tissue type. Finding particles in the gastrointestinal tract does not necessarily mean that consumers ingest the same particles when the gut is removed before cooking. This distinction is particularly important for fish that are routinely eviscerated before consumption, because removal of the digestive tract may substantially alter the fraction of detected particles that is directly relevant to dietary exposure. Recent seafood reviews consequently recommend considering the anatomical distribution of microplastics, preparation practices and the portion of the organism actually consumed when assessing potential human exposure (Woh et al., 2024; Bocca et al., 2025).

In contrast, whole-body consumption of small fish and consumption of edible tissues of bivalves may provide greater opportunities for dietary exposure. Bivalves are especially relevant because they are filter-feeding organisms capable of accumulating microplastics from the surrounding water and are commonly consumed with their digestive tissues. A comprehensive 2024 review concluded that marine bivalves can accumulate microplastics in a tissue-specific manner and highlighted their particular

relevance to human exposure because they are generally consumed whole, including the digestive system (Xu et al., 2024). Recent reviews of commercially important bivalves likewise confirm that microplastics are frequently detected in their tissues and emphasize the importance of standardized analytical approaches when comparing contamination levels among species and regions (2025).

Uptake and Ingestion of Microplastics by Fish

Fish may encounter and ingest microplastics through several exposure pathways, with direct ingestion from the surrounding water or sediments being one of the most commonly reported routes. During feeding, fish may accidentally consume plastic particles along with natural food items, particularly when the particles resemble prey in size, shape or appearance. The likelihood of ingestion can vary considerably among species because feeding behaviour, sensory perception and habitat use influence how fish interact with particles present in their environment. Recent reviews indicate that the physical characteristics of microplastics, together with the feeding behaviour of aquatic organisms, play an important role in determining the probability of ingestion (Kim et al., 2024; Wang et al., 2024).

The characteristics of the particles themselves can strongly influence their ingestion. Particle size, shape, colour and polymer type may affect whether a microplastic is encountered, recognized as food or accidentally consumed during feeding. Smaller particles can be particularly relevant because they may overlap in size with naturally available food organisms such as plankton and other small prey. A recent review of laboratory studies found that particles below approximately 300 µm can be readily available to a range of aquatic macrofauna, although the actual size range ingested differs among species and feeding modes (Kim et al., 2024). Field-based studies have also shown that fibres and fragments are frequently detected in fish, while polyethylene and polypropylene are among the commonly identified polymers. However, the characteristics of particles observed in natural environments can differ substantially from those used in laboratory experiments, emphasizing the importance of environmentally realistic exposure conditions (Alfonso et al., 2024).

Fish can also acquire microplastics indirectly through contaminated food organisms, creating a potential pathway for trophic transfer. Zooplankton, benthic invertebrates and other lower-trophic-level organisms may ingest microplastics and subsequently become prey for fish. Experimental evidence demonstrates that such transfer can occur, but its efficiency depends on particle size, food availability, prey–predator interactions and the ability of organisms to eliminate particles. For example, a 2024 experimental study involving freshwater organisms found that food availability influenced microplastic uptake and removal, while trophic transfer contributed to the ingestion of particles that were less readily detected directly by fish (2024). Therefore, the presence of microplastics in prey does not necessarily mean that all ingested particles will be retained by the predator.

Once ingested, many microplastics remain primarily within the gastrointestinal tract and may subsequently be rejected, regurgitated or eliminated through faecal material. Consequently, ingestion should be distinguished from long-term accumulation within tissues. Earlier critical reviews have shown that the overwhelming majority of field observations locate microplastics in the gastrointestinal tract rather than demonstrating persistent accumulation in other tissues, and evidence for biomagnification through aquatic food webs remains inconsistent (Burns & Boxall, 2018; Ašmonaitė et al., 2020). More recent research continues to emphasize that ingestion, retention, translocation and elimination are separate processes that can vary according to particle characteristics and fish biology (Li et al., 2024; 2026).

The extent to which fish ingest microplastics is therefore influenced by a combination of particle-related, biological and environmental factors. Particle size and shape can determine whether a particle is accessible to the fish and whether it can be physically ingested, while colour may affect visual recognition during feeding. Polymer type can also influence particle density, buoyancy and environmental distribution. At the same time, the concentration of microplastics in the surrounding habitat, availability of natural prey, feeding strategy, habitat characteristics and developmental stage can modify exposure. A recent critical review of freshwater fish identified microplastic characteristics such as size, shape and colour, together with fish feeding habits and environmental conditions, as important determinants of exposure and accumulation patterns (2025).

Feeding strategy and habitat use are particularly important because different fish species encounter microplastics in different ways. Filter- and suspension-feeding organisms continuously process large volumes of water and may therefore encounter particles suspended in the water column. Demersal and benthic-feeding fish may be exposed to particles associated with sediments, whereas predatory species can encounter microplastics through contaminated prey. Nevertheless, trophic transfer is not uniform across species or ecosystems. A 2025 review of commercially important pelagic fish from the Indian Ocean reported considerable variation among species and concluded that available evidence for trophic transfer was contradictory, highlighting the influence of ecological and environmental conditions on microplastic movement through food webs (Beeharry et al., 2025).

Thus, microplastic ingestion by fish is a multifactorial process rather than a simple consequence of environmental contamination. The interaction between particle properties, fish feeding behaviour, prey availability, habitat conditions and life stage determines the likelihood of exposure and ingestion. Recent studies consequently emphasize the need to consider realistic environmental concentrations and particle characteristics when evaluating microplastic exposure in fish, rather than relying exclusively on laboratory experiments using uniform particles and high concentrations (Alfonso et al., 2024; Beeharry et al., 2025).

Microplastics in the Aquatic Food Chain

The movement of microplastics (MPs) through aquatic food webs is a complex process and should not be interpreted simply as conventional biomagnification. In contaminant toxicology, biomagnification generally describes an increase in the concentration of a substance at successively higher trophic levels. For microplastics themselves, however, evidence for consistent biomagnification under natural conditions remains limited and sometimes contradictory. Differences in polymer type, particle size, shape, density, environmental conditions, feeding behaviour and retention within organisms can all influence their movement through food webs. Field-based evidence has generally provided stronger support for ingestion and trophic transfer than for systematic biomagnification of the particles themselves (Burns & Boxall, 2018; Walkinshaw et al., 2020; Auta et al., 2022).

Nevertheless, trophic transfer of microplastics does occur and represents an important pathway of exposure within aquatic ecosystems. Zooplankton, molluscs, benthic invertebrates and other lower-trophic-level organisms can ingest microplastics, after which the particles may become available to fish and other predators when contaminated prey are consumed. Experimental studies have demonstrated such prey-mediated transfer under controlled laboratory conditions, while recent reviews indicate that the magnitude and ecological importance of this process vary considerably among species and environmental settings (Gao et al., 2024; Zhang et al., 2024). In natural ecosystems, the fate of ingested

particles is influenced by several interacting factors, including how long particles remain within the digestive tract, rates of egestion, particle characteristics, predator–prey relationships, feeding strategies and the dilution of microplastics within the surrounding environment. Consequently, the presence of microplastics at one trophic level does not necessarily mean that their concentration will increase at the next level. A 2023 synthesis of aquatic studies, for example, found evidence of bioaccumulation in some organisms but concluded that the pathway and extent of biomagnification remained unclear.

The ecological importance of trophic transfer may also extend beyond the physical movement of plastic particles. Microplastics can interact with other contaminants present in aquatic environments because their surfaces can provide sites for the sorption of chemicals. Depending on polymer characteristics, weathering, particle size and environmental conditions, microplastics may associate with hydrophobic organic contaminants, persistent organic pollutants and metals. Recent reviews have shown that adsorption and desorption processes are strongly influenced by factors such as polymer composition, surface ageing, pH, salinity, dissolved organic matter and the chemical properties of the contaminant (Zhang et al., 2023; Bhaumik & Chakraborty, 2024). Thus, microplastics may function as mobile surfaces that participate in the transport and redistribution of some contaminants, although their importance relative to other environmental pathways depends strongly on local conditions.

Another important feature of microplastics in aquatic food webs is their ability to become colonised by microorganisms. Once plastic particles enter water, their surfaces can rapidly develop biofilms containing bacteria, fungi, algae and other microorganisms. These microbial communities are commonly referred to as the “plastisphere.” Recent research indicates that plastisphere communities can differ from microbial communities in the surrounding water and may influence the ecological behaviour and interactions of plastic particles (Bocci et al., 2024). The plastisphere therefore adds a biological dimension to microplastic pollution, because particles can provide a persistent surface for microbial attachment and transport through aquatic environments.

Taken together, ingestion of microplastics may expose aquatic organisms to a combination of the physical effects of the particle, chemicals associated with or released from the plastic, and microorganisms present on its surface. However, this does not necessarily mean that microplastics are the dominant pathway by which organisms encounter these contaminants. The relative contribution of particle-associated contaminants compared with exposure through water, sediment and naturally occurring dietary sources remains uncertain and is strongly dependent on environmental conditions. Current research therefore emphasises the need for environmentally realistic experiments and field-based studies that distinguish simple particle transfer from genuine biomagnification and assess the contribution of microplastics to overall contaminant exposure (Gao et al., 2024; Zhang et al., 2024).

Biological Effects of Microplastics on Fish

Experimental research has shown that exposure to microplastics (MPs) can influence several aspects of fish physiology, including digestive function, oxidative balance, immune responses, metabolism, growth and reproduction. However, these effects are not uniform across all fish species or experimental conditions. The biological response depends on factors such as particle size, shape and polymer composition, exposure concentration and duration, route of exposure, and the developmental stage of the fish. A recent meta-analysis of 85 laboratory studies found that microplastic exposure was associated with alterations in growth, survival, reproduction and oxidative stress, while also demonstrating

considerable variation according to particle characteristics and experimental conditions (Wang et al., 2024).

A. Physical effects

One of the most direct consequences of microplastic exposure is the physical interaction of particles with the digestive tract and, in some circumstances, the gills and other tissues. Ingested particles may cause mechanical irritation of the gastrointestinal lining, alter gut structure or interfere with normal digestive processes. The severity of these effects can depend strongly on particle size and shape, as smaller particles may interact differently with tissues than larger particles. Reviews of experimental studies in fish have reported gastrointestinal and gill alterations, including histopathological changes and disturbances in normal physiological functions (Ghosh, 2024; Zink & Wood, 2024).

However, findings obtained under highly concentrated laboratory exposures should be interpreted carefully. Experimental concentrations may sometimes exceed those encountered by fish under natural environmental conditions, and therefore the presence of an effect in the laboratory does not necessarily indicate that the same magnitude of effect occurs in wild populations. Particle characteristics and exposure conditions are important determinants of toxicity, particularly in studies using model fish such as zebrafish (Rojoni et al., 2024).

B. Oxidative stress

Oxidative stress is among the most frequently reported biochemical responses associated with microplastic exposure in fish. When exposure disturbs the balance between the production of reactive oxygen species (ROS) and the antioxidant defence system, oxidative damage can occur. Experimental studies have reported changes in antioxidant enzymes and increases in indicators of oxidative injury following exposure to different types of microplastics. A recent meta-analysis found an overall increase in oxidative damage in fish exposed to microplastics, including elevated malondialdehyde, although the magnitude of the response varied with particle size, concentration, exposure duration and other experimental factors (Wang et al., 2024).

The mechanisms underlying this response are likely to be multifactorial. Direct interactions between particles and cells, tissue irritation, inflammatory processes and disruption of cellular metabolism may contribute to increased ROS production. In addition, microplastics can interact with or transport chemical additives and other contaminants, potentially adding chemical stress to the physical effects of the particles themselves (Ghosh, 2024; Chen et al., 2024). Thus, oxidative stress is better viewed as part of a broader network of cellular responses rather than as an isolated effect of microplastic exposure.

C. Inflammation and immune responses

Microplastic exposure can also influence inflammatory and immune processes in fish. Physical contact with particles and subsequent tissue stress may activate inflammatory pathways, while oxidative stress and cellular injury can further modify immune function. Reported responses include changes in immune-related biochemical and haematological parameters, although the direction and magnitude of these changes differ among species and experimental conditions (Ghosh, 2024).

The relationship between microplastics and immune responses is complex because particle properties, exposure dose and duration can determine whether the response is transient or more persistent. Prolonged cellular stress and inflammatory activation may interfere with normal physiological functions and may also interact with oxidative and metabolic pathways. Recent reviews therefore consider inflammation, oxidative stress and immune disturbance as interconnected components of microplastic toxicity rather than independent responses (Hasan et al., 2024; Ghosh, 2024).

D. Growth and energy metabolism

Microplastic exposure may also influence fish growth and energy allocation. Ingested particles can potentially interfere with feeding behaviour, digestive processes, nutrient absorption and intestinal function. At the same time, physiological stress may increase the energetic demands associated with detoxification, tissue repair and maintenance of antioxidant and immune defences. Consequently, less energy may be available for growth and other biological processes. Experimental studies have reported alterations in growth performance, digestive activity, metabolism and related biochemical parameters in exposed fish (Ghosh, 2024).

Evidence from the 2024 meta-analysis provides broader support for this association, showing an overall reduction in fish growth following microplastic exposure across laboratory studies. Importantly, the analysis also demonstrated that the magnitude of the response was influenced by factors such as particle size, concentration, exposure duration, exposure pathway and life stage (Wang et al., 2024). Therefore, laboratory findings should be interpreted in relation to environmentally relevant concentrations and exposure scenarios rather than assuming that all experimental effects occur equally in natural populations.

E. Reproductive and developmental effects

Reproductive and developmental responses have received increasing attention because alterations at these levels could have consequences extending beyond individual fish. Experimental studies have examined effects of microplastics on gonadal tissues, gamete quality, fecundity, embryonic development and endocrine-related pathways. Recent reviews indicate that microplastic and nanoplastic exposure can affect reproductive processes through mechanisms involving oxidative stress, hormonal imbalance, altered steroidogenesis and changes in gonadal function (Hasan et al., 2024; Wang et al., 2024).

A recent review published in *Aquatic Toxicology* further highlighted possible involvement of signalling pathways associated with inflammation, oxidative stress, apoptosis and endocrine regulation, including the hypothalamic–pituitary–gonadal axis and steroidogenic processes (2025). Experimental evidence has also included changes in sperm quality, oocyte development, fertilisation, hatching and offspring development in some fish models. Nevertheless, these findings should not automatically be interpreted as evidence of equivalent reproductive effects in wild fish populations. Differences in environmental exposure levels, particle characteristics, species sensitivity and life-history conditions remain important limitations when extrapolating laboratory observations to natural ecosystems.

All the current evidence indicates that microplastics can influence multiple biological systems in fish, with oxidative stress, inflammation, digestive disturbances, altered metabolism, growth effects and reproductive responses being among the most frequently investigated outcomes. These responses are interconnected rather than independent; for example, gastrointestinal irritation may influence nutrient acquisition, while oxidative stress and inflammation may contribute to metabolic and reproductive disturbances. At the same time, the available evidence remains strongly dependent on experimental design, and the biological significance of effects observed at high concentrations cannot always be directly extrapolated to environmentally realistic exposure conditions. Recent evidence therefore supports a context-dependent assessment of microplastic toxicity, taking into account particle characteristics, exposure concentration and duration, species and life stage, and the environmental conditions under which exposure occurs (Wang et al., 2024; Ghosh, 2024; Hasan et al., 2024)

Microplastics and Seafood Safety

The increasing detection of microplastics (MPs) in fish, shellfish and other seafood products has raised growing concerns about food quality, dietary exposure and consumer safety. Seafood is recognized as one of several possible dietary sources of human exposure to microplastics, alongside drinking water, salt, packaged foods and other contaminated food commodities. However, seafood should not be considered an isolated exposure pathway because microplastics are widely distributed across environmental compartments and can also reach humans through inhalation of airborne particles and household dust, as well as through food preparation and packaging-related sources (WHO, 2022; Bocker & Silva, 2025; EFSA, 2026).

The amount of microplastics potentially ingested through seafood is influenced by several interacting factors, including the species consumed, contamination level, edible portion, serving size, frequency of consumption, geographical origin and harvesting or production conditions. Recent reviews have emphasized considerable variation in reported microplastic concentrations among seafood species and regions, partly because environmental contamination differs spatially and because sampling, digestion and particle-identification procedures are not yet fully standardized (Woh et al., 2024; Kargar et al., 2025). Consequently, estimates of dietary intake can vary substantially between populations and studies. A systematic review of 76 studies also highlighted substantial variability in estimated microplastic intake from different food categories, demonstrating the uncertainty associated with current exposure assessments (2024).

An important consideration when assessing seafood-related exposure is which tissues are actually consumed. In many commonly consumed fish, microplastics are reported predominantly in the gastrointestinal tract, particularly the stomach and intestines. These organs are generally removed during commercial processing or household preparation, meaning that the concentration detected in the whole animal or gastrointestinal tract may not directly represent the concentration ingested by consumers. EFSA similarly notes that microplastics detected mainly in the digestive tract of fish may be removed when fish are eviscerated before consumption (EFSA, 2026). Thus, measurements based exclusively on gastrointestinal contents should be interpreted cautiously when estimating actual human dietary exposure.

The situation can be different for bivalve molluscs, such as mussels, oysters and clams, because these organisms are commonly consumed whole or with their digestive tissues intact. Their filter-feeding behaviour also facilitates the accumulation of suspended particles from the surrounding water. Consequently, bivalves have received particular attention as both indicators of environmental microplastic contamination and potential dietary exposure sources (Güney et al., 2024; Kargar et al., 2025). Recent assessments have continued to report microplastics in commercially available bivalves, although the concentrations differ considerably according to species, location, environmental conditions and analytical methodology.

Crustaceans may also be relevant to dietary exposure, particularly when edible portions include tissues in which particles can accumulate. Recent reviews have reported microplastics in the digestive tract, gills and hepatopancreas of commercially consumed crustaceans, although the extent to which these particles contribute to human exposure depends strongly on how the animals are processed and which tissues are eaten (2025). Therefore, simply reporting the presence of microplastics in a seafood organism does not necessarily provide a direct estimate of the quantity ultimately reaching the consumer.

Food preparation and processing may further modify microplastic exposure. Washing, trimming, gutting, cooking, freezing, thawing and other processing operations can potentially change the abundance, distribution or detectability of particles in seafood. At the same time, processing and food-contact materials may themselves represent additional sources of microplastic contamination. Recent research on food systems emphasizes that microplastics may enter food not only from the original raw material but also during processing, packaging, storage and preparation (2024–2025). A 2025 study of commercially available ready-to-cook clams, for example, found differences in microplastic contamination between processed products, illustrating that industrial processing conditions can influence measured particle concentrations. Nevertheless, the effects of individual preparation practices on the final microplastic dose consumed by humans remain insufficiently characterized, and systematic studies under realistic household and commercial conditions are still required.

From a human-health perspective, the presence of microplastics in seafood should therefore be interpreted with caution. Experimental studies have reported mechanisms through which micro- and nanoplastics may interact with biological systems, including oxidative stress, inflammation, cellular damage and effects on epithelial barriers. However, much of the available evidence comes from in vitro experiments or animal models, and considerable uncertainties remain concerning environmentally realistic exposure concentrations, particle characteristics, absorption, dose–response relationships and long-term effects in humans (Bocca et al., 2024; Fröhlich, 2024; Bocker & Silva, 2025).

Accordingly, the detection of microplastics in seafood should not, by itself, be interpreted as evidence that seafood consumption causes adverse health effects in humans. Current evidence supports the existence of dietary exposure, but the magnitude and health significance of that exposure remain uncertain. EFSA's current assessment similarly emphasizes that knowledge concerning dietary exposure to micro- and nanoplastics and their potential effects on human health remains limited. WHO has also highlighted substantial uncertainties and research gaps concerning exposure assessment and the potential health consequences of environmental microplastic exposure (WHO, 2022).

At the same time, the issue warrants continued attention because seafood remains an important component of diets worldwide and provides high-quality protein, essential fatty acids, vitamins and minerals. The FAO/WHO expert consultation on the risks and benefits of fish consumption emphasized that fish consumption provides important nutritional benefits across the life course. Therefore, the emerging concern over microplastics should be considered within a broader seafood-safety and risk-assessment framework, rather than interpreted as evidence against seafood consumption in general. Future research should prioritize standardized analytical methods, realistic dietary exposure estimates, assessment of the edible fraction of seafood, effects of processing and cooking, and well-designed toxicological and epidemiological studies capable of determining whether measured dietary exposure translates into clinically relevant health effects (Woh et al., 2024; Bocca et al., 2024; EFSA, 2026).

Human Health Considerations

Human exposure to microplastics through seafood has emerged as an important area of food-safety and public-health research. Fish, shellfish and other aquatic foods can act as dietary sources of microplastic exposure, although the magnitude of exposure varies substantially according to the species consumed, particle characteristics, geographical location, food preparation practices and analytical methods used for detection (Woh et al., 2024; Ruggieri et al., 2025). Despite the increasing number of studies, considerable uncertainty remains regarding the actual amount of microplastics reaching humans through

the diet. In particular, reliable estimates are complicated by differences in particle size, polymer type, shape, concentration and the methods used to isolate and identify particles in food. A recent systematic review of dietary exposure studies also highlighted the substantial variability among reported estimates and the continuing lack of standardized approaches for quantifying microplastics in foods (2024).

Once ingested, the biological fate of microplastics is likely to depend strongly on their physical and chemical characteristics. Larger particles may remain within the gastrointestinal tract and subsequently be eliminated in faeces, whereas smaller particles may interact more closely with intestinal tissues and, under some experimental conditions, may cross biological barriers or become available for interaction with cells and tissues (Li et al., 2024). The gastrointestinal tract is therefore considered an important interface between dietary microplastics and the human body. However, the extent to which particles detected experimentally can be absorbed or translocated in humans under realistic dietary exposure conditions remains uncertain. Current assessments by the European Food Safety Authority (EFSA) emphasize that important gaps remain in understanding dietary exposure, absorption, biological behaviour and the potential health significance of micro- and nanoplastics in food.

Nanoplastics are receiving particular scientific attention because their much smaller dimensions may give them biological properties that differ from those of larger microplastics. Their size may facilitate closer interactions with cellular structures and potentially greater opportunities for biological uptake or translocation. Nevertheless, direct evidence concerning dietary exposure to nanoplastics in humans remains particularly limited, partly because these particles are technically difficult to detect, characterize and quantify in complex food matrices (EFSA, 2026; EFSA, 2025). Consequently, observations from experimental studies involving relatively high concentrations of well-characterized particles should not be directly equated with the effects of normal seafood consumption.

Several biological mechanisms have been investigated in experimental and human-focused research, including oxidative stress, inflammatory responses, disruption of cellular functions, changes in gut microbial communities and interactions with endocrine or other biological pathways (Enyoh et al., 2024; Ririe et al., 2025). Microplastics may also contain additives or interact with environmental contaminants and microorganisms, creating additional pathways through which exposure could influence biological systems (WHO, 2022). Recent human-focused evidence has reported associations between microplastic exposure and biomarkers related to inflammation, oxidative stress and endocrine function; however, these findings are not sufficient to establish that microplastics cause specific diseases or adverse clinical outcomes in humans. The available evidence is also constrained by differences in exposure assessment, particle characterization, study design and the relatively limited number of longitudinal human studies (Ririe et al., 2025).

For seafood consumers, an important distinction is therefore needed between the presence of microplastics in edible organisms and the demonstrated health risk resulting from their consumption. Microplastics are frequently detected in fish and seafood, but their occurrence alone does not establish that dietary exposure at currently observed levels produces clinically significant effects in humans. In many fish species, particles are predominantly reported in the gastrointestinal tract, which is commonly removed before consumption, whereas whole-body consumption of some small seafood organisms, particularly bivalves and certain crustaceans, may result in greater direct dietary exposure (Woh et al., 2024; EFSA, 2026).

Therefore, a major priority for current research is to move beyond simply reporting the presence or abundance of microplastics and instead develop realistic, exposure-based assessments of human health

risk. This requires better estimates of dietary intake, standardized analytical methods, improved detection of smaller particles and nanoplastics, and greater understanding of how particle size, shape, polymer composition, surface characteristics and associated chemicals influence biological responses. WHO has similarly emphasized the need for improved exposure data and standardized approaches to address major uncertainties in assessing the health implications of microplastic exposure (WHO, 2022). Overall, current evidence supports continued investigation of microplastics in seafood as a food-safety issue, but conclusions regarding human health effects should remain cautious until exposure levels and biologically relevant dose–response relationships are better established. EFSA's current work likewise identifies dietary exposure and potential health risks from micro- and nanoplastics as important areas requiring further scientific assessment.

Research Gaps and Future Directions

Although research on microplastic contamination in aquatic environments has expanded rapidly, important uncertainties remain regarding the actual exposure, biological relevance and ecological significance of these particles. Future investigations therefore need to move beyond simply documenting the occurrence or abundance of microplastics and place greater emphasis on understanding when, where and at what concentrations exposure is biologically meaningful. Differences in particle size, shape, polymer composition, surface characteristics, weathering state and associated chemicals can substantially influence uptake, transport and toxicity, making it difficult to compare results obtained from different studies (Xu et al., 2025; Yu et al., 2026).

One of the most immediate priorities is the standardization and harmonization of sampling, extraction, identification and quantification methods. Considerable variation among studies in sampling designs, contamination-control procedures, digestion methods, particle-size thresholds and analytical techniques continues to limit the comparability of reported microplastic concentrations. International laboratory initiatives have demonstrated that harmonized protocols, quality-control procedures, common training and interlaboratory comparisons can improve the reliability and comparability of microplastic monitoring data (Bakir et al., 2024). Future monitoring programmes should therefore incorporate standardized quality-assurance procedures and clearly report detection limits, recovery rates, blank corrections and polymer identification criteria.

Another major gap concerns the detection and characterization of the smallest plastic particles, particularly nanoplastics and very small microplastics. Conventional visual and spectroscopic approaches may have limited ability to detect particles at the lower end of the size spectrum, while nanoplastics remain especially challenging to isolate and quantify in complex environmental and biological samples. This is important because particle size can influence uptake, tissue distribution, cellular interactions and biological responses. Recent reviews emphasize that physicochemical characteristics such as particle size, shape, surface properties and polymer type can affect the transport and toxicity of micro- and nanoplastics in fish (Xu et al., 2025). Future research should therefore combine complementary analytical and imaging approaches and improve methods capable of reliably detecting environmentally relevant nanoplastic fractions.

Greater attention is also needed to environmentally realistic exposure concentrations and exposure scenarios. A substantial proportion of experimental research has used relatively high concentrations, uniform spherical particles and pristine polymers that may not adequately represent the heterogeneous particles encountered by fish in natural ecosystems. Differences between particles commonly used in

laboratory experiments and those observed in field samples can complicate interpretation of toxicological findings (Arias-Andreu et al., 2024). Future experiments should increasingly use field-derived particles, realistic concentration ranges, environmentally relevant exposure durations and more representative mixtures of polymers, shapes and sizes. Long-term and chronic exposure studies are particularly important because subtle physiological effects may become apparent only after prolonged exposure.

The relationship between particle characteristics and biological effects also requires more systematic investigation. Rather than treating microplastics as a single contaminant category, future studies should determine how size, shape, polymer composition, surface charge, degree of weathering, biofilm formation and chemical additives influence uptake and toxicity. Recent evidence indicates that these characteristics can modify the biotransport and biological responses of micro- and nanoplastics in fish, including effects on oxidative balance, cellular integrity, immune responses and other physiological processes (Xu et al., 2025). Establishing structure activity relationships would help identify which particle characteristics are most important for ecological risk assessment.

The movement of microplastics through aquatic food webs is another area where substantial uncertainty remains. Laboratory studies have demonstrated that microplastics can be transferred between prey and predators, but the extent to which such transfer occurs under natural environmental conditions, and whether it results in meaningful accumulation at higher trophic levels, remains less certain. Recent reviews continue to emphasize the need to distinguish simple ingestion and trophic transfer from sustained biological accumulation and to examine these processes within realistic food-web contexts (Kushwaha et al., 2024; Xu et al., 2025). Future studies should therefore combine field observations with controlled experiments to examine transfer among plankton, benthic organisms, forage fish and commercially important predatory species.

Particular attention should also be given to microplastic-associated chemicals and combined exposures. Plastic particles can contain intentionally added substances, such as plasticizers, stabilizers and pigments, while weathered particles may interact with environmental contaminants. Consequently, the biological response to an environmentally aged particle may differ from that of a clean, laboratory-produced polymer. Recent reviews of fish toxicology have highlighted the importance of considering plastic additives and co-occurring contaminants when evaluating microplastic effects (2025). Future research should therefore investigate the combined effects of particles, additives and environmentally acquired contaminants rather than considering microplastics exclusively as inert physical particles.

There is also a clear need for long-term, ecologically relevant studies on fish health and population-level consequences. Many existing investigations focus on short-term biomarkers such as oxidative stress, inflammation or changes in biochemical parameters. Although these responses are useful indicators of biological stress, their implications for population persistence are not always clear. Future work should establish whether repeated or chronic exposure affects growth, energy allocation, maturation, reproduction, embryonic development, recruitment, behaviour and survival, and whether these responses ultimately influence population dynamics. Recent syntheses have identified growth, reproduction, behaviour, immune function and other physiological processes as important endpoints for further investigation in fish exposed to micro- and nanoplastics (Xu et al., 2025; Yu et al., 2026).

Commercially important seafood species deserve particular attention because ecological contamination and food-safety questions overlap in this group. Monitoring should encompass commonly consumed finfish, shellfish, crustaceans and other aquatic foods and should consider differences in edible tissues,

preparation practices and consumption patterns. Importantly, detection of microplastics in seafood should not automatically be interpreted as evidence of a demonstrated human-health risk; exposure assessment requires information on particle characteristics, concentrations, consumption rates, gastrointestinal fate and potential bioavailability. International health assessments have similarly emphasized the need for better-quality occurrence data, improved understanding of particle uptake and fate, and stronger toxicological evidence before reliable human-health risk assessments can be made.

Accordingly, harmonized seafood-monitoring programmes would provide an important foundation for evaluating dietary exposure. Such programmes should use comparable sampling designs, analytical methods and reporting units across geographical regions and seafood categories. Establishing coordinated laboratory networks and reference materials could improve data comparability and allow contamination trends to be followed over time. The development of international laboratory networks has already demonstrated the value of shared protocols, infrastructure and quality-control procedures for generating comparable microplastic monitoring data (Bakir et al., 2024).

Finally, future research should place greater emphasis on human dietary exposure assessment rather than relying solely on measurements of microplastics in individual food items. Estimates of exposure should consider particle number and mass, size distribution, polymer type, edible portion, consumption frequency, food preparation and the possible loss or redistribution of particles during processing and digestion. The biological availability of particles and associated chemicals within the gastrointestinal tract also requires further investigation. Recent reviews of micro- and nanoplastics have emphasized the importance of integrating environmental exposure, biological transport and human exposure pathways when evaluating potential risks (Xu et al., 2025).

The next phase of microplastic research should become increasingly integrative and exposure-oriented. Combining environmental monitoring, analytical chemistry, molecular and cellular toxicology, fish physiology, food-web ecology, seafood science and human exposure assessment will be essential for distinguishing simple contamination from biologically meaningful risk. Such interdisciplinary approaches can also help bridge the persistent gap between laboratory observations and conditions encountered in natural aquatic ecosystems. Rather than generating increasingly large inventories of microplastic abundance alone, future research should aim to determine which particles, exposure conditions and biological responses are most relevant to ecological health and seafood safety (Bakir et al., 2024; Xu et al., 2025; Yu et al., 2026).

Conclusion

Microplastic contamination has become an important environmental and food-safety concern because of its widespread occurrence in aquatic ecosystems and its detection in fish, shellfish and other seafood organisms. These particles can enter aquatic food chains through direct ingestion and consumption of contaminated prey, allowing exposure to occur across different trophic levels. Although experimental studies have reported physical, oxidative, inflammatory, metabolic and reproductive responses in aquatic organisms, the magnitude of these effects under environmentally realistic conditions remains uncertain. Similarly, the presence of microplastics in seafood indicates a potential route of human exposure, but current evidence is not sufficient to establish a direct relationship between seafood-associated microplastic exposure and adverse health outcomes in humans. Future research should therefore focus on standardized analytical methods, environmentally relevant exposure levels, improved detection of smaller particles and nanoplastics, trophic transfer, particle-associated chemicals and realistic dietary

exposure. At the same time, reducing plastic inputs through improved waste management, responsible fisheries and aquaculture practices, and greater public awareness will be essential for protecting aquatic ecosystems, maintaining seafood quality and minimizing unnecessary exposure to microplastics.

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