Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(4): 2987 – 3007 (2025)
www.ejabf.journals.ekb.eg

Microplastics in Fish: A Comprehensive Review

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ARTICLE INFO
Article History:
Received: June 2nd, 2025
Accepted: Aug. 1st, 2025
Online: Aug. 25, 2025

Keywords:
Microplastics,
Fish contamination,
Human health,
Food chain,
Ecotoxicology,
Food safety,
Mitigation strategies

ABSTRACT
Microplastic pollution has emerged as a pervasive problem in aquatic environments, with fish playing a central role in transferring these particles through the food chain to humans. This review synthesized recent research on microplastics in fish, examining their sources, pathways into the environment, and occurrence in both wild and farmed populations worldwide. The tools and methodologies used to detect and quantify microplastics in fish were evaluated, highlighting challenges in achieving standardized and reliable results. The review further explored the impacts of microplastic exposure on fish health, including morphological, behavioral, and genetic alterations, as well as broader ecological risks such as trophic transfer and bioaccumulation. Evidence also indicates that human consumption of contaminated fish may serve as a significant route of microplastic ingestion, raising serious public health concerns. Finally, we discuss current mitigation strategies, ranging from policy interventions to emerging technologies, and identify key knowledge gaps, including the long-term health effects of microplastic exposure and the development of more effective remediation techniques. By integrating global findings, this review underscores the urgent need for coordinated action among scientists, policymakers, and industry stakeholders to address this escalating environmental and health challenge.

INTRODUCTION

Microplastics (MPs) – tiny plastic particles typically less than 5mm in size – have become ubiquitous in aquatic environments worldwide **(Pal *et al*., 2025)**. These particles originate from the breakdown of larger plastic debris and from products like microbeads and synthetic fibers, and they have infiltrated ecosystems from surface waters to deep sediments **(Ali *et al*., 2024)**. Fish are among the most studied aquatic organisms for microplastic contamination, given their ecological importance and role in human food security **(Ghosh, 2025)**. This review provides a comprehensive overview of microplastics in fish, covering their sources and pathways into aquatic environments, global distribution and prevalence in wild and farmed fish, analytical methods for detection, effects on fish health and ecosystems, transfer through the food web (including to humans), and current mitigation strategies and research gaps. Key statistics and recent findings are highlighted to illustrate the scale and complexity of this issue.

Sources and pathways of microplastics in aquatic environments

Microplastics enter water bodies through a variety of pathways, both land-based and sea-based. Land-based sources are estimated to contribute about 75–90% of marine plastic debris, while sea-based activities contribute the remainder **(Duis & Coors, 2016)**. Major land-based sources include municipal wastewater and stormwater runoff, which carry microplastics from domestic and industrial activities (e.g. fibers shed from clothing, microbeads from personal care products, and fragments from plastic waste degradation) **(Yang *et al*., 2021)**. Rivers are a critical conduit, transporting plastics from inland areas to the ocean **(Yang *et al*., 2021)**. In freshwater systems, urban runoff, industrial discharges, and the fragmentation of larger plastics are the primary sources of microplastics **(Bhardwaj *et al*., 2024)**. Sea-based sources include lost or discarded fishing gear, shipping activities, and offshore oil and gas operations, which directly release plastics (e.g. pellets, fragments, films, foam and fibers) into marine waters **(Yang *et al*., 2021; El-Naggar *et al*., 2024)**. Notably, the fishing and aquaculture industries contribute significantly through items like nets, lines, and buoys that can break down into microplastics **(Yang *et al*., 2021)**.

Once in the environment, microplastics are widely distributed by physical processes. They can float on the surface, remain suspended in the water column, or sink to the sediments depending on their density and shape **(Sunny *et al*., 2025)**. Wind and ocean currents carry microplastics over long distances, even to remote regions such as polar ice and deep-sea trenches **(Zhang *et al*., 2022)**. In fact, microplastics have been detected in virtually all aquatic habitats – from surface waters and mid-water columns to sediments and even the air above water **(Vivekanand *et al*., 2021; Sunny *et al*., 2025)**. This ubiquity means that fish in both freshwater and marine systems are continually exposed to microplastics through multiple pathways. Fish can ingest microplastics directly by mistaking them for food or indirectly by consuming prey that have already ingested microplastics. Microplastics can also enter fish via the gills during respiration or through adsorption onto the skin **(Roch *et al*., 2020; Khan *et al*., 2025)**.

Types and shapes of microplastics

Microplastics are a heterogeneous mixture of different polymer types, such as polyethylene, polystyrene, polyvinylchloride and polyurethane, and can exist in various forms including fragments, fibers, films, foam, and beads. They are primarily generated from the breakdown of larger plastic debris through processes like photodegradation and mechanical weathering **(Haque & Fan, 2023)**. Among these diverse shapes, fibers are the most common and abundant form found in the environment, followed by larger, elongated particles and those with irregular shapes **(Wu *et al*., 2018; D'Hont *et al*., 2021)**.

Global distribution and prevalence in fish

Microplastic contamination in fish has been documented across all continents and in a wide range of species, indicating a truly global issue. Surveys in both marine and freshwater systems have found microplastics in the gastrointestinal tracts, gills, and even muscle tissues of numerous fish species **(Alberghini *et al*., 2022; Who *et al*., 2024)**. For example, a global synthesis reported that microplastics were present in 84% of wild fish species examined in various studies **(Kibria, 2022)**. Another comprehensive review identified microplastics in 450 species of freshwater fish worldwide, including some endangered species **(De Araújo *et al*., 2025**). In marine environments, an estimated 386 marine fish species (including 210 commercially important species) have been observed to ingest plastic debris **(Savoca *et al*., 2021)**. These numbers underscore that microplastic ingestion is widespread across fish taxa and habitats.

The prevalence of microplastics (i.e. the percentage of fish individuals contaminated) varies by region and study, but high rates are common. In marine fish, reported prevalence ranges from 15% up to 100% in some heavily polluted areas **(Jabeen *et al*., 2017)**. One study of commercial fish from the Persian Gulf found 99% of fish samples contained microplastics **(Hosseinpour *et al*., 2021)**. In freshwater systems, prevalence is often very high as well – for instance, a study in the North Pacific reported microplastics in 100% of planktivorous fish examined **(De Araújo *et al*., 2025**). A review focusing on Asia noted that microplastics were found in 96% of marine fish and 100% of freshwater fish in the reviewed studies from that region **(Oza *et al*., 2024)**. Such high percentages suggest that avoidance of microplastic ingestion is difficult for fish in many environments. Even in relatively remote or less industrialized areas, a significant fraction of fish test positive for microplastics, though generally at lower rates than in urbanized regions **(Wootton *et al*., 2021)**. For example, one study found 61.6% of fish in a developed region (Australia) had microplastics, compared to 35.3% in a less developed region (Fiji) (**Wootton *et al*., 2021)**, highlighting how local pollution levels influence contamination.

In terms of abundance (number of particles per fish), most fish contain only a few microplastic items. Typical findings are on the order of 1–5 particles per individual fish, although ranges can be much wider **(Alberghini *et al*., 2022; Athukorala *et al*., 2024)**. For instance, a study of fish from the Persian Gulf reported an average of 1.28 ± 0.11 particles per fish **(Alberghini *et al*., 2022)**. Another survey of commercial fish from the Arabian Sea found an average of 0.40 ± 0.89 particles per fish **(Alberghini *et al*., 2022)**. In some cases, individual fish have been found with dozens of particles; for example, one fish in a study contained 49 microplastic particles **(Hurt *et al*., 2020)**. The chart below illustrates the average microplastic load found in fish across several key studies, highlighting the varying degrees of contamination.

Microplastic loads tend to be the highest in heavily polluted waters and in filter-feeding or benthic fish species that continuously ingest particles from water or sediment

(Moyo, 2022). Overall, the global data indicate that microplastic contamination of fish is not only widespread but also increasing: one global analysis found that the incidence of plastic ingestion by marine fish doubled over the last decade, increasing by about 2.4% per year **(Savoca *et al*., 2021)**. This trend is attributed to both greater environmental plastic pollution and improved detection methods revealing more particles **(Savoca *et al*., 2021)**.

Farmed fish vs. wild fish: Aquaculture systems are not immune to microplastic pollution. Farmed fish can ingest microplastics from the surrounding water or from feed that may be contaminated **(Jangid *et al*., 2025)**. Studies comparing farmed and wild fish have found microplastics in both, but patterns differ by species and environment. Some research indicates that farmed fish may have higher microplastic loads than wild fish in certain cases. For example, a study in Bangladesh found higher microplastic concentrations in farmed fish (tilapia and pangas) compared to wild carp, possibly due to more concentrated exposure in aquaculture ponds **(Garcia *et al*., 2021)**. Another study noted that farmed fish often exhibit higher contamination levels than wild fish, underscoring the need to monitor aquaculture environments **(Jangid *et al*., 2025)**. However, other comparisons have found the opposite – wild fish from polluted habitats can have more microplastics than farmed fish raised in cleaner waters **(Aiguo *et al*., 2022)**. For instance, wild mullet from the Persian Gulf had more microplastics than farmed mullet, suggesting that environmental exposure is a key factor (**Aiguo *et al*., 2022)**. In general, farmed fish can accumulate microplastics from sources like floating feed pellets, plastic netting, and wastewater, but the presence of microplastics in both wild and farmed populations indicates that no fish is entirely free from this contamination in today's world.

Analytical methods for detecting microplastics in fish

Identifying and quantifying microplastics in fish tissues requires specialized methods to separate plastic particles from organic material and then confirm their composition. The analytical process typically involves several steps: sample preparation, extraction, identification, and quantification. First, fish samples are dissected to isolate target tissues – usually the gastrointestinal tract (stomach and intestines) where ingested plastics accumulate, but also gills, muscle, or other organs if studying translocation **(Oza *et al*., 2024)**. The selected tissues are then processed to remove biological material and concentrate any microplastics present. A common approach is digestion of the organic matter using chemicals or enzymes. Alkaline digestion (e.g. with KOH) is frequently used for fish tissues due to its effectiveness in breaking down proteins and fats without destroying most plastics **(Thiele *et al*., 2021)**. Other digestion methods include acidic solutions (e.g. HNO_3) and oxidative agents (e.g. H_2O_2 or Fenton's reagent) which can rapidly decompose organic matter **(Rani *et al*., 2023)**. Enzymatic digestion is a gentler alternative that uses proteases to dissolve tissue, potentially reducing damage to microplastics **(Rani *et al*., 2023)**. Each method has trade-offs in terms of efficiency and potential to degrade certain plastics, so researchers often choose based on the sample type and study goals **(Di Fiore *et al*., 2024)**.

After digestion or tissue removal, separation techniques are employed to isolate microplastics. Density separation is widely used: the sample is mixed with a high-density salt solution (such as NaCl or $ZnCl_2$) so that plastic particles (which are less dense than the solution) float to the top while heavier inorganic and organic residues sink **(Rani *et al*., 2023)**. The floating fraction containing microplastics can then be skimmed off or filtered. Sieving and filtration through membranes are also used at various stages to separate larger debris and concentrate particles of interest **(Rani *et al*., 2023)**. For example, sample homogenates may be passed through a series of sieves (e.g. 5mm, 1mm, 300µm) to retain microplastics and then filtered onto a fine mesh filter for examination **(Masura *et al*., 2015; Ding *et al*., 2019)**. Throughout these steps, rigorous quality control is essential to avoid contamination: laboratories use filtered water, avoid plastic equipment, and include blank samples to account for any background microplastic presence **(Lin *et al*., 2023)**.

Once microplastic particles are extracted, they must be identified and characterized. The most common identification methods are spectroscopic techniques that can determine the polymer type. Fourier-transform infrared (FTIR) spectroscopy – including micro-FTIR for small particles – and Raman spectroscopy are widely used to identify plastics by their molecular fingerprint **(Jin *et al*., 2022)**. These methods can differentiate common polymers like polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyvinylchloride, polyurethane and nylon. Recent reviews indicate that FTIR is the workhorse for microplastic analysis, often used in over half of studies, followed by Raman spectroscopy **(Jin *et al*., 2022)**. For very small particles (especially nanoplastics), scanning electron microscopy (SEM) combined with energy-dispersive X-ray analysis (EDS) can provide detailed imaging and elemental analysis to distinguish plastic from organic or inorganic particles **(Wagner *et al*., 2017)**. Thermal analysis techniques are another approach: pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) can thermally degrade particles and identify the polymer by the resulting chemical fragments **(Nandikes *et al*., 2024; Singh & Kumar, 2024)**. Py-GC-MS is particularly useful for quantifying total plastic mass or analyzing mixtures of particles, though it does not provide information on particle size or shape. In practice, many studies use a combination of methods: visual inspection under a stereomicroscope to count and categorize particles by size and shape, followed by spectroscopic confirmation of a subset of particles to verify polymer types **(Xiang *et al*., 2022; De Araújo *et al*., 2025)**.

Despite advancements, methodological challenges remain. Microplastic analysis is labor-intensive and prone to contamination, and there is a need for standardized protocols to ensure comparability across studies **(Lin *et al*., 2023)**. A recent critical review of 104 fish microplastic studies found that many had suboptimal quality control –

for example, 59 out of 104 studies scored ≤10/20 on a quality assessment checklist, and only 2 studies scored above 15 **(Lin *et al*., 2023)**. Key issues included lack of proper blank controls, insufficient sample sizes, and inadequate polymer identification for all particles **(Lin *et al*., 2023)**. This highlights the need for improved standards in sampling and analysis. Another challenge is the detection of nanoplastics (particles <1 µm), which often require advanced microscopy or flow cytometry and are easily missed by conventional methods (**Jin *et al*., 2022)**. To address these challenges, researchers are exploring new technologies: for example, computed tomography (CT) scanning combined with AI has been proposed as a non-destructive method to detect microplastics in whole fish by distinguishing their density and shape **(Strafella *et al*., 2024)**. Machine l earning algorithms are also being applied to automate particle identification from spectroscopic data, improving speed and reducing human error **(Khanam *et al*., 2025; Xie *et al*., 2025)**. Overall, the analytical toolkit for microplastics in fish is expanding, but careful laboratory practices and method validation remain essential to generate reliable data.

Effects on fish health and ecosystems

The presence of microplastics in fish raises concerns about their potential impacts on fish health and the broader aquatic ecosystem. Research over the past decade has begun to elucidate both physiological effects on individual fish and ecological effects on populations and food webs.

Physiological and health effects on fish

Microplastics can harm fish in multiple ways. Physical damage is a primary concern: sharp or large plastic fragments can cause internal injuries, blockages, or irritation in the digestive tract. Studies have observed inflammation and tissue damage in the gastrointestinal lining of fish that ingested microplastics **(Bhuyan, 2022; Subaramaniyam *et al*., 2023)**. For instance, microplastic exposure has been linked to structural changes in the intestines, liver, gills, and even brain tissue of fish, along with disruptions in metabolic balance and behavior **(Zolotova *et al*., 2022)**. Microplastics can also impair the function of organs like the liver and kidneys, as demonstrated by histopathological changes in fish exposed to high concentrations of microplastics **(Subaramaniyam *et al*., 2023)**. In some cases, the presence of microplastics in the gut can lead to a false sense of satiation, potentially reducing food intake and growth – an effect observed in laboratory fish fed microplastics **(Foley *et al*., 2018)**.

Beyond physical damage, microplastics can induce toxicological effects through chemical and biological mechanisms. Plastic particles often carry additives (like phthalates, bisphenol A, or flame retardants) that can leach out and act as endocrine disruptors or toxins. They also readily adsorb hydrophobic pollutants from the surrounding water, such as PCBs, DDT, and PAHs, which can reach very high concentrations on plastic surfaces **(Alberghini *et al*., 2022)**. When fish ingest microplastics, these chemicals may be released in the gut and absorbed into the fish's tissues, leading to oxidative stress, inflammation, and cellular damage **(Alberghini *et al*., 2022; Bhuyan, 2022)**. Indeed, studies have found that microplastic exposure causes oxidative stress in fish (evidenced by elevated levels of reactive oxygen species and antioxidant enzymes) and can alter immune responses and gene expression related to stress and detoxification **(Bhuyan, 2022, Banaee *et al*., 2025)**. Chronic exposure has been shown to lead to more severe outcomes: over time, microplastics in tissues can cause chronic inflammation, cell proliferation, and even necrosis, as well as impairment of immune cells **(Alberghini *et al*., 2022)**. In laboratory experiments, fish exposed to microplastics have exhibited reduced survival, growth, and reproductive success. A recent meta-analysis of 85 studies concluded that microplastic exposure significantly inhibits fish growth and survival and impairs reproductive ability, while also increasing oxidative damage (e.g. higher malondialdehyde levels as a marker of lipid peroxidation) **(Wang *et al*., 2024)**. These effects were influenced by particle size, concentration, polymer type, and fish species, but the overall trend was clear that microplastics pose a toxicological hazard to fish **(Wang *et al*., 2024)**.

Behavioral and neurological effects have also been reported. Some fish exposed to microplastics show altered swimming behavior, reduced activity, or impaired feeding behavior, possibly due to neurological impacts or stress responses **(Bhuyan, 2022)**. There is evidence that certain microplastics can cross the blood-brain barrier in fish, leading to neurotoxic effects and changes in neurotransmitter levels **(Hasan *et al*., 2024)**. Additionally, microplastics can act as vectors for pathogenic microorganisms. Plastic particles in water often become colonized by bacteria (the "plastisphere"), including potential pathogens. Ingesting such particles may introduce harmful microbes or antibiotic-resistant bacteria into the fish's gut **(Curren *et al*., 2021; Alberghini *et al*., 2022)**. This could compromise fish immune systems or lead to disease, although research in this area is still emerging.

It is important to note that the severity of effects can vary widely. Many field studies find only low numbers of microplastics in fish, and the immediate health consequences at such low levels are not always clear. Some laboratory experiments use very high microplastic concentrations to elicit effects, which may not reflect typical environmental exposure. Nevertheless, the accumulating evidence indicates that microplastics can negatively affect fish physiology and health, especially with chronic or high-level exposure **(Bhuyan, 2022)**. Even sub-lethal effects like reduced growth or reproductive impairment could have population-level implications if widespread in natural fish stocks.

Ecological consequences and ecosystem-level effects

Microplastics not only impact individual fish but can also have broader ecological consequences. One major concern is the disruption of food webs. Microplastics are ingested by a wide range of aquatic organisms, from zooplankton and benthic invertebrates up to large fish and marine mammals **(Sunny *et al*., 2025)**. When smaller organisms consume microplastics, this can reduce their feeding efficiency and energy uptake, potentially affecting their growth and survival. For example, zooplankton that ingest microplastics may have lower reproductive output or altered behavior, which in turn affects the predators that feed on them **(Pan *et al*., 2022; Malinowski *et al*., 2023)**. In freshwater systems, studies have shown that microplastics can reduce the grazing rate of zooplankton on algae, potentially leading to algal blooms and disrupting the base of the food web (**Malinowski *et al*., 2023)**. This kind of trophic cascade – where microplastics at the lowest levels affect higher trophic levels – could alter ecosystem dynamics.

For fish, a key ecological effect is the transfer of microplastics up the food chain (discussed further in the next section). When predatory fish consume smaller fish or invertebrates that have ingested microplastics, the particles can accumulate in the predators. This means top predators (like large predatory fish, marine mammals, or seabirds) may accumulate relatively higher loads of microplastics through their diet. While true biomagnification (increasing concentration with each trophic level) is debated for microplastics (since they are not easily absorbed and can be egested), there is clear evidence of trophic transfer. For instance, experiments have demonstrated that microplastics ingested by prey fish can be transferred to and detected in the gut of predator fish that eat them **(Athey *et al*., 2020)**. This transfer means that even fish that do not directly ingest plastic from the environment can become contaminated by eating plastic-laden prey. Over time, repeated exposure could lead to bioaccumulation in certain tissues of long-lived species **(Bhuyan, 2022)**.

Another ecological impact is the transport of contaminants and organisms by microplastics. As mentioned, microplastics can carry hydrophobic pollutants and bacteria. When fish ingest microplastics, they may also be ingesting these associated contaminants, which can then move up the food chain. This “Trojan horse” effect means microplastics can enhance the bioavailability of pollutants to fish and other predators **(Banaee *et al*., 2025; Sabri *et al*., 2025)**. Similarly, microplastics can harbor non-native or pathogenic microbes; their transport could influence microbial communities in fish guts or even facilitate the spread of diseases in aquatic populations **(Alberghini *et al*., 2022)**.

On a broader scale, there is concern that chronic microplastic exposure could affect fish population dynamics and biodiversity. If microplastics reduce growth, reproduction, or survival of certain fish species, it could lead to population declines over time. Species that are particularly vulnerable (for example, filter feeders that cannot avoid ingesting particles, or species in heavily polluted habitats) might be at greater risk. Some endangered fish species have already been found with microplastics in their tissues **(De Araújo *et al*., 2025)**, raising concern about potential impacts on conservation efforts. Additionally, changes in fish health and behavior can affect ecosystem functions – for instance, fish that are stressed or less active due to microplastics might not fulfill their ecological roles (such as controlling prey populations or nutrient cycling) as effectively.

Finally, the presence of microplastics can have economic and social-ecological effects. Fisheries and aquaculture are major industries and food sources worldwide. If microplastic pollution were to reduce fish stocks or damage aquaculture operations, it could threaten food security and livelihoods **(Ali *et al*., 2024)**. There is also a growing recognition of the economic costs of plastic pollution, including damage to fishing gear, reduced tourism due to polluted waters, and cleanup expenses. Estimates of the economic loss from marine plastic pollution are on the order of $13 billion per year globally, considering factors like damage to marine industries and ecosystem services **(Xia *et al*., 2023)**. While some of these costs come from larger plastic debris (e.g. entanglement in nets), microplastics contribute indirectly by affecting fish health and ecosystem productivity. In summary, microplastics pose a multi-faceted threat to aquatic ecosystems – impacting individual fish health, disrupting food web interactions, and potentially leading to broader ecological and economic consequences.

Transfer through the food web and implications for human health

One of the most pressing concerns about microplastics in fish is their potential transfer into human food. Fish and other seafood are a major source of protein for many people, and if fish tissues contain microplastics, humans could ingest these particles by consuming seafood **(Alberghini *et al*., 2022)**. This section examines how microplastics move through food webs and what is known about their impacts on human health.

Trophic transfer to higher trophic levels

Microplastics can move up food chains through trophic transfer. Small organisms at the base of the food web (zooplankton, benthic invertebrates, small fish) ingest microplastics, and when they are eaten by larger predators, those microplastics can be passed on. There is substantial evidence that this occurs. For example, laboratory studies have shown that when predatory fish consume smaller fish that have ingested microplastics, the predator's gastrointestinal tract will contain those microplastics **(Athey *et al*., 2020)**. Field observations also support trophic transfer: higher trophic level fish often have microplastics in their guts, which likely come from eating contaminated prey **(Jiang *et al.*, 2023)**. One study in a marine ecosystem found a positive correlation between trophic level and microplastic abundance in fish, suggesting that top predators accumulate more microplastics through their diet **(Jiang *et al.*, 2023)**. However, it's important to note that not all microplastics are efficiently transferred or retained – many are excreted by organisms. Thus, while transfer happens, true biomagnification (where concentration increases exponentially at each trophic level) is not clearly established for microplastics. Nonetheless, the fact that microplastics are present in top predators (including large predatory fish, seabirds, and marine mammals) indicates that they can traverse food webs and reach higher-level consumers.

Humans occupy a high trophic level and can be exposed to microplastics by eating contaminated fish and shellfish. All major categories of seafood – finfish, crustaceans, and mollusks – have been found to contain microplastics. In fact, a recent global review documented microplastics in 926 seafood species (895 finfish, 9 crustaceans, 20 mollusks, and 2 seaweeds) across 57 countries **(Kibria, 2023)**. This includes many commonly consumed species such as tuna, salmon, mackerel, shrimp, oysters, and mussels. When humans consume whole small fish or the organs of larger fish, they ingest any microplastics present in those tissues. Even when we eat only the fillet of a larger fish, there is evidence that microplastics (especially very small ones or nanoplastics) can translocate from the gut to muscle or other tissues. Studies have detected microplastics in the muscle (edible flesh) of fish, indicating that microplastics can move beyond the digestive tract into tissues that people consume **(Hosseinpour *et al*., 2021; Woh *et al*., 2024)**. For example, a 2025 study of seafood from the Persian Gulf found that microplastics could travel from a fish's gills or gut into its muscle, meaning the plastic was present in the meat that humans eat **(Hosseinpour *et al*., 2021)**. Similarly, microplastics have been found in the muscle of fish like mackerel and sardines, and in the soft tissues of shellfish that are eaten whole **(Smith *et al*., 2018; Who *et al*., 2024)**. This indicates that simply removing the gastrointestinal tract may not eliminate all microplastic exposure from eating fish.

The amount of microplastic that an individual might ingest from seafood is still being quantified. Estimates vary widely depending on seafood consumption rates and contamination levels. One analysis suggested that an average person might ingest on the order of 10,000 microplastic particles per year from seafood, but this number can be higher or lower depending on diet **(Danopoulos *et al*., 2020)**. It's worth noting that seafood is not the only source – microplastics are also found in drinking water, salt, and other foods, so total human exposure is cumulative. Nonetheless, frequent seafood consumers could be ingesting significant numbers of microplastics over time. Even more concerning are the associated chemicals and pathogens that microplastics carry. When humans ingest microplastics, they may also be exposed to plastic additives (like bisphenols or phthalates) and adsorbed pollutants (like PCBs or PAHs) that can leach out in the human digestive system **(Alberghini *et al*., 2022)**. There is also the possibility of microbial transfer – pathogenic bacteria attached to microplastics could potentially colonize the human gut, though research on this is in early stages.

Human health risks

The health implications of microplastic ingestion by humans are still not fully understood, but emerging research raises several concerns. Physical effects are a primary consideration: if large numbers of microplastics accumulate in the gastrointestinal tract, they could potentially cause irritation, inflammation, or even blockages. While the particles found in food are usually very small (<1 mm), chronic exposure could lead to mucosal damage or other gastrointestinal issues over time. Some studies in mice have shown that microplastics can induce intestinal inflammation and alter gut microbiota composition **(Kumar *et al*., 2020; Li *et al*., 2023)**. In humans, it is hypothesized that long-term ingestion of microplastics might contribute to conditions like inflammatory bowel disease or other gut disorders, although direct evidence is currently lacking. Another physical risk is the potential for microplastics to translocate into human tissues. Extremely small particles (nanoplastics) can cross biological membranes. Studies have detected microplastics in human stool samples, lung tissue, and even the placenta, indicating that at least some particles can be absorbed and distributed in the body **(Bhuyan, 2022; Ziani *et al*., 2023)**. If microplastics enter the bloodstream or organs, they could potentially cause damage or trigger immune responses in those tissues.

Chemical risks are also significant. Many plastics contain or adsorb toxic chemicals. When microplastics are ingested, these chemicals may be released in the acidic environment of the stomach or intestines and then absorbed. Additives like bisphenol A (BPA) and phthalates are known endocrine disruptors that can leach from plastics; even at low doses, chronic exposure has been linked to developmental and reproductive problems in humans **(Alberghini *et al*., 2022)**. Similarly, persistent organic pollutants (POPs) such as PCBs and DDT that are often found on microplastics are lipophilic and can accumulate in human fat tissue, potentially leading to long-term health issues like cancer, hormonal imbalances, or immune dysfunction **(Alberghini *et al*., 2022)**. One review noted that once absorbed, these POPs can accumulate in human adipose tissue and have been associated with serious health problems including endocrine disorders, reproductive issues, cancer, cardiovascular disease, obesity, and diabetes **(Alberghini *et al*., 2022)**. While it is difficult to directly attribute such health outcomes to microplastic exposure specifically, the presence of these toxins on microplastics adds to the overall chemical burden in the human body.

Biological risks include the potential for microplastics to introduce pathogens or antibiotic resistance genes into the human body. As mentioned, microplastics in the environment can harbor bacteria (including human pathogens like *Vibrio* species) and antibiotic-resistant bacteria. If ingested, these microbes could potentially colonize the gut or cause infections. There is also concern that the biofilm on microplastics might enhance their ability to transfer harmful organisms. Although no definitive cases of illness from microplastic-associated pathogens in humans have been reported yet, this is a plausible risk that warrants further investigation.

It’s important to emphasize that research on human health impacts is still in early stages. Regulatory agencies like the European Food Safety Authority (EFSA) have begun reviewing the evidence, but so far there is no conclusive proof of adverse health effects in humans from microplastic ingestion **(Alberghini *et al*., 2022)**. The doses typically consumed via food are low, and the body may excrete many particles. However, the fact that microplastics are now found in human organs and tissues (as shown in some studies) is a cause for concern about long-term, chronic effects **(Ziani *et al*., 2023)**. There are guidelines or limits for microplastic contamination in seafood if risks are better quantified. For now, the implications for human health remain a critical area of ongoing research growing consensus that the precautionary principle should apply: given that microplastics are widespread in the food supply and potentially harmful, efforts should be made to reduce human exposure. This includes reducing plastic pollution at the source and improving water and food processing to remove microplastics. From a food safety perspective, agencies may eventually set guidelines or limits for microplastic contamination in seafood if risks are better quantified. For now, the implications for human health remain a critical area of ongoing research.

Mitigation strategies and policy responses

Addressing microplastic pollution in fish and aquatic environments requires a multi-pronged approach, including preventive strategies, technological solutions, and policy measures. The goal is to reduce the input of plastics into ecosystems, remove existing microplastics where possible, and ensure the safety of seafood for human consumption.

Reducing microplastic inputs

The most effective way to mitigate microplastic pollution is to prevent plastics from entering the environment in the first place. This involves improving waste management and reducing the use of problematic plastics. Many countries have implemented plastic waste reduction policies, such as bans on plastic bags and single-use plastics, which indirectly help by reducing overall plastic litter that can break down into microplastics. A notable direct intervention has been the ban on microbeads in personal care products: several countries (including the U.S., Canada, UK, and members of the EU) have outlawed rinse-off cosmetics containing plastic microbeads, which were a significant source of primary microplastics in wastewater **(Onyena *et al*., 2021)**. This policy has led to a measurable decrease in microbead pollution in some regions. Additionally, initiatives to reduce plastic packaging and promote recycling aim to keep plastics in use or in waste management systems rather than in nature.

Improving wastewater treatment is another key strategy. Wastewater effluent is a major pathway for microplastics (especially fibers from clothing) to enter rivers and oceans. Conventional wastewater treatment plants can remove a large fraction of microplastics (often 80–99%) through physical and biological processes, but some still escape in the effluent or sludge **(Dayal *et al*., 2024)**. Upgrading treatment plants with additional filtration steps (like fine mesh filters, sand filters, or membrane bioreactors) can capture more microplastics before they are discharged **(Arbabi *et al*., 2023)**. For example, adding a tertiary filtration or a micro-screen can trap smaller particles that would otherwise pass through. Some innovative technologies, such as dissolved air flotation units or electrocoagulation, have shown promise in improving microplastic removal efficiency **(Salahuddin *et al*., 2023)**. Another approach is addressing sources in households: installing fiber filters on washing machines can catch synthetic fibers shed during laundry cycles, preventing them from going down the drain. Several countries (like France) have mandated that new washing machines include such filters by law, which could significantly cut down on fiber emissions.

In the context of aquaculture, measures can be taken to reduce microplastic contamination at the farm level. Using non-plastic or durable infrastructure (e.g. replacing plastic nets with alternative materials or ensuring nets are well-maintained to minimize fragmentation) can reduce microplastic shedding in fish farms **(Wu *et al*., 2023)**. Additionally, sourcing fish feed that is free of microplastic contamination is important – for instance, using feed made from sustainably sourced fish or plant proteins that hasn’t been processed with plastic equipment or contaminated during transport. Some feed manufacturers are exploring encapsulation or processing methods to reduce plastic particle leaching into water. Additionally, aquaculture facilities can implement water circulation and filtration systems to remove microplastics from the water before they are ingested by fish.

Removal and cleanup technologies

Once microplastics are in the environment, removing them is extremely challenging due to their small size and vast distribution. However, some technologies and nature-based solutions are being developed or implemented:

- Filtration and Barriers: In rivers and streams, devices like trash racks, booms, and specialized filtration systems (e.g. the Interceptor devices) can capture larger plastic debris and some microplastics before they reach the ocean. While these primarily catch macroplastics, they can reduce the load of material that would eventually fragment into microplastics.

-Wastewater Sludge Management: Microplastics removed during wastewater treatment often end up in sludge. Proper treatment of sludge (like composting at high temperatures or incineration) can prevent microplastics from entering agricultural lands or water bodies when sludge is used as fertilizer.

- Biological and Chemical Removal: Researchers are investigating methods to degrade or precipitate microplastics in water. For example, certain enzymes and microbes have shown potential to break down plastic polymers (though this is more feasible for larger pieces and specific polymers).

Chemical coagulants can cause microplastics to clump together and settle, which can then be filtered out **(Arbabi *et al*., 2023)**. These methods are still experimental and need careful evaluation to avoid introducing other pollutants.

- Natural Remediation: Wetlands and other aquatic ecosystems can act as sinks for microplastics, as particles get trapped in sediments or taken up by plants. Restoring and conserving wetlands might help reduce microplastic transport to larger water bodies. Some studies suggest that certain aquatic plants and filter feeders can accumulate microplastics, and controlled use of such organisms (bioremediation) could help in specific contexts (though this must be balanced against the risk of harming those organisms).

Policy and regulatory responses

Governments and international bodies are increasingly recognizing microplastic pollution as a priority. At the international level, the United Nations Environment Programme (UNEP) launched a process in 2022 to develop a Global Plastics Treaty by 2024, aiming to end plastic pollution worldwide. This treaty is expected to address the full life cycle of plastics, from production to waste management, which would indirectly reduce microplastic generation. Even before a global treaty, many countries have enacted national policies: for example, the European Union has introduced directives to reduce plastic waste and is considering regulations on microplastics in products. The EU's Strategy for Plastics in a Circular Economy includes measures to reduce microplastic release from tires, paints, and textiles.

On the fisheries and food safety front, regulatory agencies are beginning to take notice. The Food and Agriculture Organization (FAO) and World Health Organization (WHO) have convened expert consultations to evaluate the risk of microplastics in seafood to human health. While no specific maximum limits for microplastics in food have been set yet, these bodies emphasize the importance of monitoring and research. Some countries are starting to include microplastic monitoring in their national water quality and seafood safety programs. For instance, the European Commission's Joint Research Centre has published guidelines for monitoring microplastics in marine environments, and the U.S. NOAA has developed protocols for microplastic analysis in seafood **(Masura *et al*., 2015; McCoy, 2020)**. There is also a push for industry standards: seafood producers and processors may implement quality control steps to minimize microplastic contamination (for example, filtering water used in processing or avoiding plastic packaging that could shed particles).

Public awareness and consumer actions also play a role. Initiatives to reduce plastic use (such as using reusable bags, bottles, and avoiding single-use plastics) can collectively reduce plastic waste. Proper waste disposal and participation in beach or river clean-ups help remove plastics before they fragment. Consumers can also make choices like selecting seafood that is less likely to be contaminated (though at this point, no seafood is guaranteed microplastic-free). For example, larger predatory fish might accumulate more microplastics through their diet, so eating lower on the food chain (smaller fish or herbivorous species) could reduce exposure – though this is speculative and more data are needed.

Research gaps and future directions

Despite significant progress in microplastic research, many gaps remain. Key areas needing further investigation include:

- Standardization of Methods: There is a need for standardized protocols in sampling, extraction, and analysis of microplastics in fish and water. This would improve data comparability and reliability. The development of certified reference materials for microplastics could aid in quality control **(Lin *et al*., 2023)**.

- Nanoplastics: The fate and effects of nanoplastics (particles <1 µm) in fish are poorly understood. These tiny particles can penetrate tissues and may have different toxicological profiles, but they are technically difficult to study. Advances in analytical techniques are needed to detect and quantify nanoplastics in biological samples.

- Ecological and Health Risk Assessment: More research is required to determine the actual risk posed by microplastics to fish populations and to human health. This includes long-term chronic exposure studies, field-based effect studies, and epidemiological studies in humans. Establishing dose-response relationships and safe exposure levels is essential for risk assessment.

- Trophic Transfer and Biomagnification: While transfer is documented, the extent to which microplastics and associated chemicals biomagnify in aquatic food webs needs clarification. Understanding this will help assess the risk to top predators, including humans.

- Environmental Fate: We need a better understanding of how microplastics move and degrade in different environments (freshwater vs. marine, surface vs. deep sea, etc.). This includes the role of biofouling in changing buoyancy, the rate of fragmentation into nanoplastics, and the potential for microplastics to be transported through the air (atmospheric deposition into water bodies).

- Sources and Mitigation Effectiveness: Identifying which sources contribute most to microplastic pollution in specific regions (be it textile fibers, tire wear, or plastic pellets, etc.) can help target mitigation efforts. Additionally, evaluating the effectiveness of mitigation strategies (such as wastewater upgrades or policy interventions) through monitoring is crucial to ensure we are making progress.

CONCLUSION

Algal oil emerges as a scientifically validated, sustainable alternative to microplastics in fish which represents a complex environmental issue with implications for both aquatic ecosystems and human health. The problem is global in scope – microplastics are now found in fish from remote mountain lakes to the deepest oceans. While our understanding is still evolving, the evidence so far indicates that microplastics can harm fish and are entering the human food chain. There is an urgent need for continued research, improved monitoring, and concerted action to reduce plastic pollution. By combining preventive measures (reducing plastic inputs), technological solutions (removing microplastics and cleaning up environments), and policy initiatives (regulations and international cooperation), it may be possible to mitigate the impact of microplastics on fish and ultimately protect both aquatic life and human health. The coming years will be critical in translating scientific knowledge into effective actions to tackle this pervasive form of pollution.

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