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Impact of Plastic Pollution on Freshwater Fish: Pathways, Biological Effects, and Implications

Dr. Pratibha Tripathi
Assistant Professor, Department of Zoology
D. A. V. College, Kanpur
drpratibha032@gmail.com

Abstract: *Plastic pollution is increasingly recognized as a significant threat to freshwater ecosystems, yet its impacts on freshwater fish remain less documented than those in marine systems. Freshwater fish play essential roles in ecosystem functioning and support food security and livelihoods for millions of people. This review synthesizes current evidence on the sources, types, and exposure pathways of plastic pollution in freshwater environments, with a focus on its physiological, behavioural, and ecological effects on freshwater fish. Available studies indicate that plastics are ingested through direct consumption and trophic transfer, leading to physical injury, oxidative stress, endocrine disruption, immune impairment, and reproductive effects. Although many impacts are sub-lethal, their cumulative influence can reduce population resilience and disrupt freshwater food webs. The paper also highlights regional evidence and discusses implications for inland fisheries and human health. Overall, the findings emphasize the need for targeted mitigation strategies and focused research to reduce plastic inputs into freshwater systems and protect freshwater biodiversity.*

Keywords: *Plastic pollution*

I. INTRODUCTION

Plastic pollution has emerged as a persistent environmental challenge due to the rapid increase in plastic production, usage and inadequate waste management. Today, plastics have become ubiquitous because of their low cost and durability, but these same properties have resulted in their long-term persistence in natural environments (Geyer *et al*., 2017). While the ecological impacts of plastic pollution have been widely studied in marine systems, freshwater ecosystems have received comparatively less attention, despite functioning as major sinks and transport pathways for plastic debris (Anderson *et al*., 2016).

Freshwater ecosystems including rivers, lakes, wetlands, and reservoirs support high biodiversity and provide critical ecosystem services such as drinking water supply, nutrient cycling, and inland fisheries. Freshwater fish play a central role in these systems by regulating food webs and energy transfer, and they are widely used as indicators of environmental health due to their sensitivity to water quality changes (Rochman *et al*., 2013). The increasing presence of plastic debris in freshwater environments therefore poses both ecological and socio-economic concerns.

Plastics enter freshwater systems primarily through urban runoff, industrial effluents, agricultural activities, and inefficient waste management practices (Lebreton *et al*., 2017). Once introduced, larger plastic items fragment into microplastics and nano plastics through physical, chemical, and biological processes. These smaller particles are of particular concern because of their persistence, widespread distribution, and increased bioavailability to aquatic organisms (Cole *et al*., 2011). Freshwater fish are exposed to plastics through direct ingestion and trophic transfer, increasing their susceptibility to physical damage and chemical toxicity.

Recent studies have documented plastic particles in the gastrointestinal tracts of freshwater fish across diverse geographic regions (Jabeen *et al*., 2017; Lusher *et al*., 2013). Reported effects include digestive impairment, oxidative stress, immune suppression, and reproductive disruption (Wright *et al*., 2013). Plastics may also act as vectors for toxic additives and environmental contaminants, which further amplify biological impacts (Rochman *et al*., 2013).

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This paper synthesizes current evidence on the sources, types, and exposure pathways of plastic pollution in freshwater ecosystems and critically examines its physiological, behavioural, and ecological impacts on freshwater fish. By consolidating existing research, the study aims to highlight key risks and identify priorities for mitigation and future investigation.

Sources, types and exposure pathways of plastic pollution in freshwater fish

Plastic pollution in freshwater ecosystems originates from multiple, interconnected anthropogenic sources. Unlike marine environments, freshwater systems function both as recipients and conduits for plastic debris, reflecting their close integration with surrounding terrestrial landscapes. Major inputs arise from improper solid waste management, urban runoff, industrial discharge, agricultural activities, and wastewater effluents (Geyer *et al*., 2017; Lebreton *et al*., 2017).

In urban and peri-urban regions, plastic litter from households, markets and several other activities is frequently transported into rivers and streams through stormwater runoff, particularly during rainfall events. Industrial activities contribute through the release of plastic pellets, fragments, and synthetic fibres, often via inadequately treated effluents. Wastewater treatment plants represent a significant pathway for microplastic emissions, as conventional treatment processes are inefficient at completely removing fine plastic particles derived from synthetic textiles and personal care products (Carr *et al*., 2016; Murphy *et al*., 2016). Agricultural practices further contribute through the degradation of plastic mulching films, irrigation components, and packaging materials that fragment in soils and are subsequently transported into freshwater bodies via erosion and runoff (Steinmetz *et al*., 2016). In addition, atmospheric transport and deposition of lightweight plastic fibres contaminate even the remote freshwater environments (Dris *et al*., 2016; Allen *et al*., 2019).

Once introduced, plastics persist in freshwater environments and undergo fragmentation into progressively smaller particles. Freshwater systems contain plastics across a broad size spectrum, including macro plastics, microplastics (<5 mm) and nano plastics (<1 µm). Microplastics represent the most commonly reported size class in freshwater fish due to their widespread distribution and high bioavailability (Cole *et al*., 2011). Nano plastics, although less studied, are of increasing concern because of their potential to cross biological membranes and interact at cellular levels (Geyer *et al*., 2017).

Plastic particles in freshwater systems are composed of diverse polymer types, including polyethylene, polypropylene, polystyrene, polyvinyl chloride, and polyethylene terephthalate (Zhang *et al*., 2017). Differences in polymer density influence environmental behaviour, with low-density plastics tending to remain suspended or float near the surface, while denser polymers accumulate in sediments. These characteristics shape spatial exposure patterns and contribute to species-specific ingestion risks among freshwater fish.

Freshwater fish are exposed to plastic pollution primarily through ingestion. Direct ingestion occurs when plastic particles are mistaken for natural food items due to similarities in size, shape, and colour (Lusher *et al*., 2013). Feeding strategy strongly influences exposure likelihood, with planktivorous, omnivorous, and benthic-feeding species generally exhibiting higher ingestion rates (Jabeen *et al*., 2017). Sediments often act as sinks for dense plastic particles, increasing exposure risks for bottom-dwelling fish.

In addition to direct ingestion, plastics may enter freshwater fish through trophic transfer. Plastic particles consumed by lower trophic organisms, such as zooplankton and benthic invertebrates, can be transferred to fish through predation (Wright *et al*., 2013). Although plastics themselves may not bio magnify in the classical sense, their capacity to adsorb chemical contaminants raises concern regarding the transfer of plastic-associated toxicants across trophic levels.

Environmental conditions further modulate exposure patterns. Rivers function as dynamic transport corridors, facilitating both downstream movement and localized retention of plastics within sediments and vegetation. In contrast, lakes and reservoirs often act as long-term sinks, promoting accumulation and chronic exposure for resident fish populations (Lebreton *et al*., 2017; Zhang *et al*., 2017). Together, these processes create heterogeneous exposure scenarios across freshwater habitats.

Overall, plastic pollution in freshwater fish arises from the interaction of diverse sources, particle characteristics, and ecological factors. Understanding these combined pathways is essential for interpreting observed biological effects and for designing effective mitigation strategies.

Physiological and Biological Impacts of Plastic Pollution on Freshwater Fish

Ingestion of plastic particles can induce a range of physiological and biological effects in freshwater fish, operating across multiple levels of biological organization. These effects are not limited to acute physical injury but include metabolic disruption, cellular toxicity, immune impairment, and reproductive dysfunction. Importantly, many documented impacts occur at sub-lethal levels, suggesting that plastic pollution functions as a chronic stressor rather than an immediate cause of mortality (Rochman *et al*., 2013).

Physical and digestive impacts

Macroplastics and larger microplastics may cause gastrointestinal blockage, abrasion of intestinal tissues, and localized inflammation. Such physical interference reduces digestive efficiency and nutrient absorption, leading to decreased energy availability. Repeated ingestion can result in chronic gut irritation even when particles are eventually excreted. These effects may indirectly impair growth and survival, particularly under conditions of limited food availability.

Metabolic and energetic disruption

The presence of indigestible plastic particles in the gastrointestinal tract can generate a false sense of satiety, reducing feeding motivation and food intake. As a result, freshwater fish may exhibit reduced growth rates, weight loss, and lower condition factors. Energy that would normally be allocated to growth, reproduction, or immune defence may instead be diverted toward stress responses, compromising overall fitness.

Cellular toxicity and oxidative stress

At the cellular level, exposure to microplastics and nano plastics has been associated with oxidative stress, characterized by an imbalance between reactive oxygen species and antioxidant defence mechanisms. Oxidative stress can damage lipids, proteins, and DNA, impairing cellular function and promoting tissue degeneration. Such cellular-level damage is considered a key mechanism underlying many sub-lethal physiological effects of plastic exposure.

Endocrine and reproductive effects

Plastic particles may disrupt endocrine regulation through inherent chemical additives and adsorbed environmental contaminants. Several plastic-associated compounds can mimic or interfere with natural hormones, altering endocrine signalling pathways involved in growth, metabolism, and reproduction (Cole *et al*., 2011). Experimental and field studies have reported reduced egg production, impaired fertilization success, decreased hatchability, and altered reproductive behaviour in fish exposed to plastics (Jabeen *et al*., 2017). Because reproductive processes are highly sensitive to hormonal imbalance, even low-level exposure may have population-level consequences over time.

Immune suppression and contaminant transfer

Chronic plastic exposure has been linked to suppressed immune responses, increasing susceptibility to pathogens and disease (Anderson *et al*., 2016). In addition, plastic particles can act as vectors for heavy metals, pesticides, and persistent organic pollutants. Although plastics themselves may not bioaccumulate permanently, the associated contaminants can transfer to fish tissues following ingestion, increasing toxic burden and impairing organ function, particularly in detoxification organs such as the liver (Rochman *et al*., 2013).

Overall, the physiological and biological effects of plastic pollution on freshwater fish are interconnected and cumulative. Physical injury, metabolic stress, cellular damage, endocrine disruption, immune impairment, and contaminant exposure collectively reduce individual fitness and population resilience. These findings highlight plastic pollution as a significant chronic stressor capable of influencing freshwater fish populations even in the absence of acute toxicity or mass mortality.

Behavioural and Ecological Consequences

Plastic pollution can alter the behaviour of freshwater fish in ways that amplify physiological stress and translate individual-level effects into broader ecological consequences. Behavioural responses often represent early indicators of environmental disturbance and play a key role in shaping survival, reproduction, and species interactions.

Exposure to plastic particles and associated contaminants has been linked to changes in feeding behaviour, activity levels, and risk perception. Freshwater fish exposed to microplastics may exhibit reduced feeding efficiency, impaired prey detection, or increased ingestion of non-nutritive particles. Such behavioural changes can exacerbate energy deficits already caused by digestive and metabolic disruption. Interference with sensory and neural functions may also reduce the ability of fish to detect predators or respond effectively to environmental cues, increasing vulnerability to predation, particularly during early life stages.

Behavioural disruption may also affect reproductive processes. Plastic-associated endocrine-disrupting compounds can alter courtship behaviour, mating frequency, and spawning timing. In species that rely on precise behavioural or environmental cues for successful reproduction, such interference can reduce reproductive success even in the absence of overt physiological damage.

At the population and community level, the cumulative effects of altered behaviour, reduced growth, impaired reproduction, and increased disease susceptibility can lead to shifts in population structure and species composition. More sensitive species may decline, while tolerant or opportunistic species increase in relative abundance, potentially reducing biodiversity. Changes in fish behaviour and population dynamics can further disrupt predator–prey relationships, nutrient cycling, and energy transfer within freshwater food webs.

Overall, behavioural and ecological effects serve as critical pathways through which plastic pollution influences freshwater ecosystems. By modifying how fish interact with their environment and with other organisms, plastic pollution acts as a systemic stressor capable of reshaping freshwater community structure over time.

Regional Evidence and Implications for Inland Fisheries and Human Health

Field-based studies across multiple geographic regions provide consistent evidence that plastic pollution is a widespread feature of freshwater ecosystems and that freshwater fish are routinely exposed through ingestion. Regional investigations are essential for understanding how differences in land use, waste management, and hydrological conditions influence both ecological impacts and human relevance.

In Asian freshwater systems, particularly in densely populated and rapidly urbanizing regions, studies from major river basins such as the Yangtze, Ganges, and Mekong have documented microplastic ingestion in a wide range of freshwater fish species. Fibres and fragments dominate reported particle types, reflecting strong links to wastewater discharge and urban runoff. Similar findings have been reported from freshwater bodies in India, where plastic particles have been detected in fish inhabiting rivers, lakes, and reservoirs near urban and semi-urban areas. These systems often receive continuous plastic inputs, resulting in chronic exposure for resident fish populations.

European freshwater ecosystems, despite relatively stronger waste management frameworks, also exhibit clear evidence of plastic contamination. Studies from rivers such as the Rhine, Danube, and Thames have detected microplastics in fish across multiple trophic levels. Enclosed systems, including lakes and reservoirs, function as long-term sinks for plastic particles due to limited water exchange, promoting accumulation and sustained biological exposure. Emerging evidence from African freshwater systems, although limited, indicates increasing plastic contamination in fish harvested for human consumption near major urban centres, suggesting that the scale of the problem may be underestimated in regions with limited monitoring.

The presence of plastics in freshwater fish has direct implications for inland fisheries and human populations that depend on them. Freshwater fish constitute an important source of dietary protein and income, particularly for small-scale and subsistence fishing communities. Although larger plastic debris is typically removed during processing, microplastics and associated contaminants may persist in edible tissues or indirectly affect fish quality. Plastics can act as vectors for heavy metals, pesticides, and persistent organic pollutants, raising concerns regarding long-term dietary exposure.

Beyond food safety considerations, plastic pollution may reduce fish health, growth, and reproductive success, leading to declines in fish abundance and productivity. Such effects threaten the sustainability of inland fisheries and may undermine food security and livelihoods. In addition, public perception of contamination can reduce consumer confidence, further impacting fisheries-dependent economies.

Overall, regional evidence highlights plastic pollution as a global freshwater issue with both ecological and socio-economic consequences. Integrating ecological findings with fisheries and human health considerations is essential for informing effective management and mitigation strategies.

II. CONCLUSION

Plastic pollution has emerged as a pervasive and persistent stressor in freshwater ecosystems, with freshwater fish among the most consistently affected organisms. Evidence synthesized in this review demonstrates that plastics enter freshwater systems through diverse land-based pathways, persist across habitats, and are readily ingested by fish through direct consumption and trophic transfer. Although many observed effects are sub-lethal, plastic exposure is associated with digestive impairment, metabolic stress, oxidative damage, endocrine disruption, immune suppression, and reproductive dysfunction, collectively reducing individual fitness and population resilience.

Beyond physiological impacts, plastic pollution alters fish behaviour, population dynamics, and ecological interactions, with implications for freshwater food webs and ecosystem functioning. Regional studies further indicate that plastic contamination of freshwater fish is a global issue, extending to inland fisheries that support food security and livelihoods. While uncertainties remain regarding human health risks, the presence of plastic-associated contaminants underscores the need for precautionary management.

Overall, reducing plastic pollution in freshwater ecosystems requires integrated strategies focused on source reduction, effective waste management, and targeted research. Protecting freshwater fish from plastic contamination is essential for sustaining biodiversity, ecosystem services, and human well-being.

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