



Original Research Paper

Effects of Microplastics on Aquatic Biota: Exposure Pathways, Toxic Mechanisms, and Ecosystem-Level Consequences

Rupesh B. Yadav¹, Navnath A. Pawar^{2*}, Chandani B. Jamdade³, Rutuja P. Jadhav⁴

^{1,2}Department of Zoology, Thakur College of Science and Commerce (Empowered Autonomous), Kandivali (E), Mumbai, India, 400101

³Department of Zoology, Yashwantrao Chavan Institute of Science, Satara (Autonomous) Satara, India, 415001

⁴Department of Zoology, Shivaji University, Kolhapur Vidyanagar, Maharashtra, India 416 004

Corresponding Author- napawar.tcsc@gmail.com

Abstract: Microplastics and nanoplastics have emerged as pervasive aquatic contaminants of growing academic and societal concern, reflecting modern plastic-dependent lifestyles and intensifying pressures on freshwater and coastal ecosystems. Their persistence, fragmentation into highly bioavailable size fractions, and capacity to interact with chemical co-contaminants have heightened attention to ecological and food-security risks, particularly in regions experiencing rapid urbanization and uneven waste-management capacity. This review aims to synthesize recent evidence on how microplastics move through aquatic environments, the pathways by which aquatic biota are exposed, the toxic mechanisms driving biological harm, and the ecosystem-level consequences that may result from chronic contamination. A PRISMA-guided systematic literature review was conducted, integrating peer-reviewed studies and authoritative reports published between 2021 and 2025 through qualitative synthesis of field observations, mechanistic research, and monitoring frameworks. The paper consolidates knowledge across four core areas: sources and transport processes across water columns and sediments; exposure pathways including ingestion, gill contact, and trophic transfer; organism-level toxicity encompassing physical stress, oxidative imbalance, inflammation, organ dysfunction, and reproductive and behavioural disruptions; and ecosystem-scale outcomes affecting food webs, productivity, biodiversity, and ecosystem services such as fisheries. Across the reviewed literature, consistent patterns indicate that sediments function as long-term sinks, biological exposure is strongly structured by feeding ecology and habitat use, and multi-stressor interactions may intensify adverse outcomes beyond particle effects alone. The review underscores the need for standardized monitoring, nanoplastic-sensitive analytics, long-term chronic exposure studies, and upstream interventions targeting plastic leakage. These insights support evidence-based policy and management strategies to protect aquatic health and sustain ecosystem services.

Keywords: microplastics; nanoplastics; aquatic biota; trophic transfer; ecotoxicology; ecosystem services.

***Corresponding Author:**

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1. Introduction

1.1 Microplastics as emerging aquatic contaminants

Microplastics are broadly defined as plastic particles smaller than 5 mm, while nanoplastics represent the finer fraction with substantially higher surface reactivity, biological accessibility, and potential for cellular internalization (Vivekanand et al., 2021; Kukkola et al., 2021; Kye et al., 2023). Once plastics enter aquatic environments, they undergo progressive fragmentation driven by photooxidation, mechanical abrasion, hydrolysis, and biodegradation, generating a continuous spectrum of micro- to nano-sized debris that becomes increasingly difficult to detect, quantify, and regulate (Delgado-Gallardo et al., 2021; Lv et al., 2021; Waldschläger et al., 2022). Importantly, fragmentation is not only controlled by physical forces but also by material properties; polymer type, crystallinity, and even particle colour can influence photoaging dynamics and subsequent microplastic formation, indicating that overlooked design features can shape environmental risk (Zhao et al., 2022). Even “reusable” plastic systems can contribute to microplastic generation: controlled evidence shows that mechanical wear from consumer products such as bottle screw-cap systems may release microscopic plastic fragments, highlighting the potential for chronic, low-intensity sources embedded within daily consumption patterns (Giese et al., 2021).

The microplastic issue is also expanding because global plastic production and waste generation continue to rise. Projections indicate that global plastic waste may almost triple by 2060, implying sustained pressure on aquatic systems even if current leakage rates remain unchanged (OECD, 2022). Inputs are dominated by both primary sources (industrial pellets, microbeads, synthetic fibres) and secondary sources derived from the breakdown of microplastics such as packaging materials, fishing gear, and household plastics (Vaid et al., 2021; Vivekanand et al., 2021; Kumar et al., 2021a). Wastewater discharge and urban runoff are repeatedly identified as major conduits, because microplastics generated on land can bypass imperfect treatment barriers and enter rivers that act as high-efficiency transport corridors to lakes, estuaries, and coastal seas (Kumar et al., 2021b; Lechthaler et al., 2021; Talbot & Chang, 2022). The COVID-19 period intensified plastic loading through elevated use of single-use items such as masks, gloves, and packaging, and multiple assessments have linked pandemic-associated consumption patterns to increased coastal and riverine plastic stress (Arduoso et al., 2021; Benson et al., 2021; Shams et al., 2021; Vanapalli et al., 2021). From a governance perspective, life-cycle oriented interventions are increasingly emphasized because upstream product design, consumption

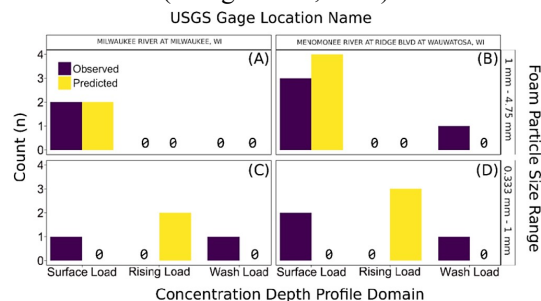
behaviour, and end-of-life management jointly determine downstream aquatic contamination (UNEP, 2021; Noklebye et al., 2023; Phelan et al., 2022).

1.2 Occurrence across aquatic environments

Evidence from field surveys and synthesis studies confirms that microplastics have become pervasive across rivers, lakes, estuaries, lagoons, and coastal waters, with contamination documented in diverse climatic zones, catchment settings, and hydrological regimes (Dusaucy et al., 2021; Talbot & Chang, 2022; Neelavannan & Sen, 2023). In India, widespread detection across freshwater systems includes lowland rivers, urban lakes, Ramsar sites, and high-altitude Himalayan waters, indicating that microplastics are no longer restricted to densely populated coastal corridors (Bharath et al., 2021; Anagha et al., 2023; Jain et al., 2024; Talukdar et al., 2023). River systems such as the Ganga, Hooghly, and Godavari show recurring reports of microplastics in both surface water and sediments, with evidence pointing toward population pressure, wastewater discharge, and local waste handling as key drivers of spatial heterogeneity (Napper et al., 2021; Singh et al., 2021a; Ghosh et al., 2021; Sekar & Sundaram, 2023; Rajan et al., 2023b). Sediment-focused investigations further demonstrate that riverbeds can operate as both storage reservoirs and delayed-release sources, particularly where hydrodynamic conditions enable deposition and later resuspension (Ayyamperumal et al., 2022; Crispin & Parthasarathy, 2023; Maheswaran et al., 2022).

A critical insight from recent hydrological and process-based studies is that microplastics are not uniformly distributed in the water column, and reliance on surface sampling can underestimate true loads and distort risk interpretation (Cowger et al., 2021; Kumar et al., 2021b).

Figure 1. Observed vs. predicted depth-profile transport domains of foam microplastics in river water columns. (Cowger et al., 2021)



This figure compares observed and model-predicted counts of foam microplastic particles across three vertical transport domains—surface load, rising load, and wash load—at two river monitoring locations, separated into two particle size classes (1.0–4.75 mm and 0.333–1.0 mm). The results show that larger buoyant particles are more concentrated

near the surface, whereas smaller particles exhibit greater redistribution into rising/wash-load domains, demonstrating that microplastics are not uniformly confined to surface waters and that vertical mixing can increase mid-water exposure risk for aquatic biota. (Cowger et al., 2021; Talbot & Chang, 2022) Riverbed and hyporheic dynamics can actively concentrate microplastics below the visible surface layer; hyporheic exchange has been identified as a mechanism that progressively drives microplastic accumulation into bed sediments from headwaters toward downstream reaches (Drummond et al., 2022). In lakes, physical stratification and settling behaviour can shape retention and exposure timing; settling velocities and thermally stratified conditions can extend particle residence and promote sedimentation-driven sinks that sustain long-term exposure for benthic biota (Elagami et al., 2022; Elagami et al., 2023). Seasonal variability is also prominent, with multiple studies showing that rainfall patterns, monsoonal flushing, and seasonal hydrodynamics modify microplastic abundance in water and sediments, producing time-dependent hotspots that complicate one-time monitoring campaigns (Cordova et al., 2022; Warriar et al., 2022; Valsan et al., 2024). Collectively, the environmental compartment perspective is essential: surface waters primarily function as transport pathways, sediments serve as major sinks, and biota represent biological exposure and transfer nodes in aquatic food webs (Vaid et al., 2021; Lechthaler et al., 2021; Waldschläger et al., 2022).

1.3 Why aquatic biota are highly vulnerable

Aquatic organisms face elevated vulnerability because exposure is continuous and occurs through multiple simultaneous pathways, including ingestion of suspended particles, sediment contact, and dietary transfer through contaminated prey (Cera & Scalici, 2021; Krause et al., 2021; Kye et al., 2023). Feeding ecology strongly controls ingestion probability: filter feeders, deposit feeders, and benthic organisms encounter microplastics at high frequency due to persistent particle availability in the water column and the long-term accumulation of plastics in sediments (Krause et al., 2021; Maheswaran et al., 2022; Talbot & Chang, 2022). Fish vulnerability is shaped by foraging strategy and habitat use; probabilistic approaches indicate that ingestion patterns depend not only on environmental concentrations but also on biological traits and ecological context, meaning risk is concentrated in specific behavioural and trophic guilds (Covernton et al., 2021; Pandey et al., 2023). Microplastics can also mimic natural food particles in size and appearance, increasing accidental ingestion, while surface conditioning processes such as biofilm formation may further modify palatability and interaction with digestive systems (Vivekanand et al., 2021; Kye et al., 2023).

Impacts extend beyond ingestion frequency because microplastics can interact with co-contaminants and amplify toxicity. In freshwater environments, microplastics have been repeatedly highlighted as potential carriers and vectors for heavy metals and other contaminants, enabling combined exposure scenarios that may exceed risks expected from plastics alone (Selvam et al., 2021; Sarkar et al., 2021; Patidar et al., 2023). This combined stressor reality is particularly relevant for commercially important fish, where microplastics have been documented in wild-caught and market-sold species, raising concerns for ecological health as well as food safety (Shukla et al., 2022; Kumari et al., 2023; Alberghini et al., 2023). The emerging human-health dimension reinforces biological vulnerability narratives, as detection of microplastics in human tissues and samples suggests that aquatic contamination can translate into dietary and systemic exposure routes (Ragusa et al., 2021; Ibrahim et al., 2021; Muhib et al., 2023).

1.4 Objectives and scope of this review

This review synthesizes recent evidence (2021–2025) to clarify how microplastics move through aquatic systems and how they affect living organisms from cellular to ecosystem scales. Specifically, it (i) consolidates current understanding of exposure pathways and uptake mechanisms across diverse aquatic taxa, emphasizing the roles of water-column transport, sediment accumulation, and trophic transfer (Krause et al., 2021; Drummond et al., 2022; Neelavannan & Sen, 2023); (ii) explains dominant toxic mechanisms and biological effects, including physical stress, oxidative imbalance, inflammation, organ dysfunction, and reproductive impacts, as reported in controlled and field-based studies on aquatic biota (Bhuyan, 2022; Pandey et al., 2023; Kye et al., 2023); (iii) connects organism-level outcomes to ecosystem-level consequences, such as altered food-web dynamics, productivity disruption, and risks to ecosystem services including fisheries (Krause et al., 2021; Wu et al., 2024; Sivadas et al., 2022); and (iv) identifies key research gaps and mitigation priorities, including improved monitoring standardization, more realistic multi-stressor experiments, and upstream interventions targeting plastic generation and leakage reduction (Delgado-Gallardo et al., 2021; Waldschläger et al., 2022; Noklebye et al., 2023).

2. Systematic Research Methodology

A PRISMA-guided systematic approach was applied to identify and synthesize recent evidence (2021–2025) on microplastics and nanoplastics affecting aquatic biota, with emphasis on exposure pathways, toxic mechanisms, and ecosystem-scale consequences. Literature was retrieved from Scopus, Web of Science, PubMed, and Google Scholar using structured keyword combinations (e.g., microplastic OR nanoplastic AND freshwater

OR river OR lake OR estuary AND fish OR biota OR toxicity OR food web OR oxidative stress OR trophic transfer), supplemented with targeted queries on wastewater, sediments, COVID-19 plastic waste, policy, and mitigation. The initial identification yielded 1,248 records. After removing duplicates using reference-manager matching rules ($n = 316$), 932 unique records remained for screening.

Inclusion criteria were defined a priori. Studies were retained if they (i) were published between January 2021 and December 2025 ($n = 932$ retained), (ii) were available in English (after excluding 52 non-English items, $n = 880$), (iii) focused on aquatic environments (freshwater, estuarine, lagoon, and coastal aquatic systems) and/or aquatic biota (after excluding 468 terrestrial-only or atmospheric-only papers, $n = 412$), and (iv) reported either environmental occurrence/transport metrics, organism exposure/uptake evidence, toxicological endpoints, or ecosystem-level implications (after excluding 91 papers with no usable data for these outcomes, $n = 321$). Exclusion criteria removed records that were purely methodological without application, commentary-only pieces, unrelated polymer studies, or papers lacking microplastic-specific evidence ($n = 321$ advanced to full-text review).

Full-text eligibility assessment was performed for 321 articles, excluding 188 studies for predefined reasons: marine-only studies without biota relevance to the scope ($n = 74$), insufficient analytical confirmation of particles ($n = 44$), absence of exposure or effects endpoints ($n = 39$), and incomplete reporting or inaccessible full text ($n = 31$). This resulted in 133 sources included in the final synthesis, comprising 131 peer-reviewed articles and 2 authoritative institutional reports used for contextual projections and life-cycle governance framing.

The final dataset ($n = 133$) was thematically categorized to support structured synthesis: occurrence and environmental distribution across compartments ($n = 46$), sources and transport/fate processes ($n = 28$), exposure pathways, uptake, and organism-level toxic mechanisms ($n = 32$), ecosystem-level consequences and food-web implications ($n = 11$), monitoring/analytical methods and QA/QC considerations ($n = 9$), and mitigation/policy and management pathways ($n = 7$). This thematic organization ensured that evidence was traceable from sources and environmental behaviour through biological effects to ecosystem-service implications.

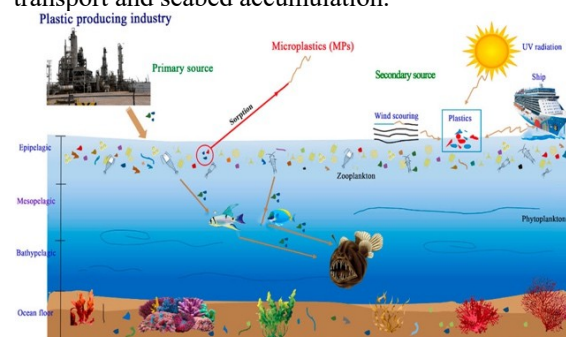
3. Sources, Transport, and Environmental Distribution

3.1 Sources of microplastics in aquatic systems

Microplastics enter aquatic environments through a combination of primary and secondary inputs, and the relative dominance of each source is strongly

shaped by local industrial activity, urban infrastructure, and waste-handling capacity (Kumar et al., 2021a; Vivekanand et al., 2021). Primary microplastics include industrial pellets used as feedstock in plastic manufacturing, pre-production resin powders, microbeads historically used in personal care products, and especially synthetic microfibers released from textiles during washing and wear (Vaid et al., 2021; Talbot & Chang, 2022). Although regulatory actions have reduced microbead usage in several regions, fibres remain persistent because they originate from unavoidable daily consumption patterns and are continuously replenished into wastewater streams (Kye et al., 2023; Neelavannan & Sen, 2023).

Figure 2. Source-to-environment pathway of microplastics from primary inputs to water-column transport and seabed accumulation.



This conceptual illustration shows how microplastics from primary sources (industrial activities and manufactured particles) and fragmented debris enter aquatic systems and partition between the surface layer, mid-water transport, and bottom sediments, creating simultaneous exposure for pelagic and benthic organisms. The figure supports the source-to-sink narrative that aquatic microplastics are sustained by continuous inputs (wastewater and runoff) and progressive redistribution into sediments, where long-term persistence increases biological encounter rates across trophic levels. (Vaid et al., 2021; Vivekanand et al., 2021; Kumar et al., 2021a; Talbot & Chang, 2022)

Secondary microplastics arise from fragmentation of larger debris such as bottles, bags, packaging films, foams, multilayer sachets, and degraded infrastructure plastics, as well as losses from fishing and aquaculture gear in productive coastal and lagoon systems (Kumar et al., 2021a; Sivadas et al., 2022). The scale of this issue is expected to intensify because global plastic waste generation is projected to almost triple by 2060 without major policy and technological shifts (OECD, 2022). In aquatic catchments, secondary formation is accelerated by mechanical abrasion, UV photoaging, and repeated wetting–drying cycles, producing a steady “background supply” that sustains contamination

even if new litter inputs are reduced (Zhao et al., 2022; Waldschläger et al., 2022).

Wastewater and stormwater represent two of the most efficient pipelines delivering microplastics into rivers, lakes, wetlands, and estuaries (Vaid et al., 2021; Kumar et al., 2021b). Evidence from a natural wastewater treatment wetland system in eastern India demonstrates how strong this link can be: treatment ponds contained 7.87–20.39 items/L in surface water and 2124.84–6886.76 items/kg in sediments, while associated wastewater canals reached 30.46–137.72 items/L in surface water and 1108.78–34612.87 items/kg in sediments (Sarkar et al., 2021). Even where treatment systems remove a portion of the load, a large residual flux persists, and the same study estimated surface-water microplastic removal efficiency of treatment ponds at 53%, implying that nearly half the floating load can remain available for downstream transport and biological exposure (Sarkar et al., 2021).

Additional “hidden” sources can arise from consumer products and reuse systems, which are increasingly promoted for sustainability but may unintentionally generate particle emissions. For example, reusable PET bottle screw-cap systems were shown to release 131 ± 25 microplastic particles/L after a single opening and 242 ± 64 particles/L after 11 openings/closings, with the increase mainly driven by polypropylene particles from the cap (Giese et al., 2021). Such findings emphasize that microplastic sources are not restricted to waste mismanagement alone, but can also occur as “use-phase emissions,” meaning that microplastics may be introduced even in settings with relatively controlled solid waste disposal (Giese et al., 2021; Muhib et al., 2023).

Finally, the COVID-19 period revealed how quickly global disruptions can reshape source profiles. Rapid increases in single-use plastics, masks, and antiviral textiles added new litter streams, especially in coastal zones and recreational areas (Ardusso et al., 2021; Benson et al., 2021). These episodic surges are significant because they create time-stamped pulses of secondary microplastics that can persist for years, gradually fragmenting into smaller particles that are harder to monitor and remove (Shams et al., 2021; Vanapalli et al., 2021).

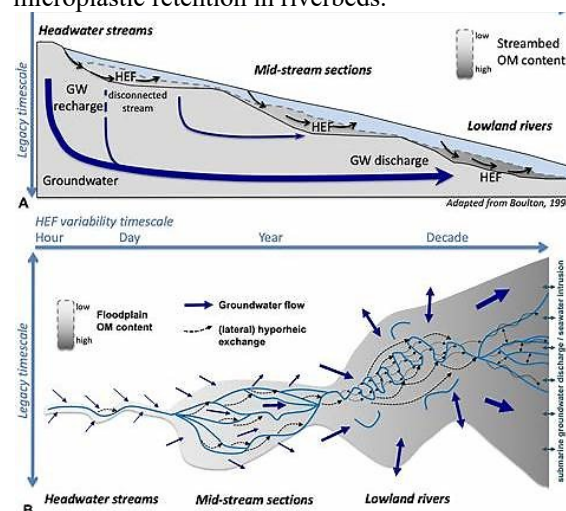
3.2 Transport and fate in aquatic environments

Once released, microplastics behave as highly mobile particulate contaminants whose transport is controlled by hydrology, turbulence, particle properties, and river–sediment exchange processes (Kumar et al., 2021b; Lu et al., 2023). Rivers act as both conduits and processors: they receive continuous inputs from urban drains and tributaries, redistribute particles across depth profiles, and ultimately deliver a fraction of the load into lakes, estuaries, and coastal waters (Vaid et al., 2021; Talbot & Chang, 2022). Field evidence from the transboundary Ganges River highlights the large-

scale connectivity of river transport, where sampling across 10 sites over 2575 km, filtering 3600 L of surface water, recovered 140 microplastics, with 91% of recovered particles being fibres, and a modelled discharge estimate of 1–3 billion microplastics per day entering the Bay of Bengal (Napper et al., 2021). This illustrates how even modest measured concentrations can translate into massive daily fluxes when integrated across river discharge volumes (Napper et al., 2021; Napper et al., 2021).

Hydrodynamic sorting governs whether microplastics remain suspended, accumulate at the surface, or deposit into benthic sediments. A key conceptual shift in recent years is the recognition that deposition is not driven only by gravitational settling, but also by hyporheic exchange, the bidirectional flow between surface water and sediment pore spaces (Drummond et al., 2022).

Figure 3. Hyporheic exchange and groundwater–surface water interactions as mechanisms for microplastic retention in riverbeds.



This conceptual schematic illustrates how groundwater flow and hyporheic exchange drive lateral and vertical water movement through streambed sediments, creating zones of particle trapping, storage, and delayed remobilization from headwaters to lowland river reaches. Such exchange processes help explain why microplastics can accumulate in riverbed sediments even when surface-water concentrations appear modest, increasing long-term exposure potential for benthic organisms and downstream food webs through episodic resuspension and re-entrainment. (Drummond et al., 2022; Waldschläger et al., 2022; Talbot & Chang, 2022)

Modelling of microplastic accumulation from headwaters to mainstems suggests that the longest residence times occur in headwaters, where residence times averaged 5 hours per kilometer but could increase to 7 years per kilometer during low-flow conditions, making small streams potential

long-term storage zones rather than mere transport pathways (Drummond et al., 2022). The same work estimated that long-term accumulation averaged about 5% of microplastic inputs per river kilometer, implying that even if only a small fraction deposits in each reach, cumulative retention across a basin can be large (Drummond et al., 2022). Importantly, deposition rates driven by hyporheic exchange can be up to 180 times greater than gravitational settling for fine particles, and exchange-to-settling ratios for microplastics can exceed 100,000, explaining why lightweight polymers can still be abundant in sediments (Drummond et al., 2022).

Transport is also highly sensitive to extreme events, especially in monsoonal regions. Heavy rainfall, floods, and high-flow pulses can rapidly mobilize plastics stored on riverbanks, dumpsites, and agricultural fields, flushing them into channels and reworking depositional zones (Das & Jain, 2023; Talbot & Chang, 2022). Evidence from northwestern Himalayan rivers shows how proximity to riverbank waste disposal can create very high local contamination, with reported concentrations of 600–2500 particles/m³ near solid-waste dumping sites (Farooq et al., 2023). These event-driven surges matter because they can overwhelm local retention processes and propagate microplastics into downstream lakes and estuaries that function as sinks (Kumar et al., 2021b; Drummond et al., 2022).

Lakes and reservoirs, unlike rivers, often behave as semi-closed systems where residence time, thermal stratification, and settling govern long-term accumulation (Dusaucy et al., 2021; Elagami et al., 2022). Settling behaviour is not fixed: colonization by biofilms increases effective density and changes sinking rates, leading to faster removal of initially buoyant polymers under certain conditions (Elagami et al., 2022; Waldschläger et al., 2022). Experimental work on stratified lake conditions showed settling velocities spanning 0.30 to 50 mm/s, illustrating that some particles may remain suspended for extended periods while others settle rapidly depending on size, density, and surface conditioning (Elagami et al., 2022).

3.3 Distribution across environmental compartments

Microplastics are distributed unevenly across the water column, sediments, and biota, and these compartments should be viewed as a connected exposure continuum rather than isolated reservoirs (Talbot & Chang, 2022; Neelavannan & Sen, 2023). The water column functions as the main transport medium, especially for fibres and low-density polymers such as polyethylene and polypropylene, which tend to remain afloat or suspended depending on turbulence and biofilm growth (Kumar et al., 2021b; Napper et al., 2021). In the Godavari River, for example, surface-water concentrations were reported at 3.9 items/L (equivalent to 3900

items/m³), emphasizing that major rivers can sustain measurable particle loads even outside coastal zones (Sekar & Sundaram, 2023).

Large lakes also show strong spatial and vertical gradients driven by local inflows, shoreline human activity, and stratification. In Vembanad Lake (Kerala), microplastic abundance in the water column ranged from 26.79 ± 3.74 items/L to 52.70 ± 5.43 items/L, indicating substantial within-lake variability linked to hydrodynamic zones and local pressures (Anagha et al., 2023). Similarly, in a southern Indian lake, seasonal differences were evident, with reported concentrations of 0.423 particles/L during the monsoon compared with 0.117 particles/L post-monsoon, reinforcing the role of rainfall-driven inflows and resuspension in shaping short-term water-column loads (Warrier et al., 2022).

Sediments are widely recognized as major sinks, where fine particles can accumulate through settling, hyporheic exchange, aggregation with organic matter, and trapping in benthic biofilms (Drummond et al., 2022; Waldschläger et al., 2022). Quantitative measurements highlight how sediment inventories can exceed water-column values when expressed per unit mass. In Chilika Lake sediments, an assessment across 22 sites collected a total concentration of 440 ± 3.53 particles/kg (wet sediments), dominated by sizes 50–500 µm, consistent with deposition of fine, bioavailable fractions (Kumar et al., 2024). In Veeranam Lake sediments, concentrations ranged from 92 to 604 items/kg, with a mean of 309 items/kg, demonstrating that even freshwater lakes away from coasts can become substantial repositories when exposed to continuous local sources (Bharath et al., 2021).

Transitional systems such as estuaries often exhibit some of the highest reported loads because they integrate upstream river delivery with coastal circulation and dense human settlement along shorelines (Sivadas et al., 2022; Rajan et al., 2023a). In the estuarine environment of Tamil Nadu, microplastic contamination in water was reported in the range 31.66–154.67 items/L, while annual plastic deposition was estimated at 7.1×10^{11} pieces per year, indicating extremely high flux potential in estuarine mixing zones (Jeyasanta et al., 2023). Mangrove waters in southwestern India also showed marked seasonal variation, with concentrations of 1.42 ± 0.92 MPs/L in pre-monsoon, 0.62 ± 0.38 MPs/L during monsoon, and 0.19 ± 0.08 MPs/L post-monsoon, reflecting both dilution effects and dynamic trapping within vegetated coastal systems (Valsan et al., 2024).

Finally, distribution across compartments becomes ecologically meaningful once microplastics enter biota, where ingestion transfers particles into food webs. Evidence from riverine fish marketed for consumption in central India indicated that 87.9% of examined fish contained microplastics, with average

abundance of 3.25 ± 2.58 MPs per gram of fish and 14.9 ± 8.12 MPs per fish, and particle sizes largely 20–300 μm , aligning with the size spectrum known to be readily ingested and retained (Shukla et al., 2022). Such findings reinforce that water- and sediment-based contamination metrics should be interpreted alongside biological monitoring, because ecological harm depends on encounter rates and uptake probability rather than environmental concentration alone (Covernton et al., 2021; Pandey et al., 2023).

3.4 Role of MP characteristics in environmental behaviour

The environmental behaviour of microplastics is highly dependent on size, shape, polymer type, and surface condition, and these properties determine both exposure pathways and eventual ecological risk (Waldschläger et al., 2022; Kukkola et al., 2021). Size is often the first-order control: smaller particles exhibit higher mobility, deeper penetration into sediment pore spaces, and stronger potential for biological uptake across trophic levels (Drummond et al., 2022; Kukkola et al., 2021). Modelling and field evidence emphasize that particles smaller than 100 μm are especially important, because they can be efficiently retained via hyporheic exchange and are likely underrepresented in many monitoring programs that use coarser filters or surface-only sampling (Cowger et al., 2021; Drummond et al., 2022). This bias is not trivial, since small fractions may dominate numerically and drive long-term sediment contamination trajectories (Drummond et al., 2022; Lv et al., 2021).

Shape strongly influences transport and retention. Fibers frequently dominate reported ingestion and water-column observations, consistent with their low settling velocity, high drag, and ease of entanglement with organic matter and biofilms (Napper et al., 2021; Talbot & Chang, 2022). In the Ganges surface-water survey, 91% of recovered microplastics were fibres, highlighting how textile-derived emissions can become the signature particle type at basin scale (Napper et al., 2021). Fibers also appear prominent in fish exposure contexts, where their shape increases the likelihood of gut retention and interaction with mucosal surfaces (Bhuyan, 2022; Shukla et al., 2022).

Polymer type determines intrinsic buoyancy and influences whether particles preferentially float, suspend, or sink. Low-density polymers such as polyethylene and polypropylene are often expected to remain near the surface, but biofilm colonization, aggregation, and sediment exchange can push these particles into benthic sinks over time (Drummond et al., 2022; Elagami et al., 2022). Polymer identity also governs chemical interactions, because different plastics display different affinities for trace metals, persistent organic pollutants, and additive chemicals, shaping the “vector role” of microplastics in contaminated waters (Patidar et al.,

2023; Sarkar et al., 2021). In wastewater-treatment wetlands, toxic metals such as As, Cd, Cr, Cu, Ni, Pb, and Zn were detected on microplastics, and polyethylene terephthalate and polyethylene were identified as major types, with the same plastic types also occurring in fish and macroinvertebrates from the system (Sarkar et al., 2021). In coastal south India, microplastics were reported up to 19.9 particles/L in surface water, with surface-water particle sizes 0.34–4.30 mm compared to groundwater sizes 0.12–2.50 mm, indicating both widespread occurrence and size-dependent transport into subsurface compartments (Selvam et al., 2021). Even visual properties such as colour may shape environmental persistence and microplastic formation rates because colour influences solar absorbance, UV transmittance, and photoaging kinetics (Zhao et al., 2022). This matters for distribution because faster aging can increase fragmentation rates, expanding the abundance of smaller size fractions that are most mobile, bioavailable, and difficult to remove through conventional filtration or cleanup methods (Kukkola et al., 2021; Waldschläger et al., 2022). Collectively, these attribute-driven behaviours explain why microplastic contamination cannot be evaluated using concentration alone: the same numeric abundance can imply very different ecological exposure scenarios depending on whether particles are primarily fibres or fragments, whether they are tens of micrometres or millimetres in size, and whether they are chemically “clean” or metal-loaded (Patidar et al., 2023; Sarkar et al., 2021).

4. Exposure Pathways and Uptake in Aquatic Biota

4.1 Direct exposure routes

Aquatic organisms experience direct microplastic exposure primarily through the water column, where suspended particles overlap strongly with the size range of planktonic prey, detrital aggregates, and natural particulates consumed by many taxa (Talbot & Chang, 2022; Kye et al., 2023). Filter-feeding organisms such as zooplankton, bivalves, and larval fish are especially prone to water-column ingestion because their feeding is driven by particle capture efficiency rather than active prey selection, increasing the likelihood of capturing microplastics present in the same hydraulic microenvironment (Kukkola et al., 2021; Krause et al., 2021). Direct ingestion risk is amplified in rivers and estuaries where microplastic loads can be persistently high; for instance, microplastics in estuarine waters of Tamil Nadu were reported at 31.66–154.67 items/L, indicating that even short-duration feeding can yield repeated encounters with plastic particles at biologically relevant frequencies (Jeyasanta et al., 2023). Comparable evidence from freshwater lakes indicates that water-column exposure can reach tens of particles per Liter, such as in Vembanad Lake, where reported abundance ranged from 26.79 ± 3.74

items/L to 52.70 ± 5.43 items/L, making routine filtering and grazing behaviour an efficient pathway for chronic uptake (Anagha et al., 2023).

In addition to pelagic ingestion, sediment-contact exposure is a dominant direct pathway for benthic and demersal organisms because sediments function as long-term sinks that continuously “reseed” the near-bottom environment through disturbance and resuspension (Drummond et al., 2022; Waldschläger et al., 2022). Many freshwater and estuarine studies show that sediment concentrations can exceed water-column loads by orders of magnitude when expressed per unit mass, such as treatment-wetland sediments reported at 2124.84–6886.76 items/kg and wastewater canal sediments reaching 1108.78–34612.87 items/kg (Sarkar et al., 2021). Such inventories are ecologically important because deposit feeders, benthic grazers, and sediment-ingesting fish integrate exposure over long timeframes, effectively sampling microplastics accumulated across seasons and hydrological events rather than only momentary water conditions (Maheswaran et al., 2022; Talbot & Chang, 2022). Even in large lagoon systems, fine particle deposition dominates sediment risk; for example, Chilika Lake sediments contained 440 ± 3.53 particles/kg, with a strong presence of 50–500 μm particles that are readily accessible to benthic invertebrates and bottom-feeding fish (Kumar et al., 2024).

A third direct route involves gill interaction during respiration, particularly under conditions where microplastics remain suspended and repeatedly pass across gill lamellae during ventilation (Bhuyan, 2022; Kye et al., 2023). The gill pathway is often underestimated because monitoring tends to focus on gut contents, yet fine microplastics can become physically trapped within gill structures and contribute to irritation, reduced gas exchange efficiency, and physiological stress responses (Bhuyan, 2022; Mishra et al., 2023). Rivers with strong vertical and depth-related gradients can expose fish to plastics throughout the water column rather than only at the surface, and depth-profile evidence underscores that sampling restricted to surface waters may not capture the actual exposure field encountered by ventilating and swimming organisms (Cowger et al., 2021; Kumar et al., 2021b). Collectively, water-column ingestion, sediment-associated feeding, and gill contact operate simultaneously in many organisms, creating multi-route exposure that can be sustained even when any one compartment temporarily declines (Talbot & Chang, 2022; Neelavannan & Sen, 2023).

4.2 Indirect exposure via trophic transfer

Beyond direct uptake, microplastics enter aquatic organisms through trophic transfer, moving from plankton and benthos into small fish and ultimately into larger predators via food-web interactions (Krause et al., 2021; Covernton et al., 2021). This

pathway is especially relevant because prey selection and feeding guild structure can concentrate microplastics in particular trophic levels even when environmental concentrations appear moderate (Covernton et al., 2021; Pandey et al., 2023). A key mechanism is that lower trophic organisms—such as zooplankton, benthic macroinvertebrates, and detritivores—frequently ingest microplastics unintentionally and then become vectors transferring particles into predators that consume them (Krause et al., 2021; Kye et al., 2023). In freshwater food webs, ecological traits such as habitat use and feeding strategy strongly mediate risk, with organisms linked to sediments or detrital pathways often acting as high-probability nodes for trophic transfer due to higher microplastic encounter rates in depositional environments (Drummond et al., 2022; Maheswaran et al., 2022).

Empirical evidence from commercially consumed fish underscores that trophic transfer is not hypothetical but measurable in real supply chains. In market-sold fish from central India, 87.9% of examined individuals contained microplastics, with reported mean abundance of 14.9 ± 8.12 particles per fish and 3.25 ± 2.58 particles per gram of tissue, demonstrating that repeated exposure and/or dietary transfer can generate substantial loads in organisms entering human food systems (Shukla et al., 2022). Similarly, studies on wild-caught fish from the Ganga River documented plastic occurrence in species occupying different ecological niches, reinforcing that trophic structure influences contamination patterns across fisheries-relevant taxa (Badola et al., 2023; Kumari et al., 2023). Evidence from Vembanad Lake on bottom-dwelling finfishes and shellfish further supports that food-web connected species, especially those interacting with sediments, can accumulate microplastics across multiple trophic interactions and feeding events (Nikki et al., 2021).

Feeding guild differences also explain why some taxa accumulate higher loads under similar environmental exposure. A Bayesian synthesis of microplastic ingestion in fishes demonstrated that ingestion probability is influenced by multiple interacting factors, including ecological traits and environmental context, implying that trophic transfer and feeding behaviour act together to shape ingestion patterns rather than concentration alone (Covernton et al., 2021). Studies emphasizing feeding selectivity provide mechanistic support: in amphibious mudskipper fish, oral cavity traits and feeding adaptations were shown to affect microplastic uptake, indicating that functional morphology can alter how efficiently plastic particles are captured, retained, or rejected during feeding (Kumkar et al., 2021). These findings align with broader ecological interpretations that deposit feeders and predators may show higher loads because they either ingest contaminated sediment-

associated prey or consume multiple prey items that have already accumulated microplastics (Krause et al., 2021; Pandey et al., 2023). Therefore, trophic transfer is best viewed as a compounding mechanism that amplifies exposure in organisms positioned higher in food webs or strongly linked to benthic prey pathways (Krause et al., 2021; Kye et al., 2023).

4.3 Internalization and translocation

Once microplastics enter the organism, biological consequences depend not only on ingestion frequency but also on internal retention, elimination efficiency, and the potential for translocation beyond the gut (Bhuyan, 2022; Kukkola et al., 2021). For larger microplastics, the dominant internal fate is typically confinement within the gastrointestinal tract, with variability in residence time driven by gut motility, feeding state, and particle shape (Kye et al., 2023; Mishra et al., 2023). Fibers may persist longer because they can entangle with gut mucus or become embedded in gut folds, potentially increasing irritation and delaying excretion compared with spherical or fragment-shaped particles (Napper et al., 2021; Bhuyan, 2022). Field studies reporting dominant fibre occurrence in river waters are therefore ecologically meaningful, because the same particle type is repeatedly associated with high ingestion frequencies and may contribute disproportionately to retention risk (Napper et al., 2021; Talbot & Chang, 2022).

In contrast, smaller microplastics and nanoplastics are more likely to cross epithelial barriers due to their higher surface area-to-volume ratios, greater mobility within biological fluids, and increased probability of cellular uptake processes such as endocytosis (Kukkola et al., 2021; Kye et al., 2023). The environmental distribution of fine particles supports this concern: in several systems, microplastics are dominated by particles <500 µm, a size range that overlaps with biological ingestion thresholds and potential for tissue interaction (Kumar et al., 2024; Shukla et al., 2022). Controlled perspectives emphasize that nano-sized fractions may have enhanced bioavailability, meaning that even if nanoplastics represent a smaller fraction by mass, they could be more important for systemic transport into organs such as liver, gills, and reproductive tissues (Kukkola et al., 2021; Bhuyan, 2022).

While direct organ-level quantification is not always reported in field studies, indirect evidence suggests the plausibility of translocation through multi-compartment contamination patterns and uptake routes that extend beyond simple ingestion. Microplastics are reported not only in fish gut contents but also within tissues and human-associated biological samples, which strengthens the argument that fine plastics can cross biological barriers under real-world conditions (Ragusa et al.,

2021; Ibrahim et al., 2021; Muhib et al., 2023). Importantly, the vector role of microplastics complicates internal exposure because adsorbed metals and chemical additives may desorb under gastrointestinal conditions, creating combined internal stress beyond the mechanical presence of particles (Sarkar et al., 2021; Patidar et al., 2023). In an eastern Indian wetland treatment system, microplastics carried multiple toxic metals including As, Cd, Cr, Cu, Ni, Pb, and Zn, and the same environment showed microplastics present across fish and macroinvertebrates, demonstrating a realistic pathway for co-contaminant uptake through particle ingestion (Sarkar et al., 2021). Therefore, internalization should be evaluated as a coupled process involving particle retention plus contaminant release potential, especially for fine particles with higher sorption capacity (Patidar et al., 2023; Waldschl ager et al., 2022).

4.4 Factors influencing uptake and retention

Microplastic uptake is not uniform across species because it is shaped by feeding behaviour, habitat preference, physiology, and environmental exposure intensity, producing clear risk contrasts between ecological guilds (Covernton et al., 2021; Krause et al., 2021). For example, organisms living near the sediment–water interface often face higher effective exposure because sediments act as reservoirs that can be resuspended during storms, bioturbation, or human disturbance, repeatedly reintroducing particles into the feeding zone (Drummond et al., 2022; Warri er et al., 2022). In monsoonal systems, seasonal changes can further intensify these dynamics; surface-water microplastic concentrations have been observed to increase during monsoon periods in some lakes, supporting the idea that rainfall and runoff can temporarily elevate exposure and drive pulses of uptake in organisms feeding during these periods (Warri er et al., 2022; Valsan et al., 2024). Evidence from northwestern Himalayan rivers also shows that localized waste dumping can create exceptionally high concentrations near riverbanks, with reported values of 600–2500 particles/m³ near disposal sites, suggesting that organisms occupying or feeding in these zones may experience chronic high-dose exposure even if broader river averages appear lower (Farooq et al., 2023).

The plastisphere effect represents another important uptake modifier. Microplastics rapidly acquire surface biofilms and microbial communities that can alter their density and sinking behaviour, while also changing their chemical signals and increasing their resemblance to natural food particles (Waldschl ager et al., 2022; Kye et al., 2023). Biofilm conditioning can therefore raise ingestion probability, especially for organisms that use olfactory or chemo-sensory cues during feeding, and may simultaneously increase sedimentation and retention in benthic environments (Elagami et al., 2022; Waldschl ager et

al., 2022). This mechanism helps explain why even low-density polymers such as polyethylene and polypropylene—which might be expected to float—are repeatedly detected in sediments and benthic fauna, because surface conditioning and aggregation can shift them from floating particles to benthic-associated contaminants (Drummond et al., 2022; Kumar et al., 2024).

Physiology and gut structure also influence retention. Species with longer gut residence times, complex intestinal folds, or feeding strategies that include detritus and sediment ingestion may retain microplastics longer and accumulate higher loads over time (Bhuyan, 2022; Maheswaran et al., 2022). Fish feeding morphology has been explicitly linked to microplastic selectivity; mudskipper oral cavity adaptations were associated with differences in microplastic uptake potential, indicating that anatomical filtering and feeding mechanics can alter particle retention probability (Kumkar et al., 2021). Similar principles apply across taxa, where filter structures, mucus production, and gut transit speed determine whether ingested plastics are efficiently expelled or persist and interact with internal tissues (Kukkola et al., 2021; Mishra et al., 2023).

Finally, repeated chronic exposure is a decisive driver of long-term accumulation, particularly in ecosystems with sustained sources such as wastewater discharge, urban runoff, and unmanaged dumping (Kumar et al., 2021b; Neelavannan & Sen, 2023). The magnitude of chronic exposure can be inferred from high daily transport estimates and persistent contamination measurements. In the Ganges River, modelled discharge of 1–3 billion microplastics per day implies that downstream food webs operate under continuous microplastic supply, supporting long-term exposure conditions for organisms across trophic levels (Napper et al., 2021). When such chronic flux intersects with high local concentrations in estuaries and mangroves—systems critical as nurseries and fisheries habitats—microplastic uptake can become a recurring ecological stressor with broad population-level implications (Jeyasanta et al., 2023; Valsan et al., 2024; Sivadas et al., 2022). Thus, uptake and retention are best conceptualized as outcomes of interacting biological traits and environmental forcing, where hydrology controls encounter rates, feeding strategy controls ingestion probability, and particle attributes control retention and internal fate (Covernton et al., 2021; Kye et al., 2023; Waldschl ger et al., 2022).

5. Toxic Mechanisms and Organism-Level Effects

Microplastics affect aquatic organisms through a multilayered toxicity framework where physical stressors (particle burden and abrasion), biochemical disruption (oxidative imbalance and inflammation), organ-level pathology (gills, gut, liver injury), and fitness-related outcomes (growth, reproduction,

behaviour) interact over time (Kukkola et al., 2021; Bhuyan, 2022; Kye et al., 2023). These impacts are rarely driven by particle presence alone, because microplastics often coexist with plastic additives and sorbed contaminants that modify toxicity, bioavailability, and internal stress responses (Ajay et al., 2021; Sarkar et al., 2021; Patidar et al., 2023). Importantly, high environmental exposure intensifies organism-level damage: in market-sold fish from India, 87.9% of examined individuals contained microplastics, averaging 14.9 ± 8.12 particles per fish and 3.25 ± 2.58 particles per gram of fish, indicating chronic ingestion pressure and repeated internal contact with plastic particles (Shukla et al., 2022). When such biological uptake occurs in ecosystems with large daily fluxes—such as the transboundary Ganges River, estimated to discharge 1–3 billion microplastics per day—the probability of sustained organism-level impacts rises substantially across food webs (Napper et al., 2021; Krause et al., 2021).

5.1 Physical and physiological stress

The most immediate biological effects of microplastics arise from physical interactions between particles and organismal surfaces, particularly in the gastrointestinal tract where ingestion leads to gut filling, abrasion, and altered digestive efficiency (Bhuyan, 2022; Mishra et al., 2023). Gut blockage does not always mean complete obstruction; more commonly, microplastics produce partial blockage, mucosal irritation, and reduced gut motility, which collectively lower assimilation efficiency even when feeding continues (Kye et al., 2023; Kukkola et al., 2021). This pathway is particularly relevant for fish and benthic feeders because they ingest plastics across a wide size spectrum that overlaps with natural prey particles and detrital fractions (Pandey et al., 2023; Neelavannan & Sen, 2023). In real-world fisheries exposure, the dominance of small particles (often tens to hundreds of micrometres) is especially concerning, because these sizes can lodge within gut folds and remain in contact with intestinal epithelia for longer residence times compared to larger fragments that may be expelled more efficiently (Shukla et al., 2022; Kumar et al., 2024).

False satiation represents another important physical mechanism. Microplastics can occupy gut volume without providing nutritional value, causing perceived fullness that suppresses feeding drive and alters energy intake, particularly in smaller-bodied organisms where gut volume is limited (Bhuyan, 2022; Kye et al., 2023). Over time, this produces energy trade-offs, where organisms must allocate limited energy to maintenance stress responses rather than growth and reproduction, resulting in reduced body condition and slower growth trajectories (Krause et al., 2021; Mishra et al., 2023). These trade-offs are expected to be strongest in environments where microplastics are persistently

abundant. For instance, estuarine waters have been reported at 31.66–154.67 items/L, meaning that filter-feeding and planktivorous organisms can encounter plastic particles at high frequency during routine feeding, magnifying the probability of gut loading and physiological strain (Jeyasanta et al., 2023).

Physical irritation can extend beyond the gut to external contact surfaces. Suspended microplastics can interact with gills during respiration, causing frictional stress, entrapment, and lamellar irritation, particularly in turbulent or particle-rich waters where ventilation exposes gill surfaces to continuous particulate contact (Bhuyan, 2022; Cowger et al., 2021). This is consistent with the observation that microplastics are not uniformly distributed only at the surface; depth profiles in river flow can vary substantially, which means fish may experience exposure throughout the water column rather than only in surface layers measured by common sampling methods (Cowger et al., 2021; Kumar et al., 2021b).

In benthic systems, physical exposure is reinforced by sediment accumulation. Sediments act as long-term microplastic sinks, and reported values such as 440 ± 3.53 particles/kg in lake sediments and ranges of 92–604 items/kg in freshwater reservoir sediments indicate persistent particle availability at the sediment–organism interface (Kumar et al., 2024; Bharath et al., 2021). This increases the likelihood of chronic ingestion by deposit feeders, benthic grazers, and bottom-dwelling fish, which can accumulate stress over longer timescales even when water-column concentrations fluctuate seasonally (Maheswaran et al., 2022; Warriar et al., 2022).

5.2 Cellular and biochemical toxicity

At the cellular level, microplastic toxicity is frequently mediated through oxidative stress, where particle exposure triggers overproduction of reactive oxygen species (ROS) and overwhelms antioxidant defence systems, leading to molecular damage and metabolic dysfunction (Kukkola et al., 2021; Bhuyan, 2022; Kye et al., 2023). ROS generation can be initiated by direct particle-cell interactions, inflammatory signalling triggered by foreign materials, and chemical stress resulting from additives or sorbed pollutants released under physiological conditions (Patidar et al., 2023; Muhib et al., 2023). Oxidative imbalance can disrupt lipids, proteins, and nucleic acids, which makes oxidative stress a central “hub mechanism” linking microplastics to broad physiological outcomes such as reduced growth, impaired immunity, and reproductive dysfunction (Krause et al., 2021; Mishra et al., 2023).

Disruption of antioxidant defences is closely connected to metabolic imbalance. Microplastics can force organisms into a stress response state where energy is diverted away from growth and

development toward detoxification, repair, and immune activation (Bhuyan, 2022; Kye et al., 2023). This diversion is particularly important in food webs, where energetic constraints govern survival and reproductive success. Freshwater food-web assessments emphasize that environmental controls determine uptake and biomagnification potential, implying that biochemical effects cannot be separated from ecological context (Krause et al., 2021; Talbot & Chang, 2022). In fish populations, ingestion probability varies with ecological traits and ambient conditions, reinforcing that biochemical damage risk becomes unevenly distributed across species and habitats (Covernton et al., 2021; Pandey et al., 2023).

Inflammation pathways represent a second major biochemical axis. Microplastics can be recognized as foreign particles, promoting inflammatory signalling and immune dysregulation, particularly when exposure is chronic and repeated (Kye et al., 2023; Mishra et al., 2023). This can reduce disease resistance and increase susceptibility to pathogens, especially in habitats already stressed by chemical pollutants or fluctuating environmental conditions (Bhuyan, 2022; Patidar et al., 2023). Importantly, inflammation is not driven only by the particle core: microplastics may act as carriers for contaminants, creating a combined stressor environment that can heighten immune activation and oxidative pressure (Selvam et al., 2021; Sarkar et al., 2021).

Evidence supporting this co-stressor mechanism is strong in wetland treatment and riverine systems. In a natural wastewater-treatment wetland in India, microplastics were found carrying multiple potentially toxic metals, including As, Cd, Cr, Cu, Ni, Pb, and Zn, and microplastics were also detected in fish and macroinvertebrates collected from the same system, indicating a realistic pathway for metal–plastic co-exposure in aquatic organisms (Sarkar et al., 2021). In coastal aquifers and waters, microplastics have been linked to heavy metal vector roles, reinforcing that biochemical toxicity may arise from both sorbed metals and polymer-associated additives (Selvam et al., 2021; Patidar et al., 2023).

Plastic additives are especially relevant for biochemical toxicity. Studies documenting co-occurrence of microplastics with contaminants such as phthalate esters in freshwater lake systems highlight a route through which endocrine-active compounds can accompany microplastic exposure, strengthening the plausibility of hormone-related disruption mediated through chemical stress (Ajay et al., 2021; Alberghini et al., 2023). Thus, oxidative stress and inflammation should be viewed as integrated outcomes of physical particle effects plus chemical stressors, rather than isolated phenomena attributable to plastics alone (Patidar et al., 2023; Kukkola et al., 2021).

5.3 Organ damage and functional impairment

Microplastic-induced organ damage is most consistently documented in gills, gut, and liver, reflecting the dominant exposure routes (respiration and ingestion) and detoxification burden (Bhuyan, 2022; Mishra et al., 2023). Gills are a primary target because they are continuously bathed in ambient water and have delicate exchange surfaces vulnerable to particulate irritation. Microplastics may cause lamellar injury, mucosal disruption, and increased susceptibility to hypoxia stress, leading to respiratory impairment when gill function is compromised (Bhuyan, 2022; Kye et al., 2023). These effects are likely amplified in systems with sustained suspended microplastic loads, including estuarine environments and urban-influenced lakes, where water-column concentrations may remain elevated and fine particles persist in suspension due to turbulence and continuous input (Anagha et al., 2023; Jeyasanta et al., 2023).

The gut is the second dominant target because it is the primary reservoir for ingested plastics. Gut histopathology may include epithelial abrasion, localized inflammation, and altered nutrient absorption capacity, all of which reduce feeding efficiency and growth potential even when organisms maintain similar feeding rates (Bhuyan, 2022; Mishra et al., 2023). The scale of gut stress depends strongly on particle morphology. Fibers tend to dominate ingestion records in many river systems—one large-scale study found 91% of recovered microplastics were fibres in surface waters—suggesting that fibre-induced gut irritation may be particularly important in basin-scale exposure scenarios (Napper et al., 2021; Talbot & Chang, 2022).

The liver is commonly implicated because it is central to detoxification and metabolic regulation. When microplastics deliver sorbed metals or leach additives under physiological conditions, hepatic detoxification pathways may become overloaded, leading to metabolic disruption and oxidative injury (Patidar et al., 2023; Muhib et al., 2023). This is especially plausible in contaminated water bodies where microplastics coexist with metals and other pollutants. In treatment-wetland contexts, detection of toxic metals on microplastics suggests that organisms ingesting these particles experience not only physical exposure but also metal-associated toxic stress, which can translate into liver strain and impaired metabolic capacity (Sarkar et al., 2021).

Functional impairment extends beyond discrete organ injuries and includes whole-organism performance reductions that are difficult to detect through short-term observation alone. For example, microplastic ingestion can reduce energetic efficiency, alter swimming performance, and compromise resilience to environmental variability, outcomes that ultimately influence population dynamics and survival (Krause et al., 2021; Kye et

al., 2023). In freshwater systems where sediments accumulate high microplastic loads, repeated exposure can act as a chronic stressor that interacts with seasonal hydrology, meaning that organisms may experience alternating periods of acute stress (during floods and resuspension) and chronic stress (during stable low-flow conditions) (Drummond et al., 2022; Warriar et al., 2022). This interaction is important because chronic organ-level strain can reduce tolerance thresholds, causing organisms to fail under additional stressors such as low oxygen, disease, or temperature extremes (Krause et al., 2021; Haque & Fan, 2023).

5.4 Reproductive and behavioural impacts

Reproductive toxicity is a high-concern outcome because reproduction directly determines population persistence and recovery. Microplastics can affect reproduction through endocrine-related pathways linked to additive leaching, oxidative stress, inflammation, and energy allocation trade-offs (Ajay et al., 2021; Bhuyan, 2022; Kye et al., 2023). Endocrine disruption risk is strengthened by evidence that microplastics are found alongside plastic-associated chemicals such as phthalate esters in freshwater systems, and these additives are widely recognized for their potential biological activity (Ajay et al., 2021; Patidar et al., 2023). Reduced fecundity, impaired gamete quality, and developmental abnormalities are mechanistically consistent with persistent oxidative stress and inflammatory signalling, because reproductive tissues are highly sensitive to redox imbalance and energy limitation (Kukkola et al., 2021; Bhuyan, 2022).

Evidence of microplastics in human tissues, including placenta and gastrointestinal samples, underscores a broader principle: fine plastics can cross biological barriers under real exposure conditions, supporting concerns that similar barrier-crossing may occur in aquatic organisms and affect reproductive organs through internal translocation (Ragusa et al., 2021; Ibrahim et al., 2021). While aquatic organism studies vary in methodology and detection limits, the increasing recognition of microplastics in internal biological compartments strengthens the plausibility that reproductive impacts may occur through systemic routes rather than gut-limited mechanisms alone (Kukkola et al., 2021; Kye et al., 2023).

Behavioural impacts represent another critical outcome class because subtle changes in feeding and predator avoidance can produce large survival effects even when mortality is not immediate. Microplastic exposure can alter feeding behaviour through false satiation, gut discomfort, and metabolic stress, reducing foraging efficiency and increasing vulnerability to starvation during resource-poor periods (Bhuyan, 2022; Mishra et al., 2023). Predator avoidance and escape performance may also decline if oxidative stress and

inflammation impair neuromuscular coordination or sensory function, creating indirect mortality pathways that are difficult to capture in short laboratory trials but highly relevant in natural ecosystems (Krause et al., 2021; Kye et al., 2023). Feeding ecology and functional morphology further shape behavioural outcomes by influencing how plastics are encountered and handled. For example, eco-morphological studies on mudskipper fish demonstrated that oral cavity structure and feeding selectivity affect microplastic uptake, implying that behavioural and anatomical traits jointly regulate exposure and retention (Kumkar et al., 2021). Bayesian evidence also emphasizes that microplastic ingestion is not random but structured by environmental and biological factors, meaning that behavioural impacts may be concentrated in specific ecological guilds, such as benthic predators and deposit feeders that accumulate plastics via sediment-linked prey pathways (Covernton et al., 2021; Krause et al., 2021).

From an applied perspective, these reproductive and behavioural impacts become particularly concerning because they align with microplastic presence in commercially important fish and shellfish, linking sublethal organism-level effects to fishery sustainability and food security considerations (Nikki et al., 2021; Shukla et al., 2022; Alberghini et al., 2023). When high ingestion prevalence is coupled with substantial environmental loading—such as the estimated 1–3 billion particles/day discharged by the Ganges—long-term risks extend beyond individual organisms to population recruitment, stock stability, and ecosystem-level resilience (Napper et al., 2021; Krause et al., 2021). In this context, reproductive and behavioural toxicity should be interpreted not as isolated endpoints, but as system-scale consequences of chronic exposure, multi-stressor interactions, and persistent contaminant supply into aquatic habitats (Haque & Fan, 2023; Sivadas et al., 2022).

6. Ecosystem-Level Consequences

Microplastic contamination has progressed from being an isolated pollution issue to a systems-level ecological stressor capable of reshaping trophic interactions, weakening ecosystem functions, and reducing the reliability of ecosystem services that support fisheries, food security, and livelihoods (Krause et al., 2021; Talbot & Chang, 2022; Wu et al., 2024). Unlike many conventional pollutants that remain primarily dissolved, microplastics behave as mobile particles that move among water, sediments, and organisms, creating exposure pathways that connect habitats and trophic compartments across space and time (Drummond et al., 2022; Waldschläger et al., 2022). This connectivity is especially important in river-dominated landscapes, where high daily plastic fluxes maintain constant ecological pressure; in the transboundary Ganges River, modelled discharge of 1–3 billion

microplastics per day to the Bay of Bengal provides a clear indicator of persistent loading capable of sustaining long-term ecological impacts downstream (Napper et al., 2021). Such chronic supply is expected to intensify globally because plastic waste generation is projected to almost triple by 2060, implying that aquatic ecosystems will face sustained particle inputs unless source-control interventions substantially improve (OECD, 2022; UNEP, 2021).

6.1 Food-web disruption and trophic implications

Food webs represent one of the most sensitive pathways through which microplastics can generate ecosystem-level consequences, because particle ingestion can occur at multiple trophic steps and spread upward through predator–prey linkages (Krause et al., 2021; Kye et al., 2023). Bioaccumulation begins with high encounter rates at lower trophic levels, where filter feeders, detritivores, and benthic invertebrates ingest microplastics that overlap in size with natural particulates and food resources, creating repeated opportunities for uptake and retention (Krause et al., 2021; Talbot & Chang, 2022). Once contaminated prey are consumed, trophic transfer allows microplastics to move into predatory fish and higher-level consumers, meaning exposure is no longer limited to organisms directly filtering water or interacting with sediments (Covernton et al., 2021; Pandey et al., 2023).

Field evidence from fisheries-relevant organisms demonstrates that trophic contamination is already measurable at scales relevant to ecosystem stability and food provisioning. In fish sold for human consumption in India, 87.9% of individuals examined contained microplastics, with reported mean abundance of 14.9 ± 8.12 particles per fish and 3.25 ± 2.58 particles per gram, reflecting high real-world ingestion pressure and strong potential for food-web propagation (Shukla et al., 2022).

Comparable concerns are reported in wild-caught fish from major river systems, where microplastic occurrence across ecologically distinct species indicates that contamination is not restricted to a single niche but distributed through multiple feeding guilds (Badola et al., 2023; Kumari et al., 2023). Such widespread contamination increases the likelihood of ecosystem impacts because trophic levels are interconnected; any stressor affecting prey availability or predator performance can restructure energy transfer efficiency and reduce food-web stability (Krause et al., 2021; Parolini et al., 2023). Microplastics can disrupt food-web dynamics not only through particle transfer, but also through trait-mediated effects that alter feeding efficiency, prey selectivity, and predator–prey interactions. A Bayesian analysis of fish ingestion patterns indicates that microplastic uptake is shaped by ecological and environmental drivers rather than random chance,

implying predictable vulnerability in certain trophic strategies and habitats (Covernton et al., 2021). Morphology also matters: feeding adaptations and oral cavity traits can influence microplastic capture and retention, meaning that vulnerability can be concentrated in taxa whose feeding structures inadvertently favor plastic intake (Kumkar et al., 2021). This selective vulnerability can shift competition dynamics, allowing tolerant or less-exposed species to dominate while sensitive species decline, ultimately changing community composition and food-web structure (Krause et al., 2021; Talbot & Chang, 2022).

Estuarine systems are particularly important in trophic contexts because they act as nurseries supporting juvenile fish and invertebrates while simultaneously accumulating and redistributing microplastics delivered from rivers and coastal activities (Sivadas et al., 2022; Jeyasanta et al., 2023). High particle loads in estuaries can amplify trophic transfer risk by increasing baseline exposure at the base of the food web; in Tamil Nadu estuarine waters, reported microplastic concentrations of 31.66–154.67 items/L and estimated annual deposition of 7.1×10^{11} pieces per year indicate sustained availability of plastic particles that can enter feeding pathways during critical life stages (Jeyasanta et al., 2023). Over time, such exposure can reduce recruitment success, alter predator–prey stability, and weaken resilience in fisheries-dependent ecosystems (Alberghini et al., 2023; Sivadas et al., 2022).

Food-web disruption becomes more complex when microplastics act as vectors for co-contaminants. Sorbed metals and associated chemicals can be transported into organisms during ingestion, potentially magnifying toxicity and influencing survival and reproduction at multiple trophic levels (Sarkar et al., 2021; Patidar et al., 2023). In a natural wetland treatment system, microplastics carried several potentially toxic metals including As, Cd, Cr, Cu, Ni, Pb, and Zn, demonstrating a pathway by which particle ingestion can deliver chemical stress across food webs (Sarkar et al., 2021). Such combined stress can reshape trophic interactions by reducing prey quality, increasing predator energetic costs, and amplifying sublethal effects that translate into population-level consequences (Bhuyan, 2022; Patidar et al., 2023).

6.2 Productivity and biogeochemical impacts

Microplastics can influence ecosystem functioning through effects on primary productivity and biogeochemical cycling, particularly via interactions with plankton communities that regulate carbon fixation, nutrient turnover, and oxygen balance (Wu et al., 2024; Haque & Fan, 2023). Primary producers and microbial communities sit at the foundation of aquatic ecosystems; therefore, even modest reductions in photosynthetic performance or shifts in microbial structure can cascade upward to affect

food-web energy availability (Wu et al., 2024; Kye et al., 2023). Current evidence indicates that microplastics can interfere with plankton growth by creating shading effects, altering particle–cell encounters, and promoting physiological stress through oxidative and inflammatory pathways (Kukkola et al., 2021; Wu et al., 2024).

A defining mechanism linking microplastics to biogeochemistry is their ability to modify particle aggregation and settling behaviour. In lakes and stratified systems, microplastic settling velocities can vary widely, and particle residence times can be extended depending on environmental conditions, allowing persistent interaction with plankton layers and nutrient-rich zones (Elagami et al., 2022; Elagami et al., 2023). These dynamics can reshape the vertical distribution of organic matter and microbial activity by acting as artificial substrates for microbial colonization and by altering the transport of particles across water layers (Waldschläger et al., 2022; Elagami et al., 2022). In river systems, hyporheic exchange provides an additional pathway for microplastics to enter sediment pore spaces, potentially modifying benthic microbial processes and nutrient release dynamics over long time periods (Drummond et al., 2022). The same mechanism can promote accumulation even for fine particles that would otherwise be expected to remain suspended, creating persistent sediment reservoirs that interact continuously with ecosystem metabolism (Drummond et al., 2022; Waldschläger et al., 2022).

Microplastics also influence carbon cycling by interacting with organic matter and affecting microbial community composition. Reviews focused on freshwater systems highlight that microplastics can influence primary productivity and carbon cycling processes by modifying plankton dynamics and by altering the balance between organic matter production, decomposition, and transport (Wu et al., 2024; Talbot & Chang, 2022). These effects are expected to be especially important in productive lakes and estuaries where microplastics are present at notable concentrations. For example, microplastic abundance in Vembanad Lake water column reached 26.79 ± 3.74 to 52.70 ± 5.43 items/L, indicating frequent particle–plankton interactions that may influence light penetration, microbial attachment opportunities, and grazing dynamics (Anagha et al., 2023). In monsoonal systems, seasonal shifts in microplastic loads can further change productivity outcomes because runoff and resuspension peaks coincide with periods of high nutrient inflow and ecological sensitivity (Warrier et al., 2022; Valsan et al., 2024).

Climate change interactions intensify biogeochemical consequences because hydrological variability and warming can modify microplastic transport, fragmentation, and exposure intensity. The fate of microplastics under climate-change

pressure includes altered transport dynamics during extreme rainfall events and changes in degradation rates under higher temperatures and UV conditions (Haque & Fan, 2023). In regions where future rainfall erosivity is projected to shift, increased runoff and sediment mobilization could enhance plastic transport and resuspension, sustaining chronic stress on plankton and nutrient processes even if local sources remain constant (Das & Jain, 2023; Haque & Fan, 2023).

6.3 Biodiversity and community structure changes

Long-term microplastic exposure can reshape biodiversity patterns by creating chronic stress conditions that reduce survival, reproduction, and competitive performance of sensitive organisms (Krause et al., 2021; Mishra et al., 2023). Ecosystem responses are unlikely to be uniform because microplastic contamination interacts with species traits such as feeding strategy, habitat use, and physiological tolerance, producing selective pressures that can alter community structure over time (Covernton et al., 2021; Talbot & Chang, 2022). Food-web studies emphasize that environmental controls determine microplastic uptake and potential biomagnification patterns, implying that microplastic pollution can shift community dominance by disproportionately affecting the taxa most likely to ingest and retain particles (Krause et al., 2021; Covernton et al., 2021).

Benthic habitats are particularly vulnerable to biodiversity shifts because sediments accumulate fine microplastics and function as reservoirs that sustain long-term exposure. Field measurements commonly show substantial sediment contamination, such as freshwater reservoir sediments with 92–604 items/kg, lake sediments at 440 ± 3.53 particles/kg, and wetland canal sediments reaching 1108.78–34612.87 items/kg, indicating persistent pressure on deposit feeders and benthic communities that support higher trophic levels (Bharath et al., 2021; Kumar et al., 2024; Sarkar et al., 2021). This chronic exposure can shift benthic community composition by reducing the abundance of sensitive taxa and increasing dominance of more tolerant organisms capable of maintaining feeding and reproduction under stress (Krause et al., 2021; Maheswaran et al., 2022).

Community restructuring can also occur through indirect pathways. When microplastics alter prey quality, reduce growth efficiency, or increase mortality risk through behavioural impairment, predators may shift diets, intensifying pressure on alternative prey species and restructuring food-web links (Bhuyan, 2022; Kye et al., 2023). This form of trophic cascading can change community composition even in species that do not directly ingest plastics at high rates, because ecosystem interactions propagate the effects of stress through

changed feeding patterns and recruitment outcomes (Krause et al., 2021; Parolini et al., 2023).

Seasonality and hydrology can further shape biodiversity outcomes because exposure intensity fluctuates with rainfall, runoff, and resuspension. In tropical monsoonal systems, seasonal variation in microplastic abundance has been documented in surface waters, suggesting periodic peaks in organism exposure that may coincide with breeding periods or juvenile recruitment windows (Warrier et al., 2022; Valsan et al., 2024). In high-flow periods, stored plastic can be rapidly mobilized from riverbanks and dumpsites, producing short-duration but high-intensity exposure pulses that can disproportionately affect early life stages and smaller-bodied organisms with limited stress tolerance (Farooq et al., 2023; Talbot & Chang, 2022). Over long timescales, repeated seasonal pulses combined with chronic background exposure can reduce ecosystem resilience by shrinking the “recovery window” between stress events, pushing communities toward simplified and less stable states (Haque & Fan, 2023; Krause et al., 2021).

6.4 Implications for ecosystem services

Microplastic pollution threatens ecosystem services by damaging the reliability of fisheries, aquaculture, water quality regulation, and habitat integrity, with direct implications for economic security and human well-being (Sivadas et al., 2022; Alberghini et al., 2023). Fisheries impact arise because contamination affects commercially important fish and shellfish at multiple levels, including ingestion prevalence, organ damage risk, and potential reductions in reproduction and growth efficiency under chronic exposure (Nikki et al., 2021; Shukla et al., 2022; Bhuyan, 2022). Evidence that market fish exhibit high contamination prevalence, combined with large riverine flux estimates, implies that fishery resources can remain under sustained microplastic pressure even without visible litter accumulation at harvest sites (Shukla et al., 2022; Napper et al., 2021). Reviews of microplastics in fish and fishery products further underline concerns about food safety and consumer exposure, linking ecosystem contamination to human-health risk discussions that can alter market perceptions and economic outcomes (Alberghini et al., 2023; Muhib et al., 2023).

Aquaculture systems may be especially exposed because they often operate near coastal zones, estuaries, and lagoons where microplastics accumulate, and where hydrodynamic trapping can sustain high concentrations. Lagoon systems such as Chilika Lake show measurable sediment-associated microplastic contamination (440 ± 3.53 particles/kg), and estuarine waters can reach tens to over a hundred items per Liter, indicating that cultured organisms can experience both water-column and benthic exposure depending on farming design (Kumar et al., 2024; Jeyasanta et al., 2023).

These risks are economically relevant because aquaculture productivity depends on high survival and growth efficiency, and sublethal stress can reduce feed conversion and increase disease susceptibility even when mortality is not immediate (Bhuyan, 2022; Mishra et al., 2023).

Water quality deterioration represents another ecosystem service risk. Microplastics can act as platforms for contaminant transport and microbial colonization, and their interactions with metals and pollutants can contribute to complex contamination mixtures that are difficult to manage through conventional water-treatment approaches (Sarkar et al., 2021; Patidar et al., 2023). Where microplastics occur alongside toxic metals, as documented in treatment wetlands, particle-bound contaminant delivery can increase ecological stress and complicate remediation because the same particle can function as both a physical hazard and a chemical vector (Sarkar et al., 2021; Selvam et al., 2021). This complexity has downstream implications for drinking-water sources, particularly in river-dependent regions where treatment infrastructure may already be challenged by high sediment and pollutant loads during monsoon periods (Kumar et al., 2021b; Das & Jain, 2023). Habitat degradation is also a long-term concern, especially for wetlands, mangroves, and estuaries that serve as nurseries and buffering systems. Seasonal microplastic variation in mangrove waters, with concentrations such as 1.42 ± 0.92 MPs/L pre-monsoon and lower values post-monsoon, suggests dynamic trapping and release processes that can expose nursery habitats during sensitive recruitment periods (Valsan et al., 2024). When combined with high plastic deposition in estuarine environments and sustained riverine discharge, these habitats may experience chronic contamination that erodes their capacity to support biodiversity and buffer coastal systems from disturbance (Jeyasanta et al., 2023; Sivadas et al., 2022).

The economic consequences of ecosystem service disruption are especially significant in regions where livelihoods depend on small-scale fishing and coastal resource use. Microplastic contamination can reduce fisheries stability, increase management costs, and damage consumer confidence in seafood safety, which can translate into income insecurity for communities relying on aquatic resources (Alberghini et al., 2023; Sivadas et al., 2022). Policy reviews emphasize that mitigation must account for socio-economic complexity, because bans and restrictions can generate uneven impacts unless alternatives, enforcement capacity, and waste-management infrastructure improve simultaneously (Noklebye et al., 2023; Raha et al., 2021). In this context, ecosystem-level consequences of microplastics should not be framed solely as ecological degradation, but as a direct risk to sustainable development goals tied to food systems,

livelihoods, and environmental health (Sunny et al., 2021; Sivadas et al., 2022).

7. Future Directions, Mitigation, and Conclusion

7.1 Major research gaps

Despite rapid growth in microplastics research, major evidence gaps persist that limit cross-study comparability, weaken ecological risk assessments, and slow translation into policy and mitigation. The most persistent gap remains the lack of standardized protocols for sampling, extraction, digestion, identification, and reporting, which creates wide variability in measured concentrations even within similar environments (Delgado-Gallardo et al., 2021; Lv et al., 2021; Grillo et al., 2022). Differences in sampling mesh size, sampling depth, seasonal timing, and contamination control procedures can fundamentally change the particle counts reported, making it difficult to determine whether observed differences between locations reflect real environmental variation or methodological bias (Cowger et al., 2021; Waldschläger et al., 2022). For example, depth-profile evidence shows that microplastics are not uniformly distributed through river flow, and surface-only sampling can underestimate loads when particles are suspended deeper due to turbulence and hydrodynamic mixing (Cowger et al., 2021). Similarly, hyporheic exchange processes can drive strong microplastic retention in riverbed sediments, meaning that exclusive monitoring of surface waters may miss key depositional reservoirs that maintain long-term exposure for benthic communities (Drummond et al., 2022).

A second major gap is the limited detection and toxicity evidence for nanoplastics, even though nanoscale fractions may have higher biological reactivity, greater likelihood of tissue translocation, and stronger biochemical impacts than larger microplastics (Kukkola et al., 2021; Kye et al., 2023). Current detection methods struggle to reliably quantify nanoplastics in natural matrices, particularly in complex environments such as sediments, biological tissues, and wastewater with high organic loads (Delgado-Gallardo et al., 2021; Mushtak et al., 2024). Because of these detection limitations, most monitoring data likely underestimates the true abundance of the smallest particles, even though these fractions may drive the most critical toxic outcomes through oxidative stress, inflammation, and barrier-crossing processes (Kukkola et al., 2021; Bhuyan, 2022).

Third, there is a shortage of long-term chronic exposure datasets, particularly under field-realistic conditions. Many studies rely on short-duration exposure experiments or snapshot field sampling, yet aquatic organisms experience repeated exposure over seasons and life cycles, especially in systems with sustained inputs from wastewater discharge, runoff, and unmanaged dumping (Kumar et al., 2021b; Talbot & Chang, 2022). Long-term retention

processes further reinforce chronic exposure. Modelling work suggests that riverbed accumulation can average around 5% of microplastic inputs per kilometer, and under low-flow conditions the residence time of microplastics in headwaters may extend to years per kilometer, indicating that biological exposure can persist long after initial inputs occur (Drummond et al., 2022). Similarly, lakes may sustain long residence times due to stratification and settling variability, supporting long-term exposure pathways for benthic food webs (Elagami et al., 2022; Elagami et al., 2023). Finally, multi-stressor experiments and field frameworks remain insufficient, even though microplastics co-occur with chemical contaminants and climate-driven stressors. Microplastics are increasingly recognized as vectors for heavy metals and additives that can amplify toxicity beyond physical particle effects (Sarkar et al., 2021; Patidar et al., 2023). In a natural wastewater-treatment wetland system, microplastics were associated with multiple potentially toxic metals (including As, Cd, Cr, Cu, Ni, Pb, and Zn), highlighting realistic co-exposure risks that laboratory experiments must incorporate to improve relevance (Sarkar et al., 2021). At the same time, climate-driven changes in hydrology and extreme rainfall influence microplastic mobilization and exposure intensity, suggesting that future risks cannot be assessed without integrating climate variability into microplastic fate and effects research (Haque & Fan, 2023; Das & Jain, 2023).

7.2 Recommendations for future research

A first priority is the development and adoption of standardized QA/QC frameworks and reporting metrics to enable meaningful comparison across geographic regions and study designs. Method harmonization should address (i) sampling depth and volume, (ii) mesh/filter size selection, (iii) digestion and density separation protocols, (iv) contamination prevention procedures (blanks, laboratory air controls, clothing controls), and (v) standardized reporting units for water (items/L or items/m³), sediments (items/kg dry or wet), and biota (items/individual and items/g tissue) (Delgado-Gallardo et al., 2021; Grillo et al., 2022; Waldschläger et al., 2022). The need for depth-considerate sampling is particularly critical because concentration-depth profiles demonstrate that surface-only sampling can misrepresent whole-column exposure, especially under high turbulence and variable flow conditions (Cowger et al., 2021). Standardization also requires consistent polymer identification workflows (FTIR/Raman or equivalent), because visual identification alone can inflate counts and obscure polymer-specific risk analysis (Lv et al., 2021; Delgado-Gallardo et al., 2021).

Second, research should expand beyond small-scale exposure tests toward mesocosm and ecosystem-

scale studies that connect organism-level effects to real ecological outcomes. Mesocosm experiments are particularly valuable because they allow controlled manipulation of microplastic concentration and composition while maintaining realistic community interactions, food-web dynamics, and environmental gradients (Elagami et al., 2023; Wu et al., 2024). Such designs are essential to identify whether sublethal impacts on growth, oxidative balance, and behaviour translate into changes in survival, recruitment, and community structure under realistic conditions (Krause et al., 2021; Parolini et al., 2023). In rivers, ecosystem-scale work should explicitly consider sediment exchange processes, because hyporheic retention can create long-lived benthic exposure even when water-column concentrations appear low, sustaining chronic stress in benthic and demersal organisms (Drummond et al., 2022).

Third, future research must integrate microplastics with climate stressors and co-pollutants, reflecting real-world exposure complexity. Climate-related variability influences microplastic transport, redistribution, and fragmentation, especially in monsoonal systems where storm events can rapidly mobilize bank-stored plastics and resuspend sediments (Haque & Fan, 2023; Warriar et al., 2022). Hydrologic extremes also coincide with nutrient pulses and sediment loading that may intensify biological stress and modify exposure pathways (Talbot & Chang, 2022; Das & Jain, 2023). At the same time, co-contaminant interactions should be treated as central rather than peripheral, because microplastics can adsorb metals and organic pollutants and act as vectors delivering chemical stress through ingestion (Patidar et al., 2023; Selvam et al., 2021). Future studies should prioritize multi-stressor designs such as MPs + metals, MPs + additives, MPs + temperature shifts, and MPs + hypoxia, to quantify synergistic and antagonistic outcomes across taxa (Haque & Fan, 2023; Patidar et al., 2023).

Fourth, improved detection and monitoring of nanoplastics is urgently needed. Advances should focus on scaling analytical techniques to handle complex environmental matrices while enabling routine, cost-effective quantification of nanoscale particles in water, sediments, and tissues (Delgado-Gallardo et al., 2021; Mushtak et al., 2024). Given that nanoplastics may have greater potential for tissue penetration and systemic toxicity, addressing this gap is central to understanding the true magnitude of organism-level risk (Kukkola et al., 2021; Bhuyan, 2022).

7.3 Mitigation and management priorities

Mitigation must prioritize upstream prevention, because once microplastics are dispersed across sediments, water columns, and food webs, remediation becomes technically difficult and economically inefficient (UNEP, 2021; Hu et al.,

2021). Strengthening waste management and source reduction requires a combination of regulatory measures and improved infrastructure, including reduction of single-use plastics, improved segregation and recycling systems, and adoption of extended producer responsibility mechanisms that shift accountability toward producers (Noklebye et al., 2023; Raha et al., 2021). Policy evidence from India highlights that plastic bans carry socio-economic complexities, meaning that mitigation must balance environmental goals with feasible alternatives, enforcement capacity, and livelihood considerations to avoid unintended inequities (Noklebye et al., 2023).

Improving wastewater and stormwater capture systems is critical because these pathways serve as major conduits of microplastics into aquatic ecosystems. Treatment wetlands and treatment ponds can remove a portion of microplastics, yet measured removal efficiencies (such as 53% reported for a wetland treatment pond surface-water microplastic load) indicate that substantial quantities still pass through and remain available for downstream transport (Sarkar et al., 2021). Therefore, mitigation strategies should combine improved filtration technologies with source reduction at household and industrial levels to lower the load entering wastewater networks (Hu et al., 2021; Kumar et al., 2021b). In urban settings, stormwater management interventions that trap plastics before they enter rivers—such as riverbank capture systems, sedimentation controls, and improved solid waste collection—can reduce flood-driven surges that mobilize mismanaged waste into aquatic systems (Das & Jain, 2023; Talbot & Chang, 2022).

Monitoring programs should be expanded as foundational management tools, with targeted surveillance in rivers, lakes, estuaries, and fisheries hotspots where ecological and human exposure risks are highest. Large-scale river monitoring is particularly important because rivers are transport corridors connecting inland sources to coastal sinks; modelling estimates of 1–3 billion microplastics per day discharged into marine systems provide a strong basis for basin-scale monitoring and intervention priorities (Napper et al., 2021). Lakes and reservoirs should also be prioritized as long-term sinks where microplastics may persist for extended periods due to stratification and slow sediment turnover (Elagami et al., 2022; Dusaucy et al., 2021). Importantly, fisheries-linked monitoring should not rely only on water sampling, because evidence from fish sold for consumption shows high prevalence and quantifiable loads, implying that biota-based surveillance is essential for risk management and food safety considerations (Shukla et al., 2022; Alberghini et al., 2023).

Public awareness and behavioural interventions remain complementary but essential measures,

particularly because a substantial fraction of plastic leakage arises from routine consumption behaviour and improper disposal practices. Surveys of student perceptions in India show that awareness and attitudes toward plastic and microplastic pollution vary, suggesting opportunities for targeted education and behaviour-change strategies that can reinforce policy measures (Dowarah et al., 2022; Chitra & Gobindgarh, 2022). Corporate commitment and packaging redesign are also critical because food and beverage packaging is a major contributor to plastic leakage, and meaningful reductions require measurable progress beyond voluntary commitments (Phelan et al., 2022; UNEP, 2021)

7.4 Conclusion

Microplastics have emerged as pervasive and persistent contaminants across freshwater and marine systems, with widespread detection in water, sediments, and aquatic organisms, including commercially important species (Talbot & Chang, 2022; Neelavannan & Sen, 2023; Shukla et al., 2022). Their environmental behaviour—driven by hydrology, sediment exchange, and particle characteristics—ensures continued mobility and long-term retention in depositional zones, sustaining exposure even when inputs fluctuate seasonally (Drummond et al., 2022; Elagami et al., 2022). Evidence strongly supports that microplastics are bioavailable and capable of producing harm across biological organization levels, ranging from physical stress and feeding disruption to oxidative imbalance, inflammatory responses, organ impairment, and reproductive risk in aquatic biota (Bhuyan, 2022; Kukkola et al., 2021; Kye et al., 2023).

At the ecosystem scale, microplastics can propagate through food webs, alter trophic interactions, and threaten fisheries sustainability, while also contributing to changes in productivity and biogeochemical processes that regulate ecosystem stability (Krause et al., 2021; Wu et al., 2024). These risks are amplified by co-contaminant transport and climate-driven hydrological variability, which together intensify exposure complexity and ecological vulnerability (Sarkar et al., 2021; Patidar et al., 2023; Haque & Fan, 2023). Addressing microplastic pollution therefore requires a coordinated scientific and policy response that combines standardized monitoring, mechanistic and ecosystem-scale research, and upstream prevention through improved waste management, wastewater controls, and stronger source-reduction strategies (UNEP, 2021; Hu et al., 2021; Noklebye et al., 2023). Without such integrated action, projected growth in plastic waste generation suggests that microplastic pressures on aquatic ecosystems and the services they provide will continue to intensify over coming decades (OECD, 2022).

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