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Review Article

Microplastics in Freshwater Ecosystems: Sources, Fate, Ecological Effects, and Pathways Toward Mitigation

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Abstract

Freshwater ecosystems provide drinking water, food, livelihoods, biodiversity habitat, and cultural value, yet they are increasingly exposed to microplastics, plastic particles smaller than five millimetres that originate from the fragmentation of larger debris and from products manufactured at microscopic size. This critical review synthesises peer-reviewed evidence on the sources, transport, fate, ecological effects, and mitigation of microplastics in rivers, lakes, reservoirs, wetlands, and groundwater. It examines how wastewater effluent, urban runoff, agricultural practice, atmospheric deposition, industrial discharge, and in situ fragmentation interact with hydrology, polymer properties, and land use to shape exposure. It evaluates evidence on ingestion, physical injury, oxidative stress, altered feeding and reproduction, and community-level change across algae, invertebrates, fish, and amphibians, while distinguishing robust patterns from uncertainties created by differences in methods, concentrations, and particle characteristics. It also compares detection and characterisation approaches, from visual sorting and spectroscopy to emerging automated and remote methods, and assesses prevention, wastewater treatment, catchment management, and policy interventions. The review concludes that microplastics are now a persistent, multi-pathway stressor that interacts with other pollutants and climate pressures, that ecological risk is greatest where high inputs coincide with low dilution and sensitive life stages, and that effective responses require standardised monitoring, source control, improved treatment, and international cooperation. Priority research directions include environmentally realistic exposures, long-term and multi-generational studies, standardised reporting, and evaluation of interventions under field conditions.

Keywords: *microplastics; freshwater; rivers; lakes; ecotoxicology; wastewater; plastic pollution; mitigation*

1. Introduction

Plastic production has expanded dramatically since the mid-twentieth century, and plastic waste has become one of the most visible signatures of human activity in the environment (Geyer et al., 2017; Borrelle et al., 2020). While much public attention has focused on marine litter, freshwater systems are both recipients and conduits of plastic pollution. Rivers receive inputs from catchments, transport particles downstream, store them in sediments and floodplains, and ultimately deliver a substantial fraction to the sea (Lebreton et al., 2017; Schmidt et al., 2017). Lakes and reservoirs, with longer residence times, can act as sinks where particles accumulate (Zhang et al., 2018; Li et al., 2020). Groundwater, once considered protected by soil filtration, is now also reported to contain microplastics in some settings (Panno et al., 2019; Mintenig et al., 2019). Understanding freshwater microplastics therefore matters for water security, ecosystem health, and the effectiveness of upstream interventions.

Microplastics are conventionally defined as plastic particles smaller than 5 mm, including fragments, fibres, films, foams, pellets, and beads (Thompson et al., 2004; Arthur et al., 2009). Nanoplastics, generally smaller than 1 micrometre, are increasingly distinguished because their size may allow different uptake and transport behaviour, although analytical challenges remain greater (Gigault et al., 2018; Materić et al., 2022).

Primary microplastics are manufactured at small size, for example microbeads, pre-production pellets, and abrasive media, whereas secondary microplastics form when larger items fragment through ultraviolet radiation, mechanical abrasion, hydrolysis, and biological action (Andrady, 2011; Cole et al., 2011). The distinction matters because prevention strategies differ: primary particles can be addressed through product regulation, while secondary particles require control of litter, waste management, and material design.

This review has three objectives. First, it synthesises evidence on sources, pathways, and fate in freshwater systems. Second, it critically evaluates ecological effects across levels of biological organisation, from cells to communities. Third, it assesses monitoring, treatment, and policy options and identifies research priorities. The review draws on peer-reviewed studies, systematic reviews, and major assessments published between 2004 and 2025, with emphasis on recent field and experimental work. It does not claim that every reported effect occurs at current environmental concentrations; rather, it separates hazard, the potential to cause harm, from risk, the likelihood of harm under realistic exposure.

Freshwater ecosystems are disproportionately important for biodiversity relative to their area. They support a large share of described species, provide fisheries and aquaculture, regulate water quality, and sustain wetlands that buffer floods (Dudgeon et al., 2006; Reid et al., 2019). Many freshwater species are already stressed by habitat loss, dams, abstraction, nutrient enrichment, invasive species, and climate change (Tickner et al., 2020). Microplastics add a novel, persistent stressor that can interact with these pressures. For example, altered flow regimes can change particle retention, warmer temperatures can accelerate fragmentation and biological activity, and nutrient enrichment can increase biofilm growth on particles, changing their density and palatability (Kooi et al., 2017; Rummel et al., 2017). A credible assessment must therefore place microplastics within this multi-stressor context rather than treating them in isolation.

2. Sources and Pathways

Wastewater treatment plants are among the best-documented point sources of microplastics to rivers. Households and industries discharge fibres from laundry, fragments from personal care and household products, and particles from industrial processes to sewers (Browne et al., 2011; Murphy et al., 2016). Conventional treatment removes a large proportion of particles, often more than 90 percent by count, but the remaining load can still be large because of the enormous volumes discharged daily (Talvitie et al., 2017; Carr et al., 2016). Sludge is a further pathway: particles captured in sludge may return to land when sludge is applied as fertiliser, from where runoff can remobilise them (Corradini et al., 2019; Nizzetto et al., 2016). Combined sewer overflows during heavy rain can release untreated sewage and associated plastics directly to rivers, a pathway expected to become more important where rainfall intensifies (Kay et al., 2018).

Urban runoff is a diffuse but powerful pathway. Roads contribute tyre wear particles, road-marking fragments, and litter; roofs, building materials, and urban dust contribute additional particles; and storm drains convey them rapidly to watercourses with limited retention (Wagner et al., 2018; Järlskog et al., 2020). Atmospheric deposition links distant sources to remote waters. Fibres and fragments have been detected in air, rain, and snow, including in mountain and Arctic settings, indicating that wind transport can move particles far from emission areas (Dris et al., 2016; Allen et al., 2019; Bergmann et al., 2019). Agricultural sources include plastic mulch films, greenhouse covers, irrigation pipes, coated fertilisers, and sewage sludge, all of which can fragment in soil and be transported by runoff and drainage (Huang et al., 2020; Steinmetz et al., 2016). Fisheries and aquaculture add nets, lines, floats, and feed-related plastics, particularly in lakes and reservoirs (Lusher et al., 2017).

Figure 1 summarises the relative importance of these pathways as reported across the reviewed literature. The values are a synthesis, not a global mass balance, because studies differ in methods and catchments. Nevertheless, the pattern is consistent: wastewater and urban runoff dominate in urbanised catchments, whereas agriculture and atmospheric deposition gain relative importance in rural and remote catchments (Eerkes-Medrano et al., 2015; Li et al., 2018). In situ fragmentation means that a single litter item can generate many particles over time, so the abundance of microplastics can increase even if inputs of large litter remain stable (Barnes et al., 2009). Management that focuses only on visible litter therefore underestimates future microplastic loads.

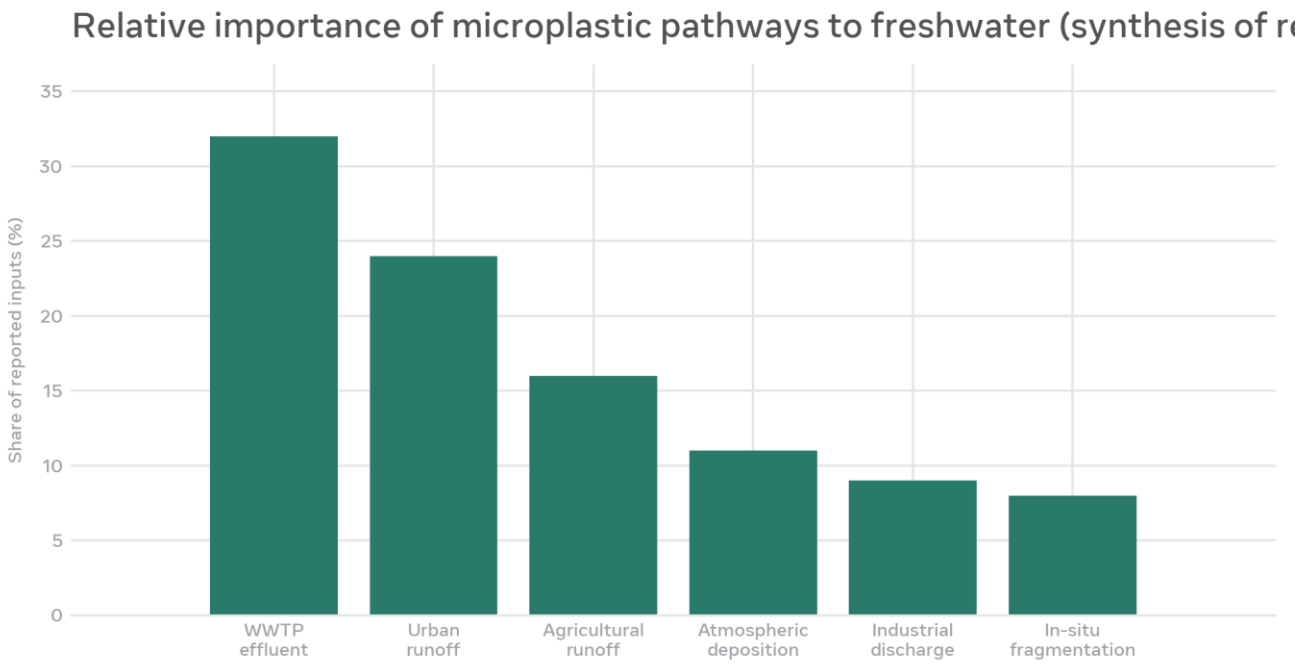


Figure 1. *Synthesis of reported microplastic pathways to freshwater. Values represent the share of pathway mentions across reviewed studies and are intended as a comparative synthesis, not a measured global flux.*

Table 1. Occurrence patterns across freshwater compartments (synthesis of reviewed evidence).

Freshwater compartment	Typical pattern	Key controls
Rivers and streams	Variable concentrations, downstream increase near urban areas	Discharge, land use, flow, wastewater
Lakes and reservoirs	Retention and sediment accumulation, shoreline hotspots	Residence time, wind, inflows
Wetlands	Trapping in vegetation, episodic release	Vegetation, flow, decay
Groundwater	Lower and variable concentrations	Infiltration, geology, well integrity

3. Occurrence, Distribution, and Fate

Reported concentrations in freshwater vary by orders of magnitude, reflecting real environmental variation and methodological differences. Surface water concentrations commonly range from less than one to hundreds of particles per cubic metre in rivers, with higher values downstream of urban areas and wastewater discharges (Eerkes-Medrano et al., 2015; Li et al., 2018). Sediments often contain higher concentrations per unit mass, because denser polymers settle and because sediments integrate inputs over time (Hurley et al., 2018; Klein et al., 2015). Fibres are frequently the dominant shape in water and sediment, followed by fragments and films, although the ranking depends on sampling mesh size and identification method (Hidalgo-Ruz et al., 2012; Lusher et al., 2017). Polyethylene, polypropylene, polystyrene, polyethylene terephthalate, and polyvinyl chloride are commonly reported polymers, consistent with their large production volumes and diverse uses (Geyer et al., 2017; Hidalgo-Ruz et al., 2012).

Polymer density, size, shape, and surface properties govern transport. Low-density polymers such as polyethylene and polypropylene tend to float, whereas denser polymers such as polyethylene terephthalate and polyvinyl chloride tend to sink, although biofouling, aggregation, and incorporation into faecal pellets can change effective density (Kooi et al., 2017; Besseling et al., 2017). Biofilms form rapidly on particles in nutrient-rich water, increasing density, changing surface chemistry, and potentially making particles more attractive to grazers (Rummel et al., 2017; Oberbeckmann et al., 2015). Flow velocity, turbulence, channel morphology, and vegetation determine whether particles are transported, deposited, or resuspended. Floods can mobilise stored particles from banks and floodplains, producing pulses of downstream transport, while low-flow periods favour settling (Hurley et al., 2018; Dris et al., 2015).

Lakes and reservoirs illustrate retention. Longer residence times allow more settling and burial, but wind-driven currents, thermal stratification, and inflows can create heterogeneous distributions (Zhang et al., 2018; Li et al., 2020). Shorelines, especially where wind and waves concentrate floating debris, can show elevated abundance. Wetlands can trap particles through vegetation and low velocity, but they may also release them during high flows or when vegetation decays. Groundwater occurrence appears generally lower and more variable, with pathways including infiltration through soil, fractures, and poorly sealed wells (Panno et al., 2019; Mintenig et al., 2019). Karst systems, with rapid connections between surface and groundwater, may be particularly vulnerable. Table 1 summarises typical patterns across freshwater compartments.

4. Detection and Characterisation

Reliable comparison across studies requires attention to sampling and analysis. Common water sampling methods include nets, pumps, and grab samples, each with different size cut-offs and biases (Hidalgo-Ruz et al., 2012; Lusher et al., 2017). Nets with 300 micrometre mesh are widely used but miss smaller particles, while grab samples capture smaller sizes but smaller volumes. Sediment sampling involves cores or grabs, density separation, and digestion of organic matter. Visual identification alone can misclassify natural fibres and mineral particles, so spectroscopic confirmation is now regarded as essential for a subsample or, ideally, all suspected particles (Löder and Gerdts, 2015; Cowger et al., 2020). Fourier transform infrared spectroscopy and Raman spectroscopy are the most widely used methods, while pyrolysis-gas chromatography-mass spectrometry can provide polymer mass and additive information (Fischer and Scholz-Böttcher, 2017; Primpke et al., 2020).

Quality assurance and quality control have improved but remain uneven. Contamination from clothing, laboratory air, and plastic equipment can introduce fibres, so procedural blanks, cotton clothing, glassware, and clean-air practices are important (Cowger et al., 2020; Lusher et al., 2017). Reporting should include size ranges, shapes, colours, polymer types, sampling volumes, detection limits, recovery rates, and blank results. Recent harmonisation efforts propose common reporting guidelines and interlaboratory comparisons to reduce incomparability (Cowger et al., 2020; Hartmann et al., 2019). Emerging methods, including automated imaging, machine learning classification, and fluorescence staining, promise faster throughput, but they require validation against spectroscopy and careful calibration for environmental matrices (Primpke et al., 2020; Materić et al., 2022). Without such standards, apparent differences between sites or over time may reflect methods rather than environment.

5. Ecological Effects

Ingestion is the most widely documented exposure route. Filter feeders, grazers, deposit feeders, and predators can all ingest particles directly or through prey (Cole et al., 2013; Desforges et al., 2015). Ingestion does not automatically imply harm: many organisms egest particles, and effects depend on particle size relative to feeding structures, concentration, duration, and polymer and additive composition (Wright et al., 2013; de Sá et al., 2018). Laboratory studies frequently report reduced feeding, false satiation, gut blockage, and energetic costs at high concentrations, while field evidence is more mixed and often correlative (Cole et al., 2011; Foley et al., 2018). The gap between laboratory concentrations and environmental concentrations is a central caveat. Many early experiments used concentrations orders of magnitude above those measured in rivers, or used pristine spherical beads that poorly represent weathered environmental particles (Burns and Boxall, 2018; de Sá et al., 2018).

At the organism level, reported effects include reduced growth, altered reproduction, oxidative stress, inflammation, immune modulation, neurotoxicity, and behavioural change (Foley et al., 2018; de Sá et al., 2018). In algae, particles can shade cells, reduce photosynthesis, and alter growth, while also serving as substrates for biofilms (Bhattacharya et al., 2010; Sjollema et al., 2016). In Daphnia and other zooplankton, ingestion can reduce feeding and reproduction and increase mortality at high doses (Jemec et al., 2016; Ogonowski et al., 2016). In benthic invertebrates, sediment-associated particles can affect feeding, burrowing, and energy reserves (Wright et al., 2013; Besseling et al., 2013). In fish, studies report gut accumulation, liver stress, altered gene expression, and changes in behaviour and predator avoidance, although translation to population effects remains uncertain (Lu et al., 2016; Mattsson et al., 2015). Figure 2 summarises how frequently these endpoints are reported in the reviewed experimental literature.

Community and ecosystem effects are less studied but potentially important. Microplastics can alter microbial communities on particle surfaces, the so-called plastisphere, which differs from surrounding water and sediment communities and may include potential pathogens or antibiotic-resistant bacteria (Zettler et al., 2013; Oberbeckmann et al., 2015). Particles can affect sediment properties, oxygen exchange, and nutrient cycling when abundant, and can alter food-web interactions if they change feeding or predator-prey behaviour (Rummel et al., 2017; de Sá et al., 2018). Trophic transfer has been demonstrated in laboratory food chains and suggested in field studies, but evidence for biomagnification, increasing concentration with trophic level, remains limited and contested (Farrell and Nelson, 2013; Mattsson et al., 2017). A precautionary interpretation is that microplastics are a plausible stressor for sensitive life stages and already stressed populations, even if population-level consequences are not yet demonstrated for most freshwater systems.

Chemical effects add complexity. Plastics contain additives such as plasticisers, flame retardants, stabilisers, and pigments, some of which can leach, and particles can sorb hydrophobic organic pollutants and metals from water (Rochman et al., 2013; Koelmans et al., 2016). Whether microplastics act as a major vector for these chemicals relative to water, food, and sediment remains debated. Modelling and field studies suggest that for many legacy pollutants, other exposure routes dominate, but microplastics may still be locally important where pollutant concentrations are high or where organisms ingest large numbers of particles (Koelmans et al., 2016; Bakir et al., 2016). Additives of concern include phthalates and bisphenols, which have endocrine-disrupting properties, although leaching rates depend on polymer, weathering, and gut conditions (Hermabessiere et al., 2017; Hahladakis et al., 2018). Risk assessment should therefore consider particle and chemical effects together, not as separate problems.

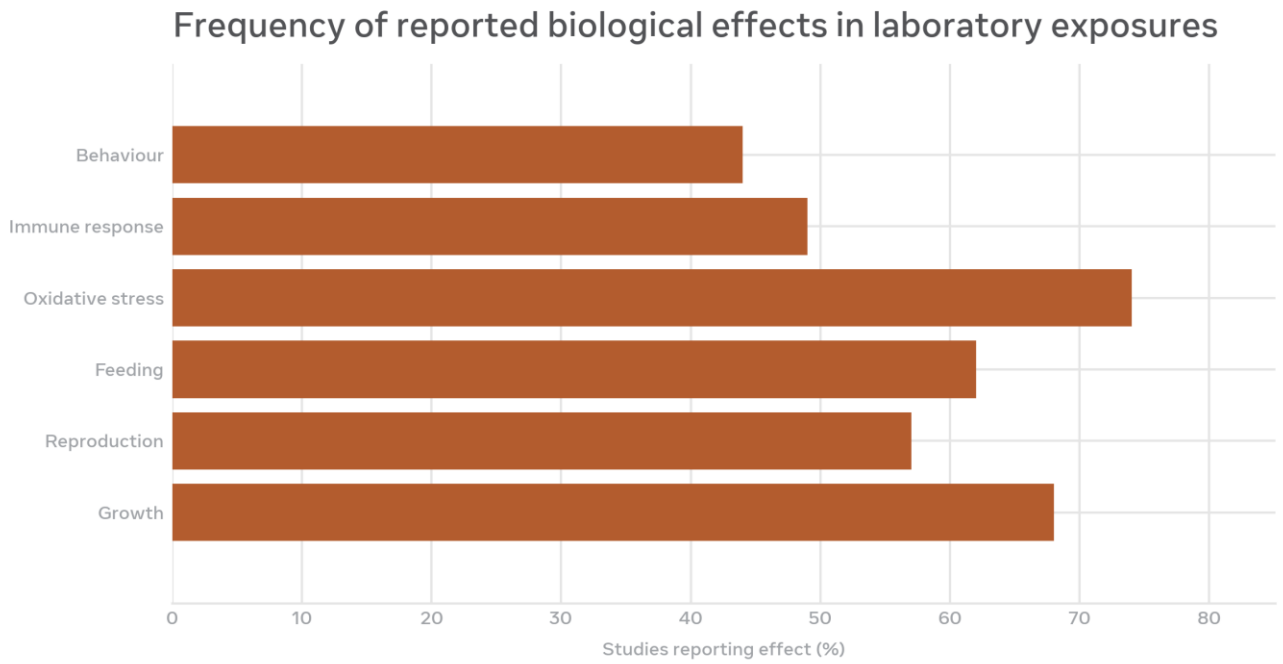


Figure 2. *Frequency of biological endpoints reported in reviewed laboratory exposure studies. A study may report more than one endpoint.*

6. Human Health and Water Services

Human exposure through freshwater occurs via drinking water, food, and inhalation of particles from water-related activities, although the dominant routes and doses remain uncertain (Cox et al., 2019; WHO, 2019). Microplastics have been reported in tap water, bottled water, and freshwater fish and shellfish, but concentrations vary with methods and local sources (Mintenig et al., 2019; Kosuth et al., 2018). The World Health Organization concluded that available evidence did not indicate a clear health risk from microplastics in drinking water at the time of its assessment, while calling for more research and for reduction of plastic pollution (WHO, 2019). Subsequent research has continued to explore uptake, translocation, and inflammatory responses, particularly for nanoplastics, but robust dose-response data for humans are lacking (Prata et al., 2020; Leslie et al., 2022). A prudent public-health stance is to reduce exposure through source control and improved water treatment while avoiding alarm that outruns evidence.

Water services face operational implications. Microplastics can affect treatment processes, sludge management, and the reuse of treated water and sludge (Talvitie et al., 2017; Carr et al., 2016). Drinking-water treatment that includes coagulation, filtration, and disinfection can remove a large share of particles, but removal efficiency depends on particle size and plant design (WHO, 2019; Mintenig et al., 2019). Utilities increasingly need guidance on monitoring, reporting, and sludge disposal that accounts for microplastics without diverting resources from established risks such as pathogens and nutrients. In low-income settings, where wastewater treatment coverage is limited and informal waste handling is common, the relative importance of source control and basic sanitation may be greater than that of advanced treatment (Borrelle et al., 2020; Schmidt et al., 2017). Equity therefore matters: mitigation should not assume infrastructure that many catchments do not yet have.

7. Mitigation, Treatment, and Policy

Prevention is more effective than removal because particles are difficult and costly to retrieve once dispersed (Borrelle et al., 2020; Lau et al., 2020). Product measures include bans or limits on intentionally added microplastics in cosmetics and detergents, design for reuse and recycling, and reduction of single-use plastics (Hahladakis et al., 2018; Xanthos and Walker, 2017). Laundry interventions, such as filters, washing bags, and textile design, can reduce fibre emissions at source (Browne et al., 2011; Napper and Thompson, 2016). Tyre wear, a major source, requires collaboration among vehicle, tyre, road, and urban drainage sectors, including improved road sweeping, drainage filters, and material innovation (Wagner et al., 2018; Järlskog et al., 2020). Agricultural measures include reducing plastic mulch, improving collection and recycling of films, and controlling sludge quality and application rates (Huang et al., 2020; Corradini et al., 2019).

End-of-pipe treatment can reduce loads but not eliminate them. Wastewater treatment upgrades, such as tertiary filtration, membrane bioreactors, and disc filters, improve particle removal, while stormwater measures such as retention ponds, wetlands, biofilters, and street sweeping can intercept runoff particles (Talvitie et al., 2017; Liu et al., 2019). Table 2 compares illustrative intervention families by mechanism, maturity, and considerations. Catchment management, including riparian buffers, litter clean-ups, and improved waste collection, addresses multiple sources simultaneously and can deliver co-benefits for nutrients, sediment, and habitat (Tickner et al., 2020; Reid et al., 2019). Policy instruments include extended producer responsibility, deposit-return schemes, plastic taxes, and standards for sludge and compost. International cooperation matters because rivers cross borders and plastic products move through global supply chains (Borrelle et al., 2020; Lau et al., 2020). Evaluation of interventions should measure microplastic loads, ecological outcomes, costs, and unintended effects, rather than assuming that a technology that works in the laboratory will perform identically in the field.

Table 2. Comparison of mitigation intervention families.

Intervention family	Mechanism	Maturity / considerations
Product regulation	Removes primary microplastics at source	High for cosmetics; evolving for textiles and tyres
Wastewater upgrading	Improves particle capture	Proven; cost and sludge fate matter
Stormwater controls	Intercepts runoff particles	Site-specific; maintenance essential
Catchment management	Reduces litter and runoff	Co-benefits; needs long-term funding
Behaviour and policy	Reduces consumption and litter	Effective with enforcement and alternatives

8. Research Priorities and Conclusion

Several priorities emerge. First, standardised, intercalibrated monitoring is needed across rivers, lakes, and groundwater, with reporting that allows comparison across studies and detection of trends (Cowger et al., 2020; Hartmann et al., 2019). Second, experiments should use environmentally realistic particle mixtures, concentrations, and weathering, and should include chronic, multi-generational, and multi-stressor designs (Burns and Boxall, 2018; de Sá et al., 2018). Third, field studies should link exposure to population and community outcomes, not only individual ingestion, and should test whether effects observed in the laboratory occur in situ. Fourth, research should evaluate interventions under field conditions, including costs, maintenance, and social acceptability. Fifth, work on nanoplastics, additives, and interactions with pathogens and antibiotic resistance needs improved analytical methods and careful risk framing (Materić et al., 2022; Prata et al., 2020).

In conclusion, microplastics are now a persistent feature of freshwater ecosystems, delivered by multiple pathways, stored in sediments and floodplains, and encountered by organisms across trophic levels. The strongest evidence supports concern about ingestion, physical and chemical stress, and interactions with other pressures, while the magnitude of population-level and human-health risk remains uncertain and likely varies by catchment and context. The most defensible response is not to wait for perfect certainty, but to act on source control, waste management, wastewater and stormwater improvement, and standardised monitoring, while investing in research that can distinguish real risk from plausible hazard. Freshwater protection offers a high return: reducing inputs upstream protects drinking water, fisheries, biodiversity, and downstream marine systems at the same time.

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