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Critical Review

Microplastic Pollution in Freshwater Ecosystems: Sources, Transport, Ecological Risks, Detection, and Mitigation Pathways

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Abstract

Freshwater ecosystems sustain biodiversity, drinking water, fisheries, agriculture, and cultural values, yet they are increasingly burdened by microplastic pollution. This critical review synthesises current understanding of how microplastics, defined here as plastic particles smaller than five millimetres, enter rivers, lakes, reservoirs, wetlands, and groundwater, how they move and transform within those systems, and what consequences they have for organisms, ecological processes, and human well-being. Evidence from field surveys, laboratory experiments, modelling studies, and treatment trials is integrated to explain why freshwater systems act simultaneously as conduits, sinks, and sources of plastic particles. The review shows that domestic wastewater, urban stormwater, agricultural runoff, atmospheric deposition, and industrial discharges interact with hydrology, sediment dynamics, and biological activity to produce highly variable concentrations in space and time. Ecological effects range from physical injury and reduced feeding to oxidative stress, inflammation, altered gut microbiota, reproductive impairment, and trophic transfer, while microplastics also act as vectors for heavy metals, persistent organic pollutants, antibiotics, and pathogenic biofilms. Detection remains constrained by inconsistent sampling, size cut-offs, and polymer identification methods, which limits comparability across studies. Mitigation requires a portfolio that combines source reduction, improved wastewater and stormwater treatment, nature-based solutions, better waste management, and coherent policy. The review identifies priorities for standardised monitoring, environmentally realistic exposure experiments, long-term ecosystem studies, and equitable solutions for low- and middle-income regions where monitoring and infrastructure are most limited.

Keywords: *microplastics; freshwater; rivers; lakes; ecotoxicology; wastewater treatment; plastic pollution; ecological risk*

1. Introduction

Plastic has become inseparable from modern life because it is light, durable, inexpensive, and versatile (Thompson et al., 2004; Geyer et al., 2017). Global plastic production has grown from about two million tonnes in 1950 to more than 400 million tonnes per year in recent years, and a substantial fraction becomes waste within a short period (Geyer et al., 2017; Borrelle et al., 2020). Although the ocean has received the greatest public attention, freshwater systems are where much plastic pollution is generated, transported, stored, and experienced by people (Eerkes-Medrano et al., 2015; Li et al., 2018). Rivers carry plastic from cities, farms, and industries toward the sea, lakes accumulate particles over decades, wetlands trap them in sediments and vegetation, and groundwater can receive them through infiltration (Eerkes-Medrano et al., 2015; Li et al., 2018; Wagner et al., 2014). Understanding freshwater microplastics is therefore not a narrow

specialist concern; it is central to water security, food security, public health, and biodiversity conservation.

Microplastics are conventionally defined as plastic particles smaller than five millimetres in their longest dimension, while nanoplastics are smaller than one micrometre (Thompson et al., 2004; Hartmann et al., 2019). This size-based definition is useful, but it hides enormous diversity in polymer type, shape, colour, density, surface chemistry, age, and associated chemicals (Hartmann et al., 2019; Rochman et al., 2019). Polyethylene, polypropylene, polystyrene, polyethylene terephthalate, polyvinyl chloride, and polyamide are among the most frequently reported polymers in freshwater, each with different densities and behaviours in water (Eerkes-Medrano et al., 2015; Li et al., 2018). Fibres from textiles, fragments from broken packaging, films from bags and agricultural mulch, foams from packaging and insulation, pellets from manufacturing, and tyre-wear particles all contribute to the mixture (Browne et al., 2011; Kole et al., 2017; de Souza Machado et al., 2018). Primary microplastics are manufactured at small size, whereas secondary microplastics form when larger items fragment through ultraviolet radiation, mechanical abrasion, hydrolysis, and biological activity (Andrady, 2011; Barnes et al., 2009).

This review has four aims. First, it synthesises evidence on the major sources and pathways by which microplastics reach freshwater. Second, it explains transport, fate, and transformation processes that control where particles go and how long they persist. Third, it evaluates ecological and human health risks, distinguishing well-supported effects from uncertain or context-dependent claims. Fourth, it assesses detection methods and mitigation options, including wastewater treatment, nature-based solutions, source control, and policy. The review draws mainly on peer-reviewed studies published between 2004 and 2025, with emphasis on field surveys, controlled experiments, systematic reviews, and meta-analyses.

It is organised so that a reader can follow the journey of a particle from source to sink, from organism to ecosystem, and from measurement to management.

A central argument runs through the review: microplastic pollution cannot be understood by counting particles alone. Concentration numbers are necessary, but they become meaningful only when combined with information on polymer type, size distribution, shape, weathering state, co-contaminants, hydrology, and ecological context (Hartmann et al., 2019; Rochman et al., 2019; Koelmans et al., 2022). Two rivers with the same particle count can pose very different risks if one carries weathered fibres loaded with metals and the other carries clean, buoyant pellets. Likewise, a laboratory experiment that exposes a single species to pristine polystyrene spheres at very high concentration may reveal a mechanism, but it does not by itself prove harm in a real lake. The review therefore emphasises environmental realism, methodological transparency, and the integration of physical, chemical, and biological perspectives.

2. Sources and Pathways to Freshwater

Freshwater microplastics originate from point sources, diffuse sources, and atmospheric deposition, and the relative importance of each varies with land use, population density, infrastructure, climate, and season (Wagner et al., 2014; Li et al., 2018; Eerkes-Medrano et al., 2015). Urban areas tend to dominate in densely populated catchments, whereas agricultural and remote catchments can still be contaminated through atmospheric transport, irrigation, and the application of sewage sludge (Nizzetto et al., 2016; de Souza Machado et al., 2018). Figure 1 presents an indicative synthesis of source contributions; it is intended to show relative patterns rather than a precise global budget, because regional studies differ in methods and definitions.

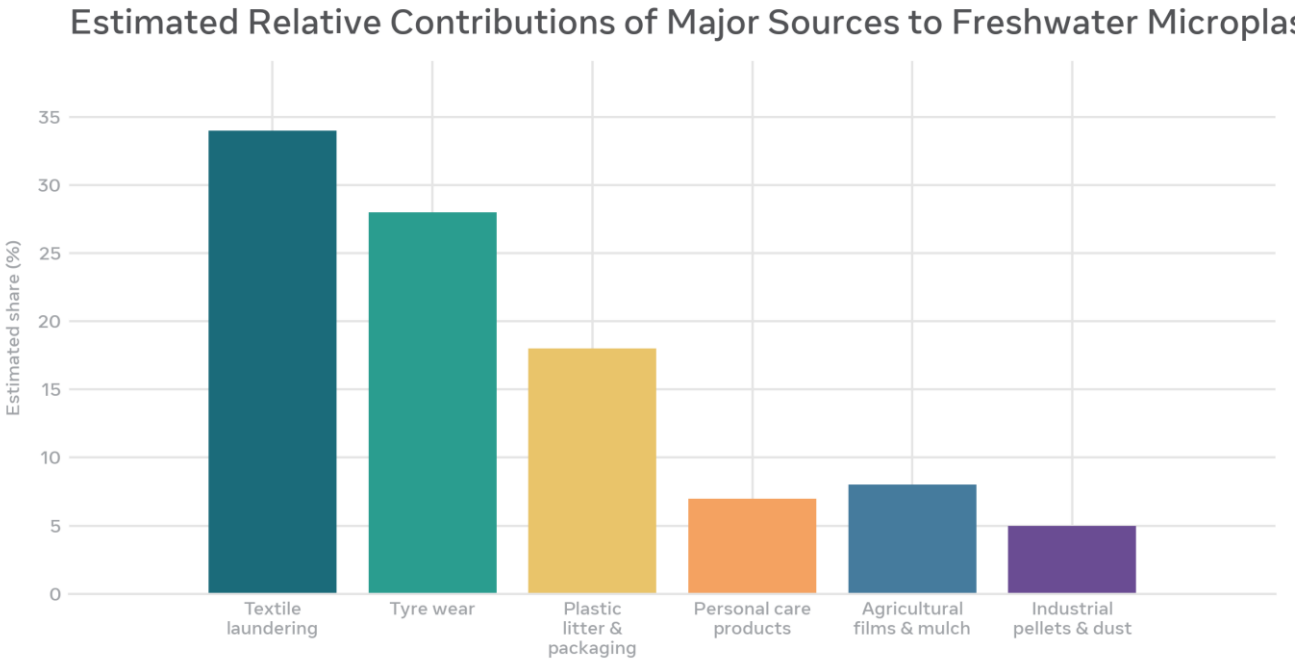


Figure 1. Indicative relative contributions of major sources to freshwater microplastics, synthesised from catchment and emission studies. Shares vary strongly by region, season, and method (Browne et al., 2011; Kole et al., 2017; de Souza Machado et al., 2018).

2.1 Domestic wastewater and laundry fibres

Domestic wastewater is one of the best-documented pathways. Washing synthetic garments releases thousands of fibres per wash, and although wastewater treatment plants remove a large proportion, the remaining effluent and the large volumes discharged still deliver substantial loads to rivers (Browne et al., 2011; Murphy et al., 2016). Browne et al. (2011) demonstrated that a single garment can shed more than 1,900 fibres per wash and that fibres accumulate in sediments near sewage outfalls. Murphy et al. (2016) found that a Scottish wastewater treatment plant removed about 98% of microplastics from influent, yet still discharged millions of particles per day because of the scale of flow. Personal care products historically contributed microbeads, but bans in several countries have reduced this source, illustrating that targeted regulation can work (Rochman et al., 2013; Eerkes-Medrano et al., 2015). In regions without centralised treatment, untreated or partially treated sewage enters rivers directly, increasing exposure (Li et al., 2018; Borrelle et al., 2020). Sludge applied to farmland can also transfer retained particles to soils, from where they may be washed into streams (Nizzetto et al., 2016; de Souza Machado et al., 2018).

2.2 Urban stormwater, roads, and tyre wear

Stormwater mobilises particles from roads, pavements, roofs, construction sites, and litter. Tyre-wear particles are now recognised as a major but often undercounted component of microplastic pollution (Kole et al., 2017; Wagner et al., 2018). Kole et al. (2017) estimated that tyre wear contributes a large share of microplastic emissions in several European countries, with particles generated by friction between tyres and road surfaces and washed into drains during rainfall. Road markings, brake wear, artificial turf, and building materials add further inputs (Wagner et al., 2018). Because stormwater systems are designed to move water quickly, first-flush events after dry periods can deliver pulses of particles to rivers, creating short-term peaks that routine monthly sampling may miss (Wagner et al., 2014; Li et al., 2018). Urban litter that fragments in situ, including bottles, bags, cups, and cigarette filters, provides a persistent secondary source (Barnes et al., 2009; Andrady, 2011).

2.3 Agriculture, industry, and atmospheric deposition

Agriculture contributes through plastic mulch, greenhouse films, irrigation pipes, fertiliser coatings, and sewage sludge (de Souza Machado et al., 2018; Nizzetto et al., 2016). Mulch films improve water retention and crop yield, but they degrade in fields and can fragment into soil and drainage water (de Souza Machado et al., 2018). Industrial sources include resin pellets lost during production and transport, abrasive blasting media, and dust from plastic processing (Thompson et al., 2004; Eerkes-Medrano et al., 2015). Atmospheric deposition is increasingly recognised as a pathway that connects distant sources to remote lakes and headwaters (Dris et al., 2016; Allen et al., 2019). Dris et al. (2016) reported microplastic fibres in atmospheric fallout over Paris, while Allen et al. (2019) detected microplastics in atmospheric deposition in a remote mountain catchment in the Pyrenees, showing that wind can transport particles far from urban centres. Rainfall, snowmelt, and dry deposition therefore help explain why even protected or sparsely populated freshwater systems are not pristine.

3. Transport, Fate, and Transformation in Freshwater

Once in water, a microplastic particle is subject to advection, dispersion, settling, resuspension, aggregation, biofouling, and degradation (Wagner et al., 2014; Besseling et al., 2017; Kooi et al., 2018). Low-density polymers such as polyethylene and polypropylene tend to float initially, whereas denser polymers such as polyethylene terephthalate and polyvinyl chloride tend to sink (Eerkes-Medrano et al., 2015; Li et al., 2018). Density alone, however, is a poor predictor over time because biofilms increase effective density, aggregation with organic matter and minerals changes settling velocity, and turbulent flow can keep even dense particles suspended (Besseling et al., 2017; Kooi et al., 2018). In rivers, particles are repeatedly deposited and remobilised; flood events can flush stored particles downstream, while low-flow periods allow accumulation in sediments and behind dams (Wagner et al., 2014; Besseling et al., 2017).

Lakes and reservoirs act as sinks because of longer residence times and lower flow velocities (Li et al., 2018; Eerkes-Medrano et al., 2015). Sediments in lakes can archive decades of plastic inputs, and sediment cores are increasingly used to reconstruct historical trends (Turner et al., 2019). Wetlands slow flow, promote settling, and support vegetation that traps particles, but they can also release particles during storms or when vegetation decays (Wagner et al., 2014). Groundwater is less studied, yet microplastics have been reported in aquifers, karst systems, and springs, suggesting transport through soil macropores, fractures, and preferential flow paths (Panno et al., 2019). The vertical distribution in a water column is therefore dynamic: a particle sampled at the surface in the morning may be in sediment by evening after biofouling or aggregation.

Weathering transforms particles chemically and physically. Ultraviolet radiation initiates photo-oxidation, creating cracks, increasing surface area, and generating oxygen-containing functional groups that alter sorption behaviour (Andrady, 2011; Gewert et al., 2015). Mechanical abrasion breaks particles into smaller fragments, progressively shifting the size distribution toward smaller particles that are harder to

detect and more likely to be ingested by small organisms (Andrady, 2011; Hartmann et al., 2019). Biodegradation of conventional plastics in freshwater is slow, although some bacteria and fungi can colonise surfaces and, under specific conditions, partially degrade certain polymers (Gewert et al., 2015; Rochman et al., 2019). Biofilms, often called the plastisphere, form within days and host distinct microbial communities that may include pathogens and antibiotic-resistant bacteria (Zettler et al., 2013; McCormick et al., 2014). The plastisphere therefore links physical transport to ecological and health questions, because a particle is not merely plastic; it is a mobile habitat.

Table 1. Behaviour of microplastics in major freshwater compartments, synthesised from Wagner et al. (2014), Besseling et al. (2017), and Li et al. (2018).

Compartment	Typical behaviour	Key controls	Implication for monitoring
Rivers	Downstream transport, episodic deposition and resuspension	Flow, floods, dams, sediment load	Sample across flow regimes, not only baseflow
Lakes and reservoirs	Accumulation in sediments, long residence	Residence time, stratification, wind	Sediment cores complement water sampling
Wetlands	Trapping in vegetation and sediment, storm release	Vegetation, hydrologic connectivity	Include vegetation and sediment matrices
Groundwater	Slow transport through pores and fractures	Soil structure, recharge, karst	Use low-contamination sampling, small pore sizes
Atmosphere–water interface	Deposition and resuspension, surface microlayer enrichment	Wind, rain, surface tension	Sample surface microlayer and deposition

3.1 Sorption and vector effects

Microplastics can sorb hydrophobic organic pollutants, heavy metals, and additives from the surrounding water, and can also leach additives such as plasticisers, flame retardants, and stabilisers (Rochman et al., 2013; Rochman et al., 2019; Brennecke et al., 2016). Sorption depends on polymer type, crystallinity, surface area, weathering, pH, salinity, and dissolved organic matter (Rochman et al., 2013; Brennecke et al., 2016). Polyethylene, for example, has shown high sorption capacity for certain polycyclic aromatic hydrocarbons and polychlorinated biphenyls, while aged particles often sorb more than pristine ones because of increased surface roughness and functional groups (Rochman et al., 2013; Gewert et al., 2015). Whether microplastics increase net exposure to co-contaminants in real ecosystems remains debated, because natural particles such as sediments and organic matter also sorb pollutants and because desorption in the gut is not always efficient (Koelmans et al., 2016; Rochman et al., 2019). Koelmans et al. (2016) modelled that microplastics are unlikely to dominate the body burden of hydrophobic pollutants for many organisms, but they may matter in highly contaminated hotspots or for specific additives that leach readily. The vector question therefore requires site-specific chemistry, not a universal answer.

4. Occurrence and Spatial Patterns

Field surveys consistently report microplastics in freshwater on all inhabited continents, but concentrations span orders of magnitude (Eerkes-Medrano et al., 2015; Li et al., 2018; Koelmans et al., 2019). Reported water concentrations range from less than one particle per cubic metre in remote lakes to tens of thousands per cubic metre in polluted urban rivers, while sediment concentrations range from a few to tens of thousands of particles per kilogram dry weight (Li et al., 2018; Koelmans et al., 2019). This variability reflects real environmental differences and methodological differences in sampling volume, mesh size, extraction, and identification (Hartmann et al., 2019; Cowger et al., 2020). A study that uses a 300-micrometre net will miss most small fibres and fragments, whereas a study that filters one litre and uses spectroscopic confirmation will report different numbers and polymer profiles (Cowger et al., 2020; Koelmans et al., 2019). Cross-study comparisons must therefore be made with caution and with explicit attention to methods.

Urban rivers and rivers downstream of wastewater treatment plants often show elevated concentrations, especially of fibres (Browne et al., 2011; Murphy et al., 2016; McCormick et al., 2014). McCormick et al. (2014) found higher microplastic concentrations downstream of a wastewater treatment plant in the North Shore Channel in Chicago, with bacterial communities on particles distinct from those in the surrounding water. In large Asian rivers, high population density, industrial activity, and plastic use have produced some of the highest reported loads (Li et al., 2018; Wang et al., 2017). Wang et al. (2017) reported microplastic pollution in the Yangtze River, linking it to urbanisation and land use. In Europe, the Rhine, Danube, and Thames have been studied extensively, with evidence that concentrations increase downstream and that tributaries and storm drains create local hotspots (Wagner et al., 2014; Eerkes-Medrano et al., 2015). In Africa, studies are fewer but growing; they show contamination in rivers and lakes used for drinking, fishing, and irrigation, often with limited wastewater treatment (Eerkes-Medrano et al., 2015; Li et al., 2018). Remote lakes in the Arctic, high mountains, and protected areas also contain microplastics, confirming atmospheric transport (Allen et al., 2019; Dris et al., 2016).

Temporal patterns are equally important. Concentrations can rise during wet seasons, after storms, and during snowmelt, when runoff and resuspension increase (Wagner et al., 2014; Li et al., 2018). Seasonal agricultural activities, tourist seasons, and festivals can also produce pulses. Long-term trends are difficult to establish because systematic monitoring is recent and methods have changed, but sediment cores and repeated surveys suggest increases over recent decades in many catchments, paralleling plastic production and consumption (Turner et al., 2019; Geyer et al., 2017). Future monitoring must therefore combine high-frequency sampling during events, standardised methods, and long-term sites that can detect trends beyond short-term variability (Cowger et al., 2020; Koelmans et al., 2022).

5. Ecological Effects: From Individuals to Ecosystems

Ecological effects have been studied most intensively in laboratory experiments, with growing evidence from field observations and mesocosm studies (Eerkes-Medrano et al., 2015; de Sá et al., 2018). Effects depend on particle size, shape, concentration, polymer, exposure duration, species, life stage, and the presence of food and other stressors (de Sá et al., 2018; Hartmann et al., 2019). Fibres may be more harmful than spheres for some organisms because they entangle, are retained longer in the gut, and are harder to egest (de Sá et al., 2018). Small particles can translocate across gut epithelia, while larger particles mainly cause physical effects in the digestive tract (Browne et al., 2008; von Moos et al., 2012). The distinction between physical and chemical effects is useful analytically, but in practice organisms experience both simultaneously (Rochman et al., 2019).

5.1 Plankton, benthic invertebrates, and fish

Zooplankton such as Daphnia ingest microplastics, sometimes mistaking them for algae, which can reduce feeding, growth, and reproduction (Besseling et al., 2014; de Sá et al., 2018). Besseling et al. (2014) showed that nanoplastics reduced growth and altered reproduction in Daphnia magna, with effects increasing at higher concentrations. Phytoplankton can be affected through shading, aggregation, and adsorption to cell surfaces, although effects are highly species- and concentration-dependent (de Sá et al., 2018). Benthic invertebrates, including worms, mussels, and insect larvae, are exposed through sediment ingestion and filter feeding (Browne et al., 2008; von Moos et al., 2012). Browne et al. (2008) demonstrated translocation of ingested microplastics from the gut to the circulatory system in mussels, while von Moos et al. (2012) reported histological changes and inflammatory responses in blue mussels after exposure. Fish ingest microplastics directly and through prey, with reports from rivers and lakes worldwide (Eerkes-Medrano et al., 2015; Li et al., 2018). Effects in fish include gut blockage, reduced feeding, oxidative stress, liver damage, altered behaviour, and changes in gut microbiota, although field evidence for population-level harm remains limited (de Sá et al., 2018; Rochman et al., 2019).

5.2 Mechanisms: oxidative stress, inflammation, and microbiota

Several mechanisms link exposure to harm. Oxidative stress occurs when reactive oxygen species overwhelm antioxidant defences, damaging lipids, proteins, and DNA (de Sá et al., 2018; Rochman et al., 2019). Inflammation and immune responses can follow particle uptake, especially for small or sharp particles (von Moos et al., 2012). Gut microbiota can shift after ingestion, potentially affecting digestion, immunity, and metabolism (de Sá et al., 2018). Endocrine disruption is plausible when additives leach, but evidence is stronger for specific additives than for microplastics as a class (Rochman et al., 2013; Brennecke et al., 2016). Trophic transfer has been demonstrated in laboratory food chains, from algae to zooplankton to fish, and from prey to predators, raising questions about biomagnification (de Sá et al., 2018; Besseling et al., 2017). However, biomagnification of plastic particles themselves is not well established in the way that it is for some chemical pollutants; particles are often egested rather than retained, and transfer efficiency depends on retention time and feeding mode (Koelmans et al., 2022).

5.3 Ecosystem-level and multi-stressor considerations

Ecosystem-level effects are harder to detect but potentially more consequential. Microplastics can alter sediment properties, microbial activity, and nutrient cycling (de Souza Machado et al., 2018; Rochman et al., 2019). In soils, microplastics have been shown to affect bulk density, water holding capacity, and microbial communities, with implications for adjacent freshwater through runoff (de Souza Machado et al., 2018). In freshwater sediments, particles may affect benthic community structure by changing habitat or food quality, although field studies that isolate microplastic effects from other pollutants are rare (Eerkes-Medrano et al., 2015). Multi-stressor interactions are the norm: organisms face microplastics together with warming, nutrient pollution, pesticides, metals, and habitat loss (Rochman et al., 2019; de Sá et al., 2018). Climate change may intensify exposure through more frequent floods, droughts, and storms, and may alter degradation and transport rates (Wagner et al., 2014; Borrelle et al., 2020). Risk assessment must therefore move from single-species, single-stressor tests toward mesocosm and field studies that capture realistic mixtures and ecological context (Koelmans et al., 2022; Hartmann et al., 2019).

Table 2. Summary of ecological effects by organism group, synthesised from de Sá et al. (2018), Besseling et al. (2014), Browne et al. (2008), and von Moos et al. (2012).

Organism group	Common exposure route	Frequently reported effects	Evidence strength
Phytoplankton	Adsorption, aggregation	Reduced photosynthesis, growth inhibition	Moderate, species-dependent
Zooplankton (e.g., Daphnia)	Ingestion mistaken for food	Reduced feeding, growth, reproduction	Strong in laboratory studies
Benthic invertebrates	Sediment ingestion, filter feeding	Gut retention, inflammation, oxidative stress	Strong in laboratory studies
Mussels and bivalves	Filter feeding	Translocation, histological changes	Moderate to strong
Fish	Direct ingestion, trophic transfer	Gut damage, oxidative stress, behavioural change	Moderate, field evidence growing
Microbial communities	Colonisation of plastisphere	Community shifts, biofilm formation	Strong for colonisation, emerging for function

6. Human Health and Socioeconomic Dimensions

Humans are exposed to microplastics through drinking water, food, and air, with freshwater fish, shellfish, and drinking water as relevant routes (Cox et al., 2019; Koelmans et al., 2019). Cox et al. (2019) estimated that Americans may ingest tens of thousands of microplastic particles per year through food, water, and air, although estimates vary widely with methods and assumptions. Drinking water studies have reported microplastics in tap water, bottled water, and groundwater, but concentrations and health significance remain uncertain (Koelmans et al., 2019; Panno et al., 2019). Fish from freshwater systems can contain microplastics in the gut, and although gutting removes most particles, small fish eaten whole and shellfish pose greater exposure (Eerkes-Medrano et al., 2015; Li et al., 2018). The World Health Organization has noted that current evidence does not establish a clear health risk from microplastics in drinking water, while calling for more research and for reductions in plastic pollution (World Health Organization, 2019). This cautious conclusion should not be read as proof of safety; it reflects limited data on chronic low-dose exposure, nanoplastics, and vulnerable groups.

Socioeconomic dimensions are unevenly distributed. Communities that depend on rivers and lakes for drinking water, fishing, and irrigation, and that lack waste collection and wastewater treatment, often face higher exposure and fewer resources to respond (Borrelle et al., 2020; Li et al., 2018). Plastic pollution can reduce the aesthetic and recreational value of freshwater, harm tourism, increase water treatment costs, and damage fishing gear and infrastructure (Barnes et al., 2009; Borrelle et al., 2020). Informal waste pickers play a critical role in recycling in many low- and middle-income countries, yet they face occupational hazards and limited protection (Borrelle et al., 2020). Solutions that ignore livelihoods, gender, and informal economies risk being ineffective or unjust. Effective mitigation must therefore be designed with affected communities, not only for them, and must consider affordability, cultural practices, and local governance.

7. Detection, Characterisation, and Monitoring

Reliable detection requires careful sampling, extraction, and identification, with contamination control at every step (Cowger et al., 2020; Hartmann et al., 2019). Sampling methods include grab samples, nets, pumps, and sediment grabs, each with different size cut-offs and biases (Eerkes-Medrano et al., 2015; Li et al., 2018). Extraction often uses density separation, digestion of organic matter, and filtration, followed by visual sorting and spectroscopic confirmation (Cowger et al., 2020; Hartmann et al., 2019). Visual identification alone is prone to false positives, especially for small, transparent, or coloured fibres, so Fourier-transform infrared spectroscopy and Raman spectroscopy are widely used to confirm polymer type (Hartmann et al., 2019; Cowger et al., 2020). Pyrolysis-gas chromatography-mass spectrometry can quantify polymer mass, while newer methods such as Nile red staining with fluorescence microscopy can speed up counting but require validation (Cowger et al., 2020).

Quality assurance is essential. Field and laboratory blanks, cotton clothing, glassware, and clean-air practices help distinguish environmental particles from contamination (Cowger et al., 2020; Hartmann et al., 2019). Reporting should include sampling volume, mesh or filter size, size range, shape categories, polymer types, colour, and detection limits (Hartmann et al., 2019; Koelmans et al., 2022). Without these details, studies cannot be compared or synthesised. Interlaboratory comparisons have shown substantial variability, underscoring the need for harmonised protocols and reference materials (Cowger et al., 2020). Emerging approaches include automated image analysis, machine learning for spectral classification, and sensor-based monitoring, but they are not yet substitutes for validated methods (Koelmans et al., 2022). A tiered monitoring strategy is pragmatic: simple, low-cost methods for screening and community monitoring, and advanced spectroscopic methods for confirmatory and regulatory monitoring.

Table 3. Common methods for microplastic detection and characterisation, synthesised from Hartmann et al. (2019) and Cowger et al. (2020).

Method	What it measures	Strengths	Limitations
Visual microscopy	Count, shape, colour, size	Low cost, accessible	High false positives, poor for small particles
FTIR spectroscopy	Polymer type	Reliable for >20 µm, libraries available	Time-consuming, size limit
Raman spectroscopy	Polymer type, small particles	Good for small particles	Fluorescence interference, slow
Pyrolysis-GC-MS	Polymer mass, additives	Quantitative mass, no visual bias	Destroys sample, no count or shape
Nile red + fluorescence	Count, approximate size	Rapid screening	Requires validation, polymer ambiguity

8. Mitigation: Source Reduction, Treatment, and Nature-Based Solutions

Mitigation is most effective when it prevents particles from entering water in the first place, because removal after release is costly and incomplete (Borrelle et al., 2020; Rochman et al., 2013). Source reduction includes reducing single-use plastics, improving product design, extending producer responsibility, banning microbeads and avoidable plastic items, and promoting reuse and refill systems (Borrelle et al., 2020; Geyer et al., 2017). Textile interventions include washing-machine filters, improved fabric design, and laundry practices that reduce fibre shedding (Browne et al., 2011; Murphy et al., 2016). Tyre-wear reduction involves road design, driving behaviour, tyre composition, and street cleaning, although evidence for effectiveness at catchment scale is still emerging (Kole et al., 2017; Wagner et al., 2018). Agricultural measures include reducing plastic mulch, improving collection and recycling of films, and controlling sludge application (de Souza Machado et al., 2018; Nizzetto et al., 2016).

Wastewater treatment is a critical barrier even though it was not designed for microplastics (Murphy et al., 2016; Talvitie et al., 2017). Primary treatment removes larger particles through screening and settling, secondary treatment removes more through biological processes and settling, and tertiary treatment, including filtration, membranes, and dissolved air flotation, can achieve the highest removal (Talvitie et al., 2017). Figure 2 summarises indicative removal efficiencies reported in the literature; values should be read as ranges that depend on influent characteristics, particle size, and operational conditions, not as fixed guarantees.

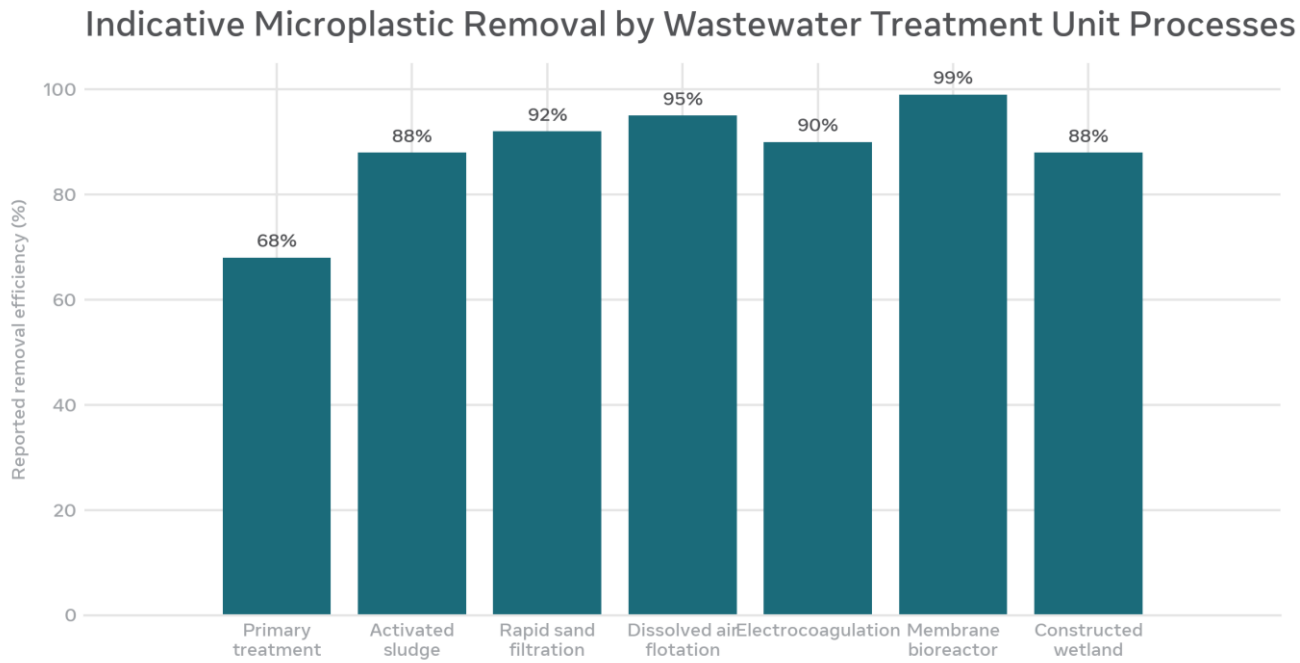


Figure 2. Indicative removal efficiencies for microplastics by wastewater treatment unit processes, synthesised from Murphy et al. (2016), Talvitie et al. (2017), and related reviews. Efficiencies are higher for larger particles and vary with influent load and operation.

Talvitie et al. (2017) reported that advanced treatment in Finnish plants removed more than 99% of microplastics from wastewater, but the remaining effluent still contained particles, and sludge retained a large fraction. Sludge management is therefore part of the treatment question: if sludge is applied to land, retained particles may re-enter freshwater through runoff (Nizzetto et al., 2016; Murphy et al., 2016). Stormwater treatment, including bioretention, permeable pavements, sediment traps, and constructed wetlands, can reduce loads, especially for larger particles and tyre wear (Wagner et al., 2018). Constructed wetlands combine filtration, settling, and biological processes, and can also provide habitat and

flood attenuation, making them attractive nature-based solutions (Wagner et al., 2014). However, wetlands can accumulate particles and may require maintenance to avoid becoming sources during storms.

Nature-based solutions extend beyond wetlands to riparian buffers, river restoration, and catchment reforestation, which reduce erosion, slow runoff, and trap litter (Wagner et al., 2014; Borrelle et al., 2020). Clean-up campaigns can remove visible litter and raise awareness, but they do not address microscopic particles and must be paired with upstream prevention (Barnes et al., 2009; Borrelle et al., 2020). Advanced technologies, including electrocoagulation, membrane bioreactors, photocatalysis, and biodegradation by engineered microbes, show promise in laboratory and pilot studies, but scalability, cost, energy use, and by-products require evaluation (Talvitie et al., 2017; Gewert et al., 2015). A systems approach that combines source control, improved infrastructure, and ecosystem restoration is more robust than reliance on any single technology.

8.1 Policy and governance

Policy has begun to respond, but coherence across levels remains limited. Microbead bans, plastic bag charges, single-use plastic restrictions, and extended producer responsibility schemes have reduced specific items in several countries (Rochman et al., 2013; Borrelle et al., 2020). The negotiation of a global plastics treaty under the United Nations Environment Programme reflects recognition that plastic pollution is transboundary and requires coordinated action on production, design, waste management, and finance (Borrelle et al., 2020). Effective policy should set measurable targets, require monitoring and reporting, support innovation in materials and treatment, and ensure that costs are not borne disproportionately by low-income communities (Geyer et al., 2017; Borrelle et al., 2020). Standards for sampling and reporting, ecolabelling, and product design can help align science, industry, and regulation (Hartmann et al., 2019; Cowger et al., 2020). Public engagement, education, and citizen science can expand monitoring coverage and build support for change, provided that data quality and community ownership are respected.

9. Research Gaps and Future Directions

Several gaps deserve priority. First, standardised methods and long-term monitoring networks are needed to produce comparable data across catchments and to detect trends (Cowger et al., 2020; Koelmans et al., 2022). Second, environmentally realistic experiments are needed that use weathered, mixed-polymer particles at concentrations found in freshwater, with food, predators, and other stressors present (Hartmann et al., 2019; de Sá et al., 2018). Third, nanoplastics remain poorly understood because they are difficult to detect and quantify in environmental samples, yet they may pose distinct risks because of their size and ability to cross biological barriers (Hartmann et al., 2019; Besseling et al., 2014). Fourth, groundwater, sediments, and atmospheric deposition need more systematic study, especially in underrepresented regions (Panno et al., 2019; Allen et al., 2019). Fifth, ecosystem-level and multi-generational studies are needed to test whether individual-level effects translate into population and community change (Rochman et al., 2019; Koelmans et al., 2022). Sixth, social science research is needed on behaviour, governance, and equity, because technical solutions alone will not solve a problem rooted in production, consumption, and waste systems (Borrelle et al., 2020; Geyer et al., 2017).

Modelling can help integrate these gaps by linking emissions, hydrology, and exposure. Models that combine land-use data, population density, wastewater and stormwater flows, and particle transport can identify hotspots, test intervention scenarios, and guide monitoring (Besseling et al., 2017; Kooi et al., 2018). Such models must be validated with field data and must transparently report uncertainty. Risk assessment frameworks should move from hazard alone to risk, combining exposure, vulnerability, and ecological context (Koelmans et al., 2022). For human health, prospective studies, improved exposure assessment, and research on vulnerable groups are priorities, alongside precautionary reductions in exposure (World Health Organization, 2019; Cox et al., 2019). Finally, solutions research should evaluate not only removal efficiency but also cost, energy, sludge and waste implications, and social acceptability, so that interventions are sustainable in practice, not only in the laboratory.

10. Conclusion

Microplastic pollution in freshwater ecosystems is a complex, persistent, and unevenly distributed problem that links consumption, infrastructure, hydrology, ecology, and health (Thompson et al., 2004; Eerkes-Medrano et al., 2015; Li et al., 2018). Sources are diverse and include wastewater, stormwater, agriculture, industry, and atmospheric deposition, while transport and fate are controlled by particle properties, biofouling, aggregation, and flow (Wagner et al., 2014; Besseling et al., 2017). Ecological effects are well documented at the organism level, with growing but incomplete evidence for ecosystem-level consequences (de Sá et al., 2018; Rochman et al., 2019). Detection remains challenging, but harmonised methods and quality assurance can improve comparability (Hartmann et al., 2019; Cowger et al., 2020). Mitigation requires prevention first, supported by improved wastewater and stormwater treatment, nature-based solutions, and coherent policy (Borrelle et al., 2020; Talvitie et al., 2017). The path forward is not to wait for perfect certainty, but to act on what is already clear while investing in the monitoring, experiments, and equitable governance needed to reduce uncertainty and protect freshwater for people and nature.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

This review is based on published literature cited in the reference list. No new experimental data were generated. Figures present synthesised indicative values from the cited studies and are intended for synthesis, not as primary measurements.

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