

MICROPLASTIC CONTAMINATION IN FRESHWATER ECOSYSTEMS

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Abstract:

Microplastics, commonly defined as plastic particles smaller than 5 mm, have become ubiquitous contaminants of the environment. Although early research focused on marine systems, freshwater ecosystems—rivers, lakes, reservoirs, wetlands and groundwater—are now recognised both as major pathways that deliver plastics to the oceans and as important sinks in their own right. This paper reviews current knowledge on the sources, occurrence, transport, ecological effects and human-health implications of microplastic contamination in freshwater environments. Principal sources include wastewater treatment plant effluent, laundering of synthetic textiles, tyre wear, urban and agricultural runoff, atmospheric deposition and the fragmentation of larger plastic debris. Microplastics have been reported from densely populated urban catchments to remote mountain lakes, with polyethylene, polypropylene, polystyrene and polyethylene terephthalate among the most frequently identified polymers. Laboratory and field studies show that freshwater organisms ingest microplastics and that

particles can act as vectors for additives and sorbed pollutants, although environmental relevance remains debated. Inconsistent sampling and analytical methods continue to limit comparability between studies. Mitigation strategies include source reduction, improved wastewater treatment, better waste management, supportive regulation and harmonised monitoring. A regional perspective on India and priorities for future research are also discussed for autism spectrum disorder identification.

Keywords: Microplastics; freshwater ecosystems; plastic pollution; wastewater treatment; bioaccumulation; sediment; environmental monitoring; mitigation; policy.

1. Introduction

1.1 Background

Plastics have become indispensable to modern life because they are lightweight, durable and inexpensive. The same durability means that plastic waste persists in the environment for decades or longer. The term “microplastics” entered the scientific literature after Thompson et al. (2004) reported the

accumulation of microscopic plastic fragments and fibres in marine sediments and plankton. Since then, microplastics have been found in oceans, polar ice, soils, the atmosphere and living organisms.

For many years, freshwater systems received far less attention than the sea, even though most plastic waste is generated and mismanaged on land. Wagner et al. (2014) and Eerkes-Medrano et al. (2015) highlighted this imbalance and showed that freshwater environments are both conduits and reservoirs for plastic particles. Rivers transport plastic from inland sources to the sea; Lebreton et al. (2017) modelled river inputs on the order of one to two and a half million tonnes of plastic per year to the oceans. At the same time, lakes, reservoirs and floodplain sediments can retain particles for long periods.

Freshwater ecosystems matter to biodiversity and to people: they supply drinking water, irrigation, fisheries and recreation. Although they cover a small fraction of the Earth's surface, they support a disproportionately large share of species. Contamination by microplastics therefore raises ecological and public-health questions that extend well beyond the water body in which particles are first detected.

1.2 Objectives and Scope

This paper provides a structured review of microplastic contamination in freshwater ecosystems. It aims to (i) define and classify microplastics; (ii) identify their main sources and pathways into freshwater; (iii) summarise patterns of occurrence,

transport and fate; (iv) outline methods of sampling and analysis and their limitations; (v) evaluate ecological and human-health effects; (vi) provide a regional perspective on India; and (vii) discuss mitigation, policy responses and research needs. The review draws on peer-reviewed literature and official policy documents, and it emphasises review articles and widely cited primary studies.

2. Definition and Classification of Microplastics

Microplastics are generally defined as synthetic polymer particles smaller than 5 mm, with a lower size limit that depends on the analytical method used. Particles below roughly 1 μm are often termed nanoplastics, though definitions vary, and Hartmann et al. (2019) proposed a framework to harmonise terminology. Microplastics are conventionally divided into two categories.

Primary microplastics are manufactured at small size, for example resin pellets (nurdles), microbeads once used in cosmetics and abrasive cleaning products, and industrial powders. Secondary microplastics form when larger items such as bottles, bags, fishing gear and agricultural films break down through ultraviolet radiation, mechanical abrasion, and biological and chemical weathering.

Particles are also categorised by shape (fragments, fibres, films, foams, pellets and beads), colour, size class and polymer type. These properties influence buoyancy, transport, bioavailability and toxicity. Table 1

summarises common polymers and their typical behaviour in water.

Table 1: Common polymers found as microplastics in freshwater environments

Polymer	Common sources	Density (g/cm ³)	Typical behaviour
Polyethylene (PE)	Packaging films, bottles, cosmetics	0.91-0.97	Floats
Polypropylene (PP)	Food containers, ropes, caps	0.90-0.91	Floats
Polystyrene (PS)	Foam packaging, disposable cutlery	1.04-1.10 (solid)	Floats or sinks
Polyvinyl chloride (PVC)	Pipes, cables, flooring	1.16-1.58	Sinks
Polyethylene terephthalate (PET)	Bottles, synthetic textile fibres	1.37-1.45	Sinks

3. Sources and Pathways

Microplastics enter freshwater through point sources, such as discharge pipes, and diffuse sources, such as runoff and atmospheric deposition. Because inputs are spread across many activities, quantifying the relative contribution of each source is difficult, and it varies greatly between catchments.

3.1 Wastewater Treatment Plants

Municipal wastewater carries microfibres from laundry, particles from personal-care products and fragments from household dust. Modern treatment plants

remove a large fraction of particles, mainly by settling into sewage sludge, but the large volumes discharged mean that substantial numbers of particles still reach receiving waters (Mintenig et al., 2017). Advanced treatments such as membrane bioreactors and tertiary filtration can improve removal considerably (Talvitie et al., 2017). Where sludge is applied to farmland, retained particles can re-enter freshwater through runoff.

3.2 Textiles and Laundry

Washing synthetic garments releases large numbers of fibres. Napper and Thompson (2016) showed that a single wash can release hundreds of thousands of fibres, depending on fabric type and washing conditions. Fibres are among the most commonly reported particle shapes in rivers and lakes. In regions where untreated or partially treated domestic wastewater is discharged directly into streams, this pathway bypasses treatment altogether.

3.3 Tyre and Road Wear

Abrasion of tyres and road markings produces particles that are washed into drains and surface waters during rain. Kole et al. (2017) identified tyre wear as a major, though often overlooked, contributor to environmental microplastics, particularly in urban catchments. Intense rainfall events can flush accumulated particles into waterways in short pulses.

3.4 Runoff, Agriculture and Fragmentation of Macroplastics

Mismanaged solid waste, littering, plastic mulch films, greenhouse covers and fertiliser coatings contribute to diffuse inputs. Larger debris degrades progressively into secondary microplastics along riverbanks and lake shores. Storms and floods can mobilise large quantities of accumulated debris at once. Browne et al. (2011) demonstrated that populated areas and wastewater discharge are linked to the accumulation of microplastic fibres on shorelines, underlining the connection between human activity and contamination.

3.5 Atmospheric Deposition

Dris et al. (2016) showed that atmospheric fallout of synthetic fibres contributes to microplastic loads in an urban setting, linking air, land and water compartments. Particles deposited on roofs, roads and soils can later be washed into drains and streams, while deposition directly onto lakes and reservoirs adds to the load.

3.6 Other Local Sources

Fishing and aquaculture gear, boating, recreational activity, tourism and industrial discharges, including pellet losses during plastic production and transport, are additional local sources. In small or enclosed water bodies, these local inputs can dominate over regional ones.

4. Occurrence, Transport and Fate

4.1 Global and Regional Occurrence

Microplastics have been reported from freshwater systems on every inhabited continent. Eriksen et al. (2013) documented widespread contamination in surface waters of the Laurentian Great Lakes, with the highest concentrations near large urban centres. Free et al. (2014) found considerable pollution even in a large, remote mountain lake in Mongolia, indicating that long-range transport and local tourism can both play a role. Reviews by Li et al. (2018) and Horton et al. (2017) confirm that concentrations vary by orders of magnitude between sites, reflecting differences in population density, land use, hydrology and sampling methods. Table 2 summarises representative studies.

Table 2: Representative studies of microplastics in freshwater-related environments

Study	Setting	Matrix	Main finding (summary)
Eriksen et al. (2013)	Laurentian Great Lakes, North America	Surface water	Widespread contamination, with the highest concentrations near large urban areas
Free et al. (2014)	Lake Hovsgol, Mongolia	Surface water	Considerable pollution detected even in a large, remote mountain lake

Study	Setting	Matrix	Main finding (summary)
Mintenig et al. (2017)	Wastewater plants, Germany	Treated effluent	Microplastics, including small particles, detected in effluents of treatment plants
Napper & Thompson (2016)	Laboratory washing experiments	Washing-machine effluent	Fibre release varies with fabric type and washing conditions
Sruthy & Ramasamy (2017)	Vembanad Lake, Kerala, India	Lake and estuarine sediments	First report of microplastics in lake and estuarine sediments of India
Panno et al. (2019)	Karst aquifer, Illinois, USA	Groundwater	Microplastics detected in karst groundwater systems
Mintenig et al. (2019)	Groundwater-fed supplies, Germany	Drinking water	Low numbers of microplastics detected

4.2 Transport Processes

Transport depends on particle size, shape and density, as well as on flow velocity, turbulence, seasonal discharge and the presence of dams and weirs. Low-density polymers such as polyethylene and polypropylene tend to float, whereas denser polymers such as PVC and PET settle. In practice, biofouling by algae and bacteria, aggregation with organic matter and ingestion and egestion by organisms alter buoyancy, so

particles may move between the surface, water column and bed over time.

Rivers act as both transport routes and temporary storage zones. During high flows, particles are carried downstream and can be exported to estuaries and the sea; during low flows, they may settle in slow-moving reaches, behind barriers or in riparian vegetation. Dams and reservoirs interrupt this movement, so the water bodies behind them can accumulate particles that would otherwise travel to the coast.

4.3 Weathering and Degradation

Once in the environment, plastics undergo photo-oxidation, thermal and mechanical degradation and, to a limited extent, biodegradation (Andrady, 2011). Ultraviolet radiation embrittles the polymer surface, making it more prone to cracking and fragmentation under abrasion. Fragmentation increases the number of particles and their surface area, potentially enhancing sorption of contaminants and release of additives. Weathering is slower in cold, dark or buried conditions, so particles in sediments may persist far longer than those at the surface.

4.4 Sediments as Sinks

Lake and river sediments are important long-term sinks. Bellasi et al. (2020) reviewed interactions between microplastics, sediments and benthic organisms, noting that deposition zones, such as reservoirs, lake basins, river deltas and floodplains, often hold the highest particle counts. Floods may remobilise buried particles, turning sediments into a secondary

source. Burial of particles also places them in contact with benthic invertebrates that feed on or burrow through sediments.

4.5 Groundwater, Wetlands and Drinking Water

Freshwater contamination is not limited to surface waters. Panno et al. (2019) reported microplastics in a karst groundwater system, where fast flow through fractures and conduits can move particles quickly from the surface. In contrast, Mintenig et al. (2019) found only low numbers of microplastics in drinking water supplied from groundwater sources in Germany. Koelmans et al. (2019) reviewed data on freshwater and drinking water and emphasised that concentrations reported in the literature are strongly influenced by the size range measured, with smaller particles far more numerous than larger ones. Wetlands may trap particles through sedimentation and vegetation, but they have been studied much less than rivers and lakes.

5. Sampling, Detection and Analytical Challenges

5.1 Sampling

Studies use different sampling devices, including manta and plankton nets, pumps, bulk water samples and sediment grabs or corers. Net mesh size determines the smallest particles collected; commonly used nets miss the numerous small particles that pass through the mesh, while bulk sampling captures smaller sizes but processes much

smaller volumes. Sampling depth, season, flow conditions and recent rainfall also influence the results.

5.2 Sample Processing

Organic matter is typically digested using hydrogen peroxide, enzymes or other reagents, and particles are separated from mineral material by density using salt solutions. Each step can lose or alter particles, so recovery tests using spiked samples are recommended.

5.3 Identification and Quantification

Visual identification under a stereomicroscope is common but error-prone for small and transparent particles. Polymer identification relies on Fourier-transform infrared (FTIR) spectroscopy, Raman spectroscopy or thermal-analytical techniques such as pyrolysis-gas chromatography-mass spectrometry. Imaging approaches, such as the focal plane array FTIR method used by Mintenig et al. (2017), allow automated analysis of many particles but require specialist equipment.

5.4 Quality Assurance and Comparability

These differences make comparison across studies difficult. Koelmans et al. (2019) assessed the quality of data on microplastics in freshwater and drinking water and concluded that only a limited share of studies met the quality criteria they applied, highlighting the need for standardised protocols, procedural blanks and contamination control. Airborne fibres from

clothing and laboratory air can contaminate samples, so clean-air workspaces, cotton laboratory coats and blank controls are essential. Reporting in common units (particles per cubic metre or per kilogram dry sediment) together with size ranges is also needed.

6. Ecological Effects

6.1 Ingestion and Physical Effects

Freshwater organisms from zooplankton and insect larvae to molluscs, crustaceans and fish ingest microplastics, either directly or through contaminated prey. Scherer et al. (2017) showed that ingestion by invertebrates depends strongly on feeding type and developmental stage, and ingestion of textile fibres by the water flea *Daphnia magna* has been documented (Jemec et al., 2016). Reported physical effects include gut blockage, reduced feeding, altered energy budgets and abrasion of tissues, as reviewed for marine species by Wright et al. (2013); comparable mechanisms are expected in freshwater taxa.

6.2 Chemical Effects and Vector Role

Plastics contain additives such as plasticisers, flame retardants and stabilisers, and they can sorb hydrophobic contaminants from surrounding water (Teuten et al., 2009). Rochman et al. (2013) found that fish exposed to plastic that had been in the marine environment accumulated hazardous chemicals and showed signs of liver stress. The extent to which microplastics increase chemical exposure relative to other pathways

in natural settings is still debated, and many effects have been observed at concentrations above those typically found in the environment.

6.3 Biofilms, Microbial Communities and Food Webs

Microplastic surfaces are colonised by microbial biofilms. McCormick et al. (2014) found that microplastics in an urban river supported microbial communities distinct from those in the surrounding water and on natural organic material. Such biofilms could carry pathogens or antibiotic-resistance genes, although the significance of this has not been firmly established. Trophic transfer from prey to predators has been demonstrated in laboratory experiments with aquatic organisms (Farrell & Nelson, 2013), although evidence of biomagnification in natural food webs is limited.

6.4 Effects on Primary Producers and Ecosystem Functions

Microplastics may also affect algae and plants. Sjollem et al. (2016) examined the effects of plastic particles on microalgal photosynthesis and growth, and reported effects that depended on particle size. Because algae underpin aquatic food webs, even subtle effects could propagate through ecosystems. Possible consequences for nutrient cycling, sediment structure and decomposition are still poorly understood, and further research is needed to link individual-level responses with ecosystem-level outcomes.

7. Implications for Human Health

People may be exposed to freshwater microplastics through drinking water, fish and shellfish, salt, and other foods, as well as through inhalation of airborne particles. Cox et al. (2019) estimated that annual intake of microplastic particles through food, water and air runs to tens of thousands of particles per person, although estimates are uncertain and depend heavily on the data used.

Wright and Kelly (2017) reviewed the potential for harm and noted that while larger particles are likely to pass through the digestive tract, smaller particles may cross biological barriers and cause inflammation or oxidative stress, in addition to exposing tissues to associated chemicals. Toxicological understanding of effects on humans remains incomplete, and current evidence does not allow firm conclusions regarding health risks. Precautionary source reduction and improved risk assessment are therefore widely recommended.

8. Regional Perspective: India and South Asia

Large and growing populations, rapid urbanisation, and gaps in waste collection and wastewater treatment make South Asia an important region for microplastic research. Jambeck et al. (2015) ranked countries by the quantity of mismanaged plastic waste in coastal regions, and several Asian countries, including India, feature among those with large amounts. Lebreton et al. (2017) identified rivers in Asia as significant contributors to riverine plastic transport to the sea.

Despite this, measurements of microplastics in Indian freshwater bodies have been relatively limited. Sruthy and Ramasamy (2017) provided the first report of microplastics in lake and estuarine sediments in India, based on samples from Vembanad Lake in Kerala, a large wetland system that supports fisheries, agriculture and tourism. Their work demonstrated that even ecologically and economically valuable tropical water bodies are affected, and it has encouraged further studies of rivers, reservoirs and estuaries.

Several features of the Indian context are likely to shape contamination patterns: monsoon-driven flushing that delivers pulses of litter and runoff; direct discharge of untreated sewage into some urban rivers; dense informal settlements along waterways; widespread use of synthetic textiles; and plastic mulch and packaging in agriculture. Priorities for the region include standardised monitoring in major river basins and urban lakes, assessment of seasonal variability, evaluation of drinking-water sources and community-based clean-up and awareness programmes.

9. Mitigation and Management Strategies

Because removing particles from the environment is difficult once they have dispersed, the most effective strategies prevent them from entering water in the first place. Table 3 summarises the main strategies and their limitations.

Table 3: Summary of mitigation strategies for freshwater Microplastic pollution

Strategy	Examples	Main limitation
Source reduction	Microbead bans, reduced single-use plastics, low-shedding fabrics, tyre and road-wear innovations	Needs regulation, industry change and consumer behaviour change
Wastewater treatment	Tertiary and membrane filtration, sludge management, washing-machine filters	Cost; captured particles concentrate in sludge
Stormwater control	Constructed wetlands, bioswales, retention ponds, trash racks	Variable efficiency for small particles and fibres
Waste management	Better collection, recycling, landfill practice, river and shoreline clean-up	Infrastructure gaps in rapidly urbanising regions
Remediation	Filtration, coagulation, sedimentation, emerging biological and magnetic methods	Largely at laboratory or pilot scale; not practical for open waters
Monitoring and policy	Harmonised methods, long-term programmes, extended producer responsibility	Requires sustained funding and coordination across basins

9.1 Prevention and Source Reduction

- **Product bans and redesign:** restrictions on microbeads in rinse-off cosmetics, reduction of single-use plastics, and

redesign of products and fabrics to shed fewer particles.

- **Textile solutions:** washing-machine filters, laundry bags and fabric design that limits fibre shedding.
- **Transport:** tyre and road-surface innovations and better street sweeping and drainage management to limit wear particles reaching waterways.

9.2 Wastewater and Stormwater Treatment

Upgrading treatment plants with tertiary or membrane filtration reduces discharge of particles (Talvitie et al., 2017), but retained particles concentrate in sludge, so sludge management is critical. Constructed wetlands, bioswales and retention ponds can capture urban runoff and tyre-wear particles before they reach rivers, while trash racks and booms help intercept larger debris before it fragments.

9.3 Waste Management and Remediation

Improving waste collection, recycling and landfill practices – particularly in rapidly urbanising regions – addresses the largest upstream source of secondary microplastics. Clean-up of riverbanks and shorelines before debris fragments is more effective than attempting to recover small particles afterwards. Technologies such as coagulation, filtration and emerging biological or magnetic methods have shown promise for removing particles from water in laboratory and pilot studies, but they are not practical for restoring open water bodies, which reinforces the priority of prevention.

10. Policy and Regulatory Frameworks

Governments have begun to respond to plastic pollution through a mix of product restrictions and waste-management requirements. In the United States, the Microbead-Free Waters Act of 2015 prohibited the manufacture and sale of rinse-off cosmetics containing plastic microbeads. The European Union adopted Directive (EU) 2019/904 to reduce the impact of certain single-use plastic products and, in 2023, adopted Regulation (EU) 2023/2055, which restricts the sale of synthetic polymer microparticles intentionally added to products, with transition periods for different product categories.

In India, the Plastic Waste Management Rules, 2016, as amended, set out responsibilities for producers, importers and brand owners, and later amendments introduced extended producer responsibility and prohibited the manufacture, sale and use of identified single-use plastic items. Such measures mainly target macroplastics, which are the main source of secondary microplastics, but they have not been designed specifically around unintentional sources such as textile fibres and tyre wear.

Effective policy will likely require measures that address unintentionally released particles, harmonised monitoring requirements, transparent reporting and cooperation across jurisdictions that share river basins. Regular evaluation is needed to show whether restrictions lead to measurable reductions in environmental concentrations.

11. Knowledge Gaps and Future Research Directions

Several priorities emerge from the literature.

- **Methods:** standardised, quality-assured methods are needed to detect and quantify particles, especially in the smaller size fractions (below about 100 μm), where data remain scarce.
- **Nanoplastics:** these are poorly characterised in freshwater, and analytical tools for detecting them in complex natural samples are still developing.
- **Geographic coverage:** most data come from temperate regions of Europe and North America; tropical and developing-country river systems, where population pressure and waste mismanagement may be high, are underrepresented.
- **Ecotoxicology:** studies should use environmentally realistic particle types, concentrations and exposure durations, including weathered and mixed-polymer particles.
- **Modelling and monitoring:** long-term monitoring and models of retention, remobilisation and export from catchments will improve risk assessment and help evaluate whether policy interventions work.
- **Human health:** better exposure data and toxicological studies are needed to determine whether current levels pose risks.

12. Conclusion

Microplastic contamination is a widespread and growing concern for freshwater ecosystems. Particles originate from many diffuse and point sources, from wastewater effluent, textiles and tyre wear to fragmented litter, and are distributed through rivers, lakes, groundwater and sediments, reaching even remote areas. Freshwater organisms ingest these particles, and potential chemical and ecological consequences are under active investigation, although uncertainty remains regarding effects at environmentally relevant concentrations and risks to human health.

Progress depends on harmonised monitoring methods, better data from understudied regions such as South Asia, and ecologically realistic experiments. In the meantime, precautionary action focused on reducing plastic production and leakage, improving wastewater treatment, strengthening waste management and adopting supportive regulation offers the most reliable route to protecting freshwater ecosystems and the services they provide.

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