

Review

Microplastics in Aquatic Ecosystems: Sources, Environmental Fate, and Policy Perspectives

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Abstract

Microplastics (MPs; <5 mm) represent a growing environmental concern that increasingly challenges environmental monitoring, governance, and evidence-based decision-making. This review critically examines how current scientific understanding of microplastic sources, classification, occurrence, and environmental behavior can support environmental governance. MPs are classified as primary and secondary particles; however, persistent inconsistencies in size definitions, shape descriptors, and polymer identification limit the comparability of monitoring data and constrain the development of coherent regulatory frameworks. Evidence on the occurrence of MPs in surface waters and sediments highlights widespread contamination and pronounced spatial variability, raising challenges for risk assessment and policy harmonization across regions. Key transport pathways, including atmospheric deposition, terrestrial runoff, and riverine fluxes, are analyzed to illustrate how local emissions translate into large-scale environmental impacts. Rivers emerge as key components linking sources to receptors, offering relevant points for policy intervention and management measures. The review evaluates current policy responses to microplastic pollution, identifying significant gaps in standardized monitoring, data integration, and risk assessment approaches. It emphasizes the need for stronger alignment between scientific outputs and policy requirements, including the co-production of knowledge involving scientists, regulators, and stakeholders. By outlining pathways through which scientific evidence can inform regulatory design and environmental management, this study provides actionable insights for improving policy effectiveness. Advancing harmonized methodologies and integrating science into decision-making processes are essential steps toward mitigating microplastic pollution and supporting sustainable environmental governance.

Keywords: microplastics; environmental governance; science–policy interface; evidence-based decision-making; environmental monitoring; policy integration; riverine transport; aquatic ecosystems



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1. Introduction

Synthetic organic polymers, commonly referred to as plastics, are widely used in modern society due to their favorable physicochemical properties and low production costs [1–3]. Their hydrophobicity, durability, resistance to thermal stress, and insulating properties have enabled extensive applications across sectors such as packaging, construction, textiles, transportation, and consumer goods, resulting in a continuous increase in global production and consumption since the mid-20th century [3–5]. This rapid expansion has generated large volumes of plastic waste, with production rising from approximately

300 million tons in 2016 to 359 million tons in 2018 and projected to reach up to 33 billion tons cumulatively by 2050 [1]. The environmental consequences are increasingly evident in freshwater and marine systems, where plastics represent persistent and widespread contaminants [6–8]. Additional inputs associated with the COVID-19 pandemic have further intensified plastic pollution [9–12]. Due to their long degradation times, plastics accumulate in the environment over decades or centuries [13,14], with increasing attention shifting from macro plastics to smaller fractions such as microplastics (MPs, <5 mm), generally defined as heterogeneous synthetic polymer particles ranging from approximately 0.1 μm to 5 mm in size and occurring in diverse morphologies, including fragments, fibers, films, foams, and beads, often containing additives or sorbed contaminants [15–19]. Nano plastics (NPs) are considered a smaller fraction derived from the further fragmentation of microplastics, exhibiting enhanced mobility and bioavailability due to their reduced size.

Microplastics encompass a wide range of polymer types, including polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC), as well as high-performance polymers such as PTFE, PMMA, and PHEMA [20,21]. They are commonly classified as primary MPs, intentionally manufactured at a microscopic scale, and secondary MPs, generated through fragmentation of larger plastic debris [22–24]. Secondary MPs dominate environmental observations and originate from diverse sources, including packaging materials, synthetic textiles, tire wear, fishing gear, and paints [25,26]. Their physicochemical properties strongly influence environmental fate, with low-density polymers prevailing in surface waters and higher-density polymers accumulating in sediments [27–30], contributing to their widespread occurrence across environmental compartments, including water, sediments, soils, and the atmosphere [25,31,32].

Recent review articles have extensively addressed specific aspects of microplastic pollution, including analytical methodologies, occurrence in aquatic systems, ecotoxicological effects, and human exposure pathways. However, most existing reviews tend to focus on isolated environmental compartments or thematic perspectives, such as marine pollution, wastewater systems, polymer characterization, or toxicological implications, often without integrating environmental transport mechanisms with regulatory and monitoring dimensions [26,30]. Furthermore, comparatively limited attention has been paid to the interactions between atmospheric deposition, terrestrial runoff, riverine transport, and marine accumulation as interconnected pathways shaping microplastic distribution patterns across aquatic ecosystems.

Despite the rapid expansion of microplastic research, significant uncertainties remain in linking emission sources, transport pathways, and environmental distribution patterns [33–35]. Current evidence consistently demonstrates that microplastics are ubiquitous contaminants detected in water, sediments, soils, biota, and the atmosphere, and that polymer density, shape, and size strongly influence environmental fate and compartmentalization. Rivers are increasingly recognized as both transport corridors and temporary sinks regulating retention, fragmentation, and remobilization processes [25,36,37]. However, important uncertainties remain regarding the relative contribution of different transport pathways, the temporal variability of microplastic fluxes, long-range atmospheric transport, and the cumulative interactions between freshwater and marine systems. In addition, methodological inconsistencies related to sampling strategies, particle classification, extraction, and analytical identification continue to limit cross-study comparability and the establishment of robust environmental baselines [25,36,37].

These scientific limitations have direct implications for environmental policy and decision-making. Methodological heterogeneity and fragmented datasets continue to hinder comparability across regions and constrain the development of harmonized monitoring

frameworks and risk assessment strategies. As a result, the translation of scientific evidence into effective regulatory measures remains limited, despite increasing policy attention to microplastic pollution.

In this context, this review synthesizes current knowledge on microplastics in aquatic ecosystems, focusing on sources, classification, polymer diversity, occurrence, and environmental transport processes, while explicitly examining their relevance for environmental governance. The present manuscript adopts an integrative perspective by connecting environmental pathways, methodological challenges, and policy-related implications within a unified framework. Particular attention is given to the role of interconnected pathways, linking atmospheric, terrestrial, freshwater, and marine systems, and to the implications of methodological variability for monitoring and policy implementation. European regulatory frameworks are critically evaluated to assess how scientific evidence is currently integrated into policy and to identify existing gaps. By bridging environmental processes with policy needs, this review aims to support the development of harmonized monitoring strategies, improved risk assessment approaches, and more effective evidence-based decision-making for the management of microplastic pollution.

2. Materials and Methods

2.1. PRISMA-Based Literature Selection

This review was conducted in accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, reproducibility, and methodological rigor in the literature selection process. A systematic literature search was conducted between October 2025 and March 2026 using the scientific databases Web of Science, Scopus, ScienceDirect, and Google Scholar, which were selected to ensure broad coverage of environmental, ecological, and engineering studies related to microplastics in aquatic systems. The search strategy was developed using predefined combinations of keywords related to microplastics, environmental compartments, transport mechanisms, and pollution pathways. Boolean operators (“AND”, “OR”) were applied to optimize retrieval. Representative search strings included: “microplastics” AND (“aquatic ecosystems” OR freshwater OR marine OR river OR sediment OR atmosphere OR soil), “microplastic transport” AND (“environmental fate” OR deposition OR riverine transport OR atmospheric transport), and “sources of microplastics” AND (“wastewater” OR textile fibers OR tire wear OR plastic degradation). Citation tracking of key review articles was additionally performed to identify relevant publications.

The PRISMA-based screening procedure was applied exclusively to peer-reviewed scientific literature, including original research articles and review papers addressing microplastic occurrence, sources, transport mechanisms, environmental distribution, analytical methodologies, and ecological implications across atmospheric, terrestrial, freshwater, estuarine, and marine systems (checklist in Supplementary). Studies were included if they provided sufficient methodological and contextual information relevant to the objectives of the review. Exclusion criteria included studies not directly focused on microplastics or aquatic systems, insufficient thematic relevance, and methodological or contextual overlap. The literature selection process for scientific publications is summarized in the PRISMA flow diagram (Figure S1), which describes the identification, screening, eligibility, and inclusion of peer-reviewed scientific studies.

To support cross-study interpretation, a qualitative methodological appraisal was additionally considered during evidence synthesis. Particular attention was given to polymer confirmation, contamination control (field/procedural blanks), particle-size thresholds, and reporting units, as these factors strongly influence comparability among MP studies (Table S1).

2.2. Policy and Regulatory Documents

Because this review also addresses governance and regulatory dimensions, policy and legal documents were identified separately and were not included in the PRISMA workflow. Regulatory sources were selected through targeted searches of official institutional websites and databases, including the European Commission, European Chemicals Agency (ECHA), European Environment Agency (EEA), European Parliament, European Union legal databases (EUR-Lex), ISO and ASTM standards, as well as reports from environmental agencies and international organizations. These documents were included based on relevance to microplastic monitoring, environmental risk assessment, wastewater treatment, regulatory restrictions, and harmonized policy frameworks. Policy and regulatory documents were considered complementary sources intended to contextualize environmental governance and were therefore treated separately from the scientific evidence synthesis.

2.3. Software and Data Visualization Tools

Figures and graphical materials included in this review were prepared using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA), Microsoft PowerPoint (Microsoft Corporation, Redmond, WA, USA), and Canva (Canva Pty Ltd., Sydney, Australia).

3. Sources and Classification of Microplastics

The occurrence of MPs in aquatic ecosystems is intrinsically linked to their sources and release pathways. MPs are generally classified into primary microplastics, intentionally manufactured at a microscopic size, and secondary microplastics, generated through fragmentation of larger plastic materials [22–24]. Although this classification remains useful for source attribution and management prioritization, it only partially reflects the environmental complexity of MPs, which vary substantially in size, morphology, chemical composition, and environmental behavior.

3.1. Primary and Secondary Microplastics

Primary microplastics are intentionally produced for industrial, biomedical, and commercial applications. Historically, cosmetic and personal care products represented a major source through the use of plastic microbeads in exfoliating products and toothpaste [38,39]. Although bans have reduced these applications in several countries, industrial abrasives, biomedical polymers, and specialized commercial uses continue to contribute to environmental releases [40–49]. Their persistence reflects the limited availability of alternatives and incomplete waste management systems. In contrast, secondary microplastics dominate environmental observations and arise from the progressive fragmentation of larger plastic debris through physical, chemical, and biological weathering [49,50]. Mechanical abrasion, ultraviolet-induced photooxidation, and thermal degradation progressively weaken polymer structures, while microbial degradation generally remains slow and incomplete [51–56]. Major contributors include textile fibers released during washing, tire wear particles transported via runoff, paint particles, packaging materials, and agricultural plastics [33,57–63]. These diffuse and cumulative sources explain why secondary MPs are widely distributed across aquatic and terrestrial systems and remain considerably more difficult to control than intentional emissions.

From an environmental management perspective, primary MPs can be partially mitigated through regulatory restrictions, whereas secondary MPs require systemic interventions targeting plastic production, wastewater treatment, and diffuse urban runoff. Therefore, mitigation strategies should be adapted to source-specific emission pathways rather than generalized pollution control approaches [64,65].

3.2. Polymer Types and Physicochemical Diversity

The environmental fate of MPs strongly depends on polymer composition and physicochemical properties (Table 1). Common polymers include polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyethylene terephthalate (PET), and polycarbonate (PC), each characterized by distinct density, crystallinity, and chemical resistance [66,67]. These properties influence buoyancy, persistence, degradation, and contaminant interactions. Low-density polymers such as PE and PP tend to remain in surface waters, whereas denser polymers, including PET, PVC, and PS, are more frequently associated with sediment accumulation [68–70]. However, environmental distribution cannot be explained solely by density, as biofouling, fragmentation, turbulence, and hydrodynamic conditions can substantially alter particle transport and settling behavior [71,72].

Table 1. Main types of plastics: classification, monomers, properties, and general applications.

Polymer	Abbreviation	Monomer (s)	Key Properties	Main Applications
Polyethylene terephthalate	PET	Terephthalic acid + Ethylene glycol	Transparent, heat-resistant, and good impact strength	Food & beverage containers, clothing fibers, electronics, and recycled PET clothing
Polyethylene	PE	Ethylene	Flexible (LDPE) or rigid (HDPE), good chemical resistance	Plastic bottles, containers, and packaging
Polyvinyl chloride	PVC	Vinyl chloride	Flame retardant, resistant to acids & inorganic chemicals, versatile	Pipes, bottles, construction materials
Polypropylene	PP	Propylene	Low density, rigid, resistant to acids, solvents, and heat	Bottle caps, packaging, automotive parts
Polystyrene	PS	Styrene	Transparent, brittle (rigid PS), impact-resistant when modified (HIPS), foamable	Food containers, disposable packaging, ion-exchange resins, insulation foams
Polycarbonate	PC	Bisphenol A	Hard, durable, heat-resistant	Construction materials, roofing, partitions, consumer products
Polymethyl methacrylate	PMMA	Methyl methacrylate	UV-resistant, durable, hard	Aviation & automotive parts, orthopedic prostheses, dental applications
Polytetrafluoroethylene	PTFE	Tetrafluoroethylene	High chemical resistance, thermal stability, and low flammability	Pipes, containers for corrosive media, electrical insulators, and food industry molds
Acrylonitrile-butadiene-styrene	ABS	Acrylonitrile + Butadiene + Styrene	Strong, rigid, impact-resistant	Electronic casings, automotive parts, protective gear
Polyamide	PA	Caprolactam or Hexamethylenediamine + Adipic acid	High strength, durable, semi-crystalline	Engine covers, airbags, sports equipment, submarine pipes
Polychloropren	CR	Chloroprene	Elastic, resistant to heat & water, durable	Wetsuits, footwear, weather balloons, and industrial seals

Beyond physical transport, polymer composition affects the environmental role of MPs as contaminant vectors. Hydrophobic polymers with high surface-area-to-volume ratios can sorb persistent organic pollutants (POPs), including polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), potentially altering contaminant mobility and organism exposure pathways [18,73–78]. Nevertheless, the extent to which MPs act as

dominant pollutant carriers compared with natural particulates remains debated and likely depends on local environmental conditions (Figure 1).

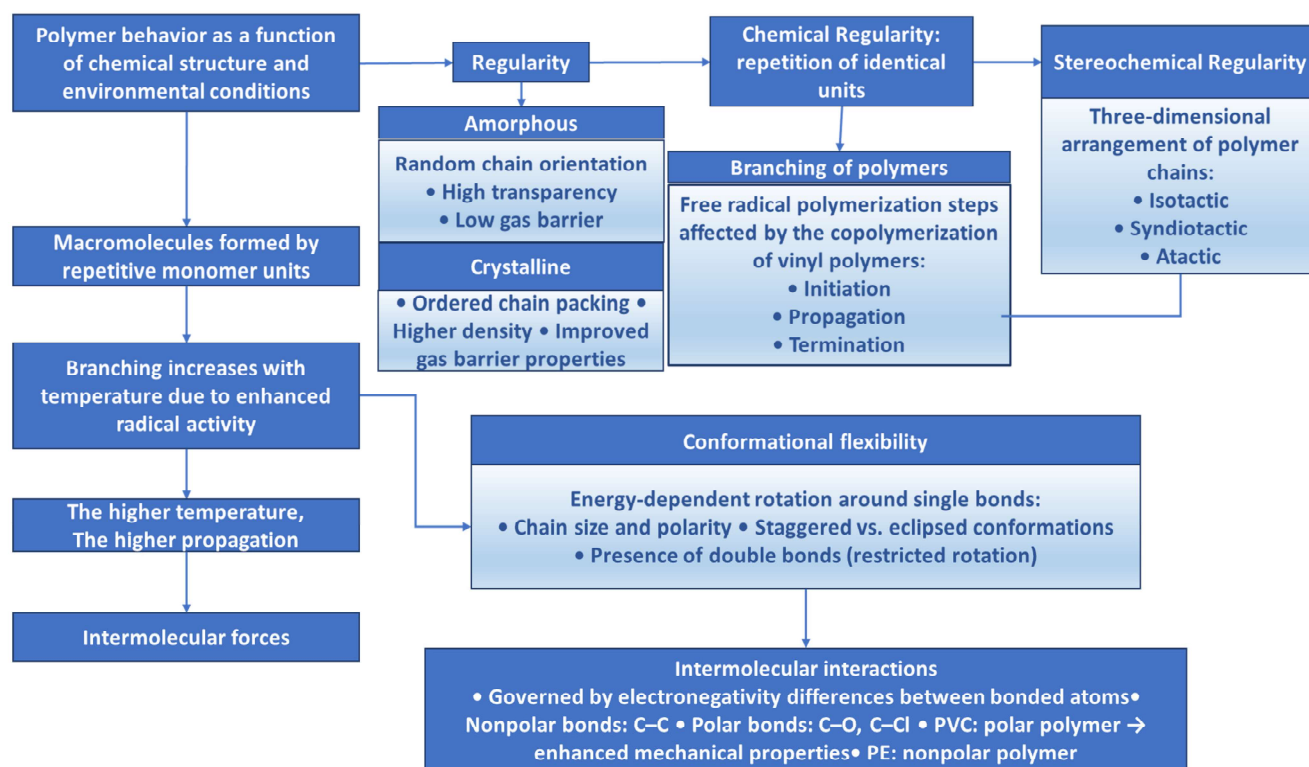


Figure 1. Relationship between the basic structure of a polymer and its properties [72].

3.3. Classification Challenges

Although the distinction between primary and secondary MPs remains widely accepted, environmental MPs rarely fit into simple categories. Particle size, morphology, polymer composition, additives, and weathering processes generate substantial heterogeneity that complicates classification and cross-study comparisons [22,79]. Morphological variability—including fragments, fibers, films, foams, and pellets—directly influences environmental transport and bioavailability. Fibers may remain suspended longer in the water column, whereas denser fragments preferentially accumulate in sediments [80–82]. In parallel, additives such as plasticizers, flame retardants, pigments, and stabilizers modify polymer behavior and toxicity, meaning that particles composed of the same base polymer may exhibit different environmental risks [83,84]. A major unresolved challenge concerns smaller particle fractions, particularly nano plastics, which remain difficult to detect despite potentially higher mobility and biological reactivity. Consequently, methodological heterogeneity in sampling, extraction, and analytical identification continues to hinder comparability among studies and may contribute to underestimation of environmental burdens [85,86].

These limitations emphasize the need for harmonized classification frameworks and standardized analytical protocols. Ongoing efforts by organizations such as ASTM and ISO represent important progress; however, future standardization efforts should better account for variability in particle size, morphology, additives, and composite materials to improve environmental risk assessment and policy implementation [87–90].

4. Occurrence and Levels of Microplastic Contamination in Aquatic Systems

Microplastics (MPs) are widely detected in marine and freshwater environments, including surface waters, sediments, biota, and remote aquatic habitats [25]. However, reported concentrations vary substantially due to differences in environmental conditions, analytical sensitivity, and methodological choices, particularly mesh size, sampling depth, and polymer identification methods [21,91,92]. This variability complicates direct comparisons among studies and emphasizes the need for integrated assessments that account for transport among environmental compartments.

4.1. Microplastics in Surface Waters

Surface waters are among the most intensively investigated compartments for assessing microplastic contamination, largely because many low-density polymers such as polyethylene (PE) and polypropylene (PP) remain suspended or float after release [31,36,81]. Nevertheless, surface concentrations should not be interpreted as representative of total microplastic burdens. Vertical distribution is strongly influenced by hydrodynamics, turbulence, particle size, density, and biofouling processes, which may redistribute MPs throughout the water column or promote temporary sediment deposition [28,68,70]. Smaller particles may remain suspended for prolonged periods, whereas denser or biofouled particles sink more rapidly. Consequently, surface-only sampling may underestimate contamination levels, particularly for smaller and denser particles.

Sampling methodology remains one of the primary sources of uncertainty in MP monitoring. Nets and filtration systems with mesh sizes between 100 and 500 µm are widely used, yet methodological inconsistencies substantially affect reported concentrations [87,91,92]. Larger meshes may underestimate contamination by excluding smaller particles, whereas finer meshes improve recovery but increase clogging and reduce sampling efficiency. As a result, apparent regional differences may partly reflect methodological artifacts rather than true environmental contrasts. For example, rivers sampled with a 300 µm mesh may appear less contaminated than those sampled at 100 µm, despite comparable environmental burdens [37,80].

Microplastic transport in surface waters is additionally influenced by meteorological and hydrological forcing. Wind-driven transport, stormwater pulses, floods, and seasonal mixing may redistribute particles horizontally and vertically, while convergence zones can promote local accumulation [28,35,37]. Therefore, surface waters should be viewed as dynamic transport interfaces rather than static reservoirs of contamination. Reliable assessments require harmonized methodologies and integration with sediment, atmospheric, and wastewater pathways to better represent the broader microplastic cycle [33,81,93].

4.2. Global Evidence of Contamination

Table 2 provides a comparative overview of microplastic (MP) concentrations reported in surface waters across diverse geographical regions [94–109]. Reported concentrations range across several orders of magnitude, from <0.05 particles/L in some Southeast Asian rivers to >10,000 particles/L in heavily urbanized waterways such as the Los Angeles River [93–101]. Higher concentrations are frequently reported in densely populated and industrialized regions, where urban runoff, wastewater discharges, and insufficient waste management contribute to continuous inputs. For example, the Saigon River (Vietnam) exhibited concentrations exceeding 40 particles/L, while Indonesian rivers showed elevated abundances of fragments and films associated with urban and industrial activities [94,95]. In contrast, several rivers in Malaysia and Thailand reported lower average concentra-

tions (<0.3 particles/L), although methodological differences and hydrological dilution complicate direct comparison [96–98].

Table 2. Representative studies on microplastic occurrence in surface waters.

Location	Size (µm)	Methodological Context	Predominant MP Types	Maximum Reported Concentrations (MP/L)	Reference
Citarum River, Indonesia	125–5000	River system	Films, fragments	9×10^{-5}	[99]
Ciwalengke River, Indonesia	50–2000	Fine mesh	Films, fragments	9.13	[95]
Cherating River, Malaysia	100–5000	River system	Films, fragments	1×10^{-5}	[96]
Dungun River, Malaysia	60–5000	Fine mesh	Fibers, fragments, films, foams	0.30	[97]
Chao Phraya River, Thailand	50–5000	Fine mesh	Hard/soft plastics, foams	0.052	[98]
Saigon River, Vietnam	53–5000	Urban watershed	Fibers, fragments, films	41.8	[94]
Tollense River, Germany	50–300	High resolution detection	Fibers, fragments, films	1728	[80]
Lake Geneva, Switzerland	2000–5000	Lake systems	Hard/soft plastics, foams	2100	[99]
Lake Constance, Switzerland	2000–5000	Lake systems	Hard/soft plastics, foams	320	[99]
Lake Neuchâtel, Switzerland	2000–5000	Lake systems	Hard/soft plastics, foams	700	[99]
Lake Maggiore, Switzerland	2000–5000	Lake systems	Hard/soft plastics, foams	1100	[99]
Lake Zurich, Switzerland	2000–5000	Lake systems	Hard/soft plastics, foams	460	[99]
Lake Brienz, Switzerland	2000–5000	Lake systems	Hard/soft plastics, foams	2500	[99]
Seine River, France	2000–5000	Riverine transport focus	Plastic fragments, fibers	100	[109]
Los Angeles River, USA	1000–4750	Highly urbanized watershed	Plastic fragments	12,932	[101]
San Gabriel River, USA	1000–4750	Urban river	Foamed plastics	411	[101]

European studies reveal a more nuanced pattern. Although some freshwater systems reported relatively moderate particle abundances, lower concentrations do not necessarily indicate reduced environmental significance [99]. For example, the Seine River contributes an estimated 924–1675 tons of plastic debris annually to marine environments, highlighting the importance of considering mass fluxes alongside concentration-based metrics [100]. Similarly, Swiss lakes function as long-term sinks due to limited flushing, allowing MPs to accumulate over time despite comparatively moderate inputs [99].

North American rivers, particularly highly urbanized systems, show some of the highest reported MP concentrations globally. The Los Angeles River exhibited values reaching nearly 13,000 particles/L, likely reflecting the combined effects of urban runoff, stormwater discharges, and the use of finer analytical methodologies [101]. These findings illustrate that extreme values may result from both environmental pressures and methodological sensitivity, reinforcing the need for caution when comparing datasets across studies.

Methodological differences continue to limit direct comparison among regions and may contribute to the underestimation of the true scale of microplastic pollution in surface waters.

4.3. Spatial Variability

Spatial variability in MP contamination reflects the interaction among urbanization, hydrology, land use, wastewater treatment efficiency, and monitoring methodology [102–104]. Highly urbanized catchments generally exhibit elevated MP abundances, particularly where industrial discharges, stormwater runoff, and inadequate waste management generate continuous inputs. However, concentration differences among regions should be

interpreted cautiously, as methodological sensitivity strongly influences reported values. Regional contrasts further emphasize the importance of integrating concentration-based metrics with transport dynamics. For example, some European rivers may exhibit moderate particle concentrations but still contribute substantial annual plastic fluxes to marine systems, as reported for the Seine River [105,106,109]. Consequently, river systems should be viewed not only as contamination hotspots but also as transport corridors linking terrestrial, urban, and marine environments.

Evidence from North American rivers similarly highlights the combined influence of anthropogenic pressure and methodological choices. Urbanized systems, such as the Los Angeles River, reported among the highest MP abundances globally, although the use of finer analytical approaches may partly explain extreme concentrations [101]. Seasonal hydrology and storm-driven transport further contribute to spatial variability, reinforcing that MP contamination is not a steady-state process but one influenced by episodic mobilization events [106]. Importantly, rivers interact continuously with adjacent compartments. Atmospheric deposition, soil runoff, wastewater discharges, and sediment remobilization may all contribute to riverine MP burdens, while flood events can redistribute stored particles across terrestrial and aquatic systems [107]. This interconnected behavior supports the conceptual model proposed in Figure 2, where MPs circulate dynamically among atmosphere, soils, wastewater treatment plants, rivers, sediments, and marine environments.

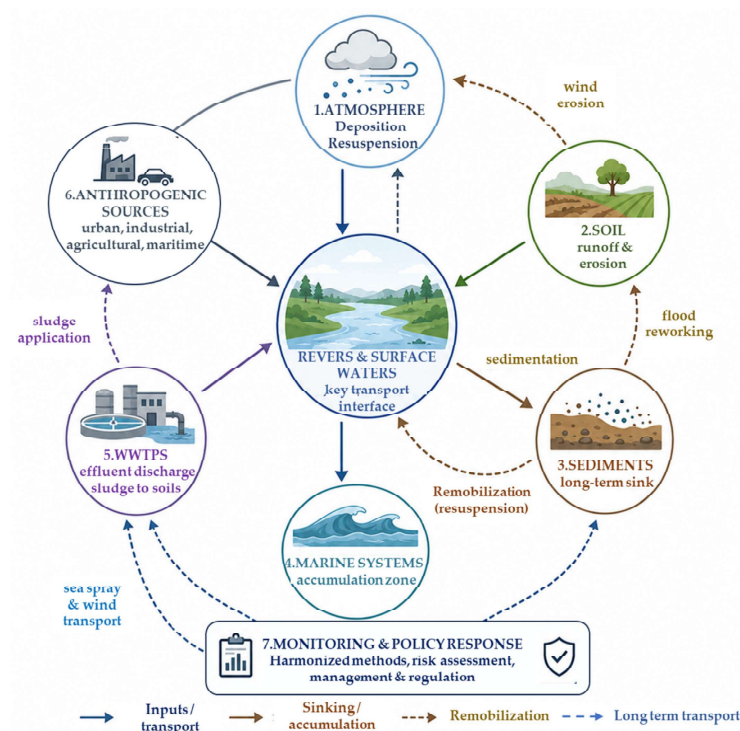


Figure 2. Microplastic cycle across interconnected compartments. Solid and dashed arrows indicate transport pathways, accumulation, remobilization, long-range transport, atmospheric exchange, and anthropogenic inputs connecting the atmosphere, soils, surface waters, sediments, wastewater treatment plants, and marine systems.

Lakes and sediments often function as long-term accumulation zones, whereas rivers act primarily as transport pathways. Biotic studies further demonstrate that exposure patterns vary considerably among species and habitats, indicating that ecological traits, particle size, and local hydrodynamics influence MP uptake [107]. Regional patterns indicate that urbanization, wastewater treatment, hydrology, and land use shape MP

occurrence, although methodological uncertainty continues to limit confidence in cross-regional comparisons [107].

4.4. Environmental Significance and Methodological Uncertainty

The environmental significance of MPs extends beyond occurrence data, as contamination patterns are closely linked to human activities, hydrological conditions, and polymer-specific behavior [108,110]. Urbanization, industrial activities, and ineffective waste management consistently emerge as key drivers of elevated MP burdens, while polymer composition may provide useful information regarding likely emission sources.

Hydrological forcing strongly modulates MP fate. Flow velocity, turbulence, floods, and seasonal discharge determine whether particles remain suspended, accumulate in sediments, or are remobilized downstream [111–113]. Consequently, environmental monitoring should consider both short-term hydrological variability and long-term storage processes. At the same time, methodological heterogeneity remains a major source of uncertainty. Sampling depth, mesh size, extraction efficiency, and polymer identification methods substantially influence reported concentrations and may limit comparability among studies [100,114,115]. In particular, smaller and potentially more bioavailable particles are frequently underestimated due to analytical constraints. Part of the reported spatial variability may therefore reflect methodological artifacts rather than genuine environmental differences [115–117]. Consequently, evidence confidence varies across compartments and monitoring approaches, underscoring the need for harmonized protocols and integrated assessment frameworks (Table 3).

Table 3. Critical synthesis of evidence, methodological limitations, confidence level, and policy relevance across major environmental compartments involved in the microplastic cycle.

Environmental Compartment	Main Evidence of MP Occurrence and Transport	Major Methodological Limitations	Confidence Level	Policy Relevance
Atmosphere	MPs detected in urban, rural, and remote areas; atmospheric deposition contributes to redistribution between terrestrial and aquatic systems. Fibers dominate airborne MPs, suggesting textile and urban sources.	Lack of harmonized sampling devices, inconsistent deposition metrics, contamination risks, and limited nano plastic detection.	Moderate	Supports policies targeting textile emissions, urban dust, air filtration, and source reduction strategies.
Surface waters (rivers, lakes)	Rivers act as major transport pathways linking terrestrial sources to marine systems; concentrations increase in urbanized catchments and after storm events. Lakes function as accumulation zones.	High variability in mesh size, sampling depth, flow conditions, and polymer identification methods. Surface sampling may underestimate total burdens.	High	Supports river basin management, wastewater control, stormwater mitigation, and harmonized monitoring frameworks.
Wastewater treatment plants (WWTPs)	WWTPs remove substantial fractions of MPs but remain important pathways for smaller particles and fibers into receiving waters; sludge represents an important sink.	Differences in treatment technologies, inconsistent reporting units, and limited assessment of smaller MPs and nano plastics.	High	Relevant for tertiary/quaternary treatment upgrades, sludge management, and effluent regulations.
Sediments	Sediments function as long-term sinks for denser and biofueled MPs; resuspension during floods or turbulence may remobilize particles.	Difficult standardization of sediment sampling and extraction; variability in density separation methods.	Moderate–High	Supports sediment quality monitoring and risk assessment in depositional zones.
Soils and terrestrial systems	Agricultural plastics, sludge application, atmospheric deposition, and runoff contribute to soil contamination; soils may act as temporary reservoirs before river transfer.	Limited long-term datasets; strong spatial heterogeneity; poor harmonization of extraction methods.	Moderate	Relevant for agricultural plastic management, biosolid regulation, and soil protection strategies.

Table 3. Cont.

Environmental Compartment	Main Evidence of MP Occurrence and Transport	Major Methodological Limitations	Confidence Level	Policy Relevance
Biota and food webs	MPs detected in fish, invertebrates, and plankton, with uptake influenced by particle size and morphology; trophic transfer remains uncertain.	Lack of standardized digestion protocols and uncertainty regarding ecological thresholds.	Moderate	Supports ecological risk assessment and food safety monitoring.
Marine systems	Oceans act as long-term accumulation zones receiving MPs from rivers, atmospheric deposition, and maritime activities; coastal hotspots linked to urbanization and shipping.	Strong spatial variability; inconsistent methodologies across marine studies; underestimation of smaller particles.	High	Supports marine litter legislation, regional monitoring programs, and transboundary pollution management.

The critical synthesis provided in Table 3 and the integrated conceptual framework (Figure 2) highlight that effective management of MP pollution requires cross-compartment monitoring strategies linking atmospheric deposition, terrestrial transport, wastewater pathways, rivers, sediments, and marine systems [25,56,115–118].

5. Sources, Transport, and Distribution of Microplastics in the Environment

The dispersal of microplastics (MPs) across aquatic ecosystems results from a complex interplay of emission sources, transport pathways, and environmental redistribution processes [25,119]. MPs are not only released directly into rivers, lakes, and coastal waters but also enter aquatic systems through atmospheric deposition, agricultural runoff, and urban wastewater effluents [120–122]. Once introduced, their transport and retention are controlled by hydrodynamics, geomorphology, and particle properties (Figure 3).

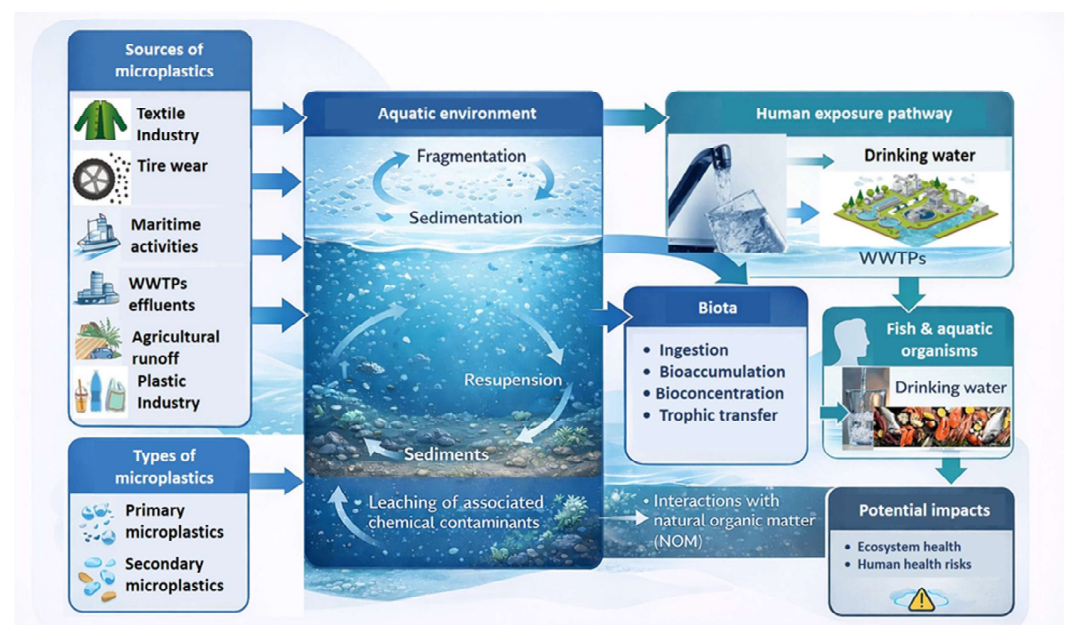


Figure 3. Conceptual overview of microplastic sources, transport, exposure, and impacts in aquatic systems.

5.1. Major Emission Sources

Microplastics originate from a wide variety of human activities, and their pathways into aquatic systems are shaped by both point and diffuse sources (Figure 4). Wastewater treatment plants (WWTPs) are widely recognized as major point sources of MPs, receiving

particles from domestic and industrial activities, particularly textile fibers and personal care products (Table 4) [123–126]. Although treatment processes such as sedimentation, filtration, and activated sludge can remove a substantial portion of these particles, the sheer volume of wastewater processed daily means that effluents still discharge significant loads of MPs into receiving rivers and lakes [127–129]. Despite technological improvements, complete MP removal remains difficult, and WWTPs continue to represent important point sources of contamination [126,129].



Figure 4. Major point and diffuse sources of microplastics entering aquatic systems.

Industrial processes add another critical dimension. Plastic production, pellet handling, and textile manufacturing release MPs directly into wastewater streams [125,130]. In contrast, incomplete incineration of plastic waste can generate airborne particles that later deposit into soils and surface waters [131]. Textile-derived microfibers represent one of the most persistent and poorly controlled sources of MPs. Household laundering continuously releases synthetic fibers from polyester, nylon, and acrylic fabrics, many of which bypass conventional treatment barriers due to their small size [57,58,132–134]. This recurring source explains the dominance of fibers observed in many wastewater and atmospheric studies. Agricultural practices also play a key role in the dissemination of MPs [135]. Sewage sludge application and the degradation of agricultural plastics—including mulch films, greenhouse materials, and silage covers—introduce diffuse but continuous MP inputs into soils [136,137]. As these materials degrade under solar radiation, mechanical stress, and tillage, they fragment into microplastics that persist in soils for prolonged periods [26].

The synthesis presented in Table 4 highlights pronounced methodological heterogeneity in WWTP studies, including variability in particle-size detection, analytical sensitivity, and polymer identification [124,138–142]. Studies using finer mesh sizes and advanced spectroscopic techniques, such as micro-Fourier Transform Infrared (micro-FTIR) imaging or Raman spectroscopy, consistently report smaller and more diverse MP fractions, suggesting that conventional monitoring likely underestimates total burdens [141,142]. Moreover, the recurrent dominance of fibers across treatment stages reinforces the conclusion that textile-related emissions remain insufficiently controlled [57,58,126]. Solid waste mismanagement remains another important diffuse source [143–153]. Landfills and open dumps may gradually release MPs through fragmentation, leachate generation, and wind dispersal, particularly where containment and recycling systems are inadequate [38,154–156]. MP emissions arise from interconnected urban, industrial, agricultural, and domestic activities, highlighting the need for integrated source-control approaches across environmental compartments [33,157,158].

Table 4. Sampling, detection, and characterization of microplastics in wastewater treatment plants (WWTPs).

Country/Region	Treatment Stage	MP Size Range	Dominant Shapes	Sampling Approach	Analytical Techniques	Reference
India	Tertiary	~1.25 mm	Foams, fragments, fibers	Grab sampling (glass containers)	FTIR spectroscopy	[143]
Iran	Tertiary	37 µm–5 mm	Particles, fibers	Grab sampling (1–20 L), sieving	Transmittance FTIR	[144]
USA	Secondary & tertiary	20–400 µm	Fibers, fragments, spheres	Continuous flow, stacked sieves	Microscopy, ATR-FTIR	[140]
France (Paris)	Secondary	100–5000 µm	Fibers	24 h composite sampling	Stereomicroscopy	[145]
Australia (NSW)	Tertiary	N.I.	N.I.	Grab sampling (glass bottles)	Transmittance FTIR	[146]
Finland (Lake Saimaa)	Tertiary	<0.25–>5 mm	Fibers, particles	Grab sampling, sieving	Optical microscopy, µ-FTIR, Raman	[147]
Netherlands	N.I.	<300–5000 µm	Fibers, foils, spheres	Grab sampling (2 L)	Density separation, microscopy	[148]
USA (California)	Secondary	0.125–5 mm	Fibers, pellets, fragments	Continuous filtration	Microscopy, µ-FTIR	[147]
USA	Secondary & tertiary	125–355 µm	Fibers, films, fragments	Pumped effluent, sieving	Microscopy	[139]
UK (Scotland)	Tertiary	~600 µm	Films, fibers, beads	Grab sampling, sieving	µ-FTIR	[149]
Czech Republic	DWTP	1–100 µm	Fragments, fibers	Grab sampling (1 L)	SEM, µ-FTIR, Raman	[141]
Denmark	Secondary	≤600 µm	N.I.	Automatic samplers	FTIR imaging	[150]
Japan & USA	Advanced filtration	>20 µm	Fragments, films	Pumped sampling, composites	FTIR imaging	[142]
Australia	Primary–tertiary	25–500 µm	Granular, fibers	Pumped filtration	ATR-FTIR	[151]
Australia	Secondary	>250 µm	Fibers, films	Grab sampling	Density separation, FTIR	[152]
India (Tamil Nadu)	Secondary	25–104 µm	Fragments	Manual grab sampling	FTIR	[153]

5.2. Atmospheric Pathways

The atmosphere is increasingly recognized as an important pathway for the transport and redistribution of microplastics (MPs), linking terrestrial and aquatic systems through deposition and resuspension processes (Figure 5) [159–161]. MPs are emitted into the air from multiple sources, including textile fibers released during wear and laundering, tire abrasion, road dust, and incomplete combustion of plastics [108]. Available evidence suggests that airborne MPs may be transported across urban, rural, and remote regions, although transport distances vary according to particle size, meteorological conditions, and atmospheric dynamics [161,162]. Atmospheric fallout generally correlates with population density, with urban areas showing substantially higher concentrations than less populated regions due to traffic, textile emissions, and waste-management activities [108]. Deposition studies in metropolitan regions report atmospheric fallout rates reaching thousands of particles $\text{m}^{-2} \text{day}^{-1}$, supporting the role of air as both a transport pathway and a temporary sink for MPs [163,164]. Atmospheric MPs are redistributed through both wet and dry deposition. Rain and snow may transfer particles into rivers, lakes, soils, and marine environments, whereas dry deposition and wind-driven resuspension promote repeated cycles of redistribution across environmental compartments [165,166]. These processes highlight the dynamic nature of MP cycling and support the interconnected environmental compartments (Figure 5).

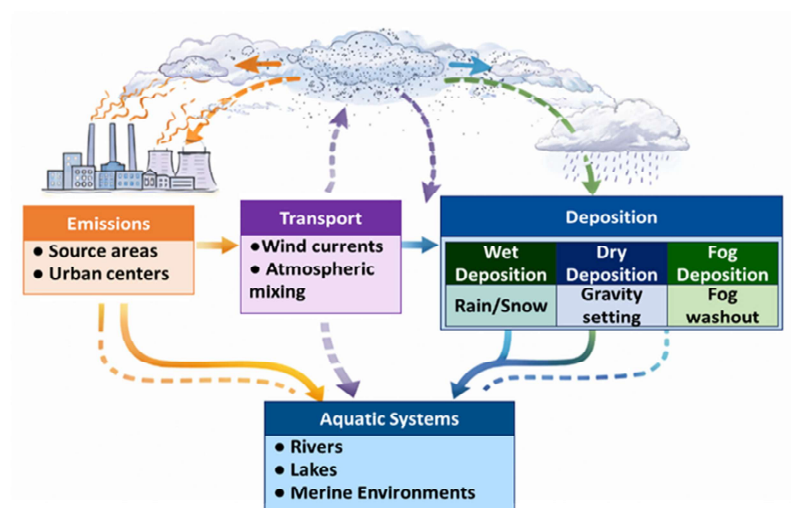


Figure 5. Schematic overview of major points and diffuse sources of microplastics entering aquatic systems. Solid and dashed arrows indicate different atmospheric transport, deposition, and transfer pathways between emission sources, the atmosphere, and aquatic systems.

The detection of MPs in remote and high-altitude regions, including mountain systems, protected areas, and marine atmospheres, suggests that atmospheric transport may contribute to long-range dispersal beyond local emission sources [167–169]. However, the relative importance of atmospheric transport compared with local inputs remains insufficiently quantified and likely varies across environments. The synthesis presented in Table 5 reveals pronounced contrasts in atmospheric deposition among environmental settings, ranging from $<10 \text{ items m}^{-2} \text{ day}^{-1}$ in remote regions to $>10^3\text{--}10^4 \text{ items m}^{-2} \text{ day}^{-1}$ in densely populated urban centers [163–178]. Across most studies, fibers dominate atmospheric fallout, frequently accounting for $>80\%$ of detected particles, supporting textile-related emissions as a major contributor [170,176]. Fragments and films become relatively more abundant in industrialized or traffic-influenced settings, indicating additional inputs from abrasion and plastic degradation [166,175].

Table 5. Atmospheric microplastics: environmental compartment, abundance range, and dominant characteristics.

Environmental Compartment	Geographic Setting	Abundance Range	Dominant MP Features	Main Polymer Groups	References
Urban atmospheric fallout	Major cities (Europe, Asia, Americas)	$2\text{--}11,000 \text{ items m}^{-2} \text{ day}^{-1}$	Fibres dominant ($>80\%$), fragments secondary; wide size spectrum ($50\text{--}5000 \mu\text{m}$)	PET, PE, PP, PS, PVC, PES	[163,164,170,171]
Sub-urban/peri-urban fallout	Residential outskirts	$9\text{--}394 \text{ items m}^{-2} \text{ day}^{-1}$	Predominantly fibres; limited polymer identification	PET, PAN, PE, PP	[172–174]
Remote & high-altitude deposition	Mountains, protected areas	$132\text{--}455 \text{ items m}^{-2} \text{ day}^{-1}$	Fragments and fibres; smaller size fractions ($<25 \mu\text{m}$ detected)	PE, PP, PET, PS, PVC	[165,168]
Suspended atmospheric MPs (air column)	Urban & regional air masses	$0.09\text{--}13.9 \text{ items m}^{-3}$	Fibres and fragments; sub- $100 \mu\text{m}$ fraction common	PET, PA, PP, PE, PS, PES	[18,167]
Dustfall & particulate deposition	Megacities	$24\text{--}225 \text{ MP g}^{-1}$	Fragments dominant ($>70\%$); limited size range	PA, PC, PET, PP, PS, PVC	[176]
Marine atmospheric interface	Coastal & oceanic air	$0.05\text{--}0.84 \text{ items m}^{-3}$	Fibres and films; marine-influenced polymers	PET, PA, PP, PS	[169,178]

Indoor environments (Table 6) frequently exhibit MP concentrations comparable to or exceeding outdoor levels, largely due to textile shedding, furnishings, household activities, and ventilation systems [179–183]. Fibres overwhelmingly dominate indoor assemblages, while polymer profiles rich in PET, polyester (PES), polyamide (PA), and polypropylene (PP) indicate strong contributions from consumer materials [184–189]. Importantly, indoor and outdoor atmospheric compartments are closely connected through ventilation, deposition, and resuspension processes, suggesting bidirectional exchange between built and natural environments [181].

Table 6. Indoor microplastics: exposure-relevant compartments and contamination profiles.

Indoor Microenvironment	Abundance Range	Dominant Morphologies	Size Domain	Polymer Fingerprints	Representative Studies
Indoor air (residential & occupational)	0.4–1583 items m ⁻³	Fibres (>85%), fragments	4–>5000 µm	PET, PES, PA, PP, PE	[181,183–185]
Indoor deposition (settled dust/fallout)	1600–9.6 × 10 ⁴ items m ⁻² day ⁻¹	Fibres and fragments; films locally relevant	20–10,000 µm	PET, PE, PS, PVC, PA, PAN	[179,180,186,187]
Mechanically influenced indoor air	1.6–1.8 fibres m ⁻³	Fibres	19–3948 µm	PET	[182]
High-density indoor environments	>10 ³ items m ⁻³	Fragments dominant (>85%)	5–1000 µm	PES, PA, PP, PET	[188,189]

Atmospheric pathways indicate that MP contamination extends beyond aquatic systems and involves continuous exchange among atmospheric, terrestrial, and aquatic compartments [190,191]. Nevertheless, substantial uncertainties remain regarding long-range transport, deposition rates, and the contribution of atmospheric inputs to aquatic MP burdens, reinforcing the need for harmonized monitoring approaches and integrated mass-balance assessments.

5.3. Terrestrial Runoff and Soil–Water Transfer

Soils are increasingly recognized as both long-term sinks and potential secondary sources of microplastics (MPs) in terrestrial–aquatic systems [135,192], particularly sewage sludge application and the degradation of agricultural plastics, including mulch films, silage covers, and greenhouse materials (Figure 6) [41,42]. Repeated inputs may progressively enrich soils with MPs, promoting long-term retention within the soil matrix. Accumulated MPs may alter soil structure, microbial communities, and biogeochemical functioning, although the magnitude and persistence of these effects remain incompletely understood [193–195].

The synthesis provided in Table 7 demonstrates widespread MP occurrence across agricultural, urban-adjacent, and remote soils, with most studies focusing on surface layers (0–30 cm), where anthropogenic inputs and biological activity are greatest [164,169,195]. Across continents, density separation combined with spectroscopic identification techniques—most commonly µ-FTIR, Raman spectroscopy, or Py-GC-MS—dominates analytical workflows, reflecting the need for robust polymer confirmation in complex soil matrices [196,197]. Polymer profiles consistently show the predominance of polyethylene (PE) and polypropylene (PP), followed by polyethylene terephthalate (PET) and polystyrene (PS), reflecting the widespread use of agricultural plastics, packaging materials, and synthetic textiles [198,199].

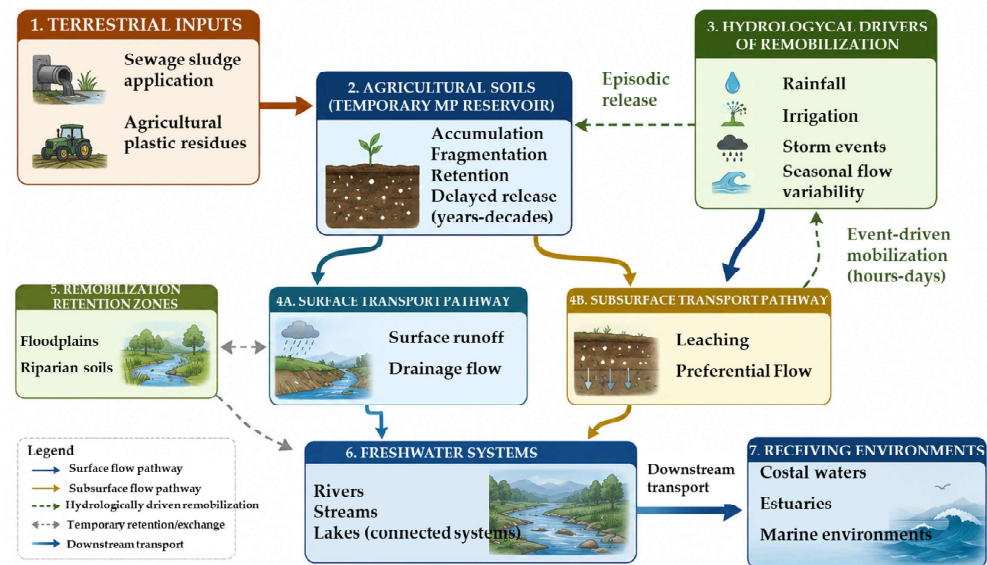


Figure 6. Conceptual framework of soil-mediated microplastic retention and hydrologically driven transfer to aquatic systems.

Table 7. Overview of soil microplastics studies: depth ranges, analytical approaches, and dominant polymer types.

Geographic Region	Typical Soil Depth Investigated (cm)	Predominant Analytical Approaches	Dominant Microplastic Polymer Groups	References
Northeast China (Heilongjiang, Jilin, Liaoning)	0–30	Density separation coupled with μ -FTIR, FTIR, Py-GC-MS, and microscopy	PE, PP, PS, PET, PVC, PA, polyester	[119,165,200,201]
North China Plain (Beijing, Hebei, Tianjin, Shandong)	0–30 (occasionally up to 50)	Density separation with μ -FTIR/Raman/ATR-FTIR and microscopy	PE, PP, PET, PS, PVC, PAN, rayon	[195,198,202,203]
Yangtze River Basin (Jiangsu, Zhejiang, Shanghai)	0–30 (up to 150 in deep cores)	Density separation + μ -FTIR, LDIR, Py-GC-MS	PE, PP, PET, PA, PS, EVA, PTFE	[196,204–206]
South & Central China (Hubei, Sichuan, Chongqing, Yunnan, Guangxi)	0–25	Density separation with FTIR/Raman/microscopy	PE, PP, PS, PET, rayon, PMMA, PU	[84,131,164,207]
Northwest & Plateau regions (Xinjiang, Qinghai–Tibet Plateau)	0–30 (locally > 50)	Density separation combined with μ -FTIR, Raman, and LDIR	PE, PP, PS, PU, silicone, PLA, PTFE	[176,208,209]
East & Southeast Asia (Korea, Japan)	0–20	Density separation with μ -FTIR, FTIR, Raman	PE, PP, PET, PS, nylon, PMMA	[210–213]
South Asia (India, Pakistan, Bangladesh)	0–30 (locally deeper layers)	Density separation with ATR-FTIR, FTIR, Raman	PE, PP, PET, PVC, PS, PA	[50,214–216]
Middle East (Iran, Turkey)	0–30	Density separation + Raman/FTIR/microscopy	PE, PP, PET, PS, PA, PVC	[197,217]
Europe (Germany, France, Spain, the Netherlands, Greece)	0–35	Density separation with μ -FTIR, ATR-FTIR, Py-GC-MS	PE, PP, PS, PET, rubber, PVC	[215]
Americas (USA, Canada, Mexico, Brazil)	0–20	Density separation with FTIR/ATR-FTIR/Py-GC-MS	PE, PP, PET, PS, synthetic rubber	[218–220]
Remote & polar environments	0–1 to 0–20	Density separation with μ -FTIR, ATR-FTIR	PET, phenoxy resin, PE	[221]

Several studies additionally report MPs at depths > 50 cm, indicating vertical redistribution through tillage, soil cracking, percolation, and bioturbation [196,215]. These findings

suggest that soils function not only as surface repositories but also as delayed-release reservoirs with long-term storage potential.

However, soils should not be considered static compartments. Under specific hydrological conditions, rainfall, irrigation, and stormwater runoff may remobilize stored MPs through surface and subsurface transport pathways, transferring particles into rivers and drainage systems [199,222,223]. In intensively cultivated regions, such mobilization events may generate episodic pulses of contamination linked to seasonal precipitation and land-management practices [224,225]. The degradation of crop-protection films and silage covers under ultraviolet radiation, mechanical stress, and tillage further contributes to soil MP accumulation and delayed remobilization [62,135,137,145,226].

This dual role complicates catchment-scale MP budgets and highlights the importance of explicitly considering terrestrial–aquatic linkages when evaluating environmental transport, as neglecting soil-mediated pathways may underestimate delayed MP inputs into freshwater systems and overlook long-term legacy effects associated with sludge application and agricultural plastic use [227–230]. Figure 6 emphasizes that soils act as intermediate reservoirs within the broader MP cycle, linking agricultural, atmospheric, and hydrological pathways. Consequently, targeted interventions—including improved sludge management, reduced agricultural plastic use, and erosion-control measures—may substantially reduce downstream contamination before particles enter aquatic systems.

5.4. Riverine Transport

Rivers are key transport pathways in the global microplastic (MP) cycle, connecting terrestrial environments with marine systems through continuous downstream transfer (Figure 7) [33,34,51]. Rivers receive MPs from multiple interacting sources, including wastewater effluents, stormwater runoff, atmospheric deposition, and agricultural drainage [33,34,51]. Modeling studies suggest that riverine pathways contribute substantially to marine plastic pollution, although reported estimates vary depending on watershed characteristics and model assumptions [8,231]. This variability indicates that rivers should be considered not only as transport routes but also as regulators of MP retention and release.

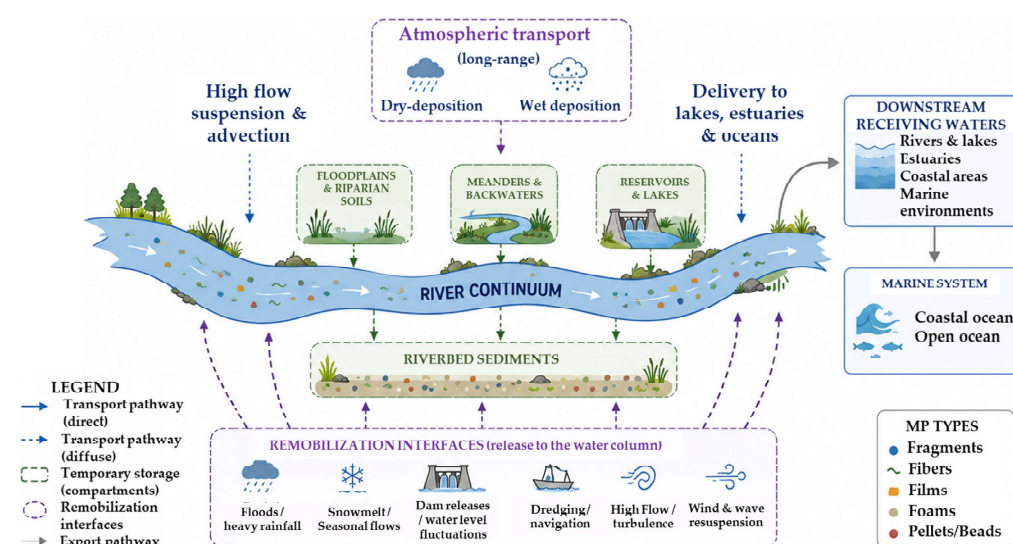


Figure 7. Rivers as dynamic interfaces in the MP cycle: transport pathway, temporary storage compartments, and remobilization interfaces. The white arrows within the river channel represent the main downstream transport direction along the river continuum, while the purple dashed arrows indicate remobilization pathways from sediments and storage compartments back into the water column. Both arrow types are already defined in the figure legend as “Transport pathway (direct)” and “Remobilization interfaces”, respectively.

Riverine transport is governed by the interaction among hydrodynamics, particle characteristics, and geomorphology [232,233]. Flow velocity and turbulence strongly influence whether MPs remain suspended in the water column or are deposited in sediments and riverbanks. In high-energy systems with strong currents, MPs are more likely to remain suspended, facilitating rapid downstream transport, whereas depositional environments favor localized accumulation [112,234]. Particle characteristics further modulate riverine fate. Size, density, and morphology influence settling behavior and resuspension potential [112]. Fibers generally remain suspended longer due to lower settling rates, whereas irregular fragments and denser particles accumulate more readily in sediments [235]. Similarly, denser polymers such as polyethylene terephthalate (PET) and polystyrene (PS) are frequently associated with sediment accumulation, whereas polyethylene (PE) and polypropylene (PP) are more likely to remain near the surface [233–236]. This selective transport influences both spatial contamination patterns and exposure pathways for aquatic organisms.

Geomorphological features—including reservoirs, floodplains, and meanders—act as temporary retention zones where MPs may accumulate before subsequent remobilization [232,236–238]. Floods, snowmelt, and dam releases can reactivate stored particles, generating episodic contamination pulses [224,227,236]. Empirical studies frequently report higher MP abundances in sediments than in overlying waters, indicating that riverbeds function as important temporary reservoirs [234,235,237]. However, hydrological disturbances and anthropogenic activities, including dredging and navigation, may remobilize deposited particles, highlighting sediments as both sinks and secondary sources [232,233,238]. Accounting for these interconnected retention and release mechanisms is essential for improving mass-balance estimates and predicting long-term transport across terrestrial–aquatic–marine systems [231,232,237].

5.5. Retention and Redistribution

The movement of microplastics (MPs) within river systems is governed by a dynamic balance between retention and remobilization processes rather than simple downstream transport [25,28]. Microplastics may remain temporarily stored in river sediments, floodplains, riparian soils, and reservoirs, which function as intermediate sinks within the broader MP cycle [65,233]. Deposition is influenced by particle density, morphology, and hydrodynamic conditions, with fine sediments and low-flow environments favoring retention [109].

However, retention is rarely permanent. Hydrological disturbances—including floods, snowmelt, stormwater pulses, and dam releases—may increase turbulence and flow velocity, remobilizing previously stored particles [224,227]. Such events can generate episodic contamination pulses, increase downstream transport, and redistribute MPs across aquatic compartments. This episodic behavior suggests that single-time-point monitoring may underestimate temporal variability and fail to capture remobilization events.

Retention–remobilization cycles have important ecological implications [13,108]. Sediments may function as temporary reservoirs that become secondary exposure sources during disturbance events, particularly for benthic organisms. From a monitoring perspective, this variability complicates the interpretation of concentration data, as sampling may reflect either baseline conditions or short-term contamination peaks depending on hydrological timing [16,18]. At the catchment scale, rivers should therefore be considered regulators of MP fluxes rather than passive conduits, temporarily storing particles and releasing them intermittently under changing environmental conditions [37]. This buffering capacity may delay downstream contamination signals and complicate mass-balance assessments, particularly when retention phases alternate with episodic release [118]. As illustrated in Figure 6, retention and remobilization processes shape the temporal variability and

environmental fate of MPs across interconnected systems. Accounting for these dynamics is essential to improve long-term flux estimates and exposure assessments.

6. Legislation and Policy Frameworks

The recognition of microplastic (MP) pollution as a pervasive and transboundary problem has prompted policymakers, particularly within the European Union (EU), to strengthen regulatory frameworks. These initiatives focus on both reducing intentional uses of MPs and preventing the release of secondary MPs from consumer and industrial products. As summarized in Table 8, current regulatory frameworks increasingly recognize the relevance of microplastics to aquatic systems, shifting from narrow, product-specific bans toward broader, lifecycle-based approaches that directly or indirectly limit MP inputs to rivers, lakes, and marine environments.

The environmental evidence summarized in the previous sections highlights several regulatory challenges. High variability in reported MP concentrations, inconsistent size thresholds, and strong methodological heterogeneity complicate cross-regional comparisons and limit the translation of scientific evidence into harmonized policy measures. In particular, evidence from wastewater effluents, atmospheric deposition, and riverine transport indicates that diffuse emission pathways remain insufficiently addressed by existing regulatory frameworks. These findings support the need for source-specific prevention strategies and more harmonized monitoring approaches.

A milestone in this process was the 2020 opinion of the European Chemicals Agency (ECHA) Committee for Risk Assessment (RAC), which supported restrictions on intentionally added microplastics in products at concentrations above 0.01% by weight. The RAC further recommended stricter criteria for biodegradable polymers, highlighting the need for scientific evidence that these materials degrade effectively in natural environments such as soil, freshwater, or marine systems. The proposed restriction aims to prevent long-term accumulation of MPs by targeting avoidable uses in cosmetics, detergents, fertilizers, and industrial applications [239]. Building on this, the EU adopted Commission Regulation (EU) 2023/2055 in October 2023, which amends Annex XVII of the REACH Regulation to restrict the placing on the market and use of intentionally added microplastic particles (synthetic polymer microparticles) in products and mixtures (effective with phased deadlines through 2025–2035) (European Commission, REACH 2023) [240]. This regulation imposes detailed labelling, reporting, and information obligations on manufacturers, importers, and downstream users of products containing microplastics, representing the first EU-level binding instrument explicitly targeting microplastic sources beyond cosmetics and personal care products (European Commission, REACH 2023). Complementing the REACH restriction, the EU has introduced specific measures to reduce unintended microplastic releases from industrial handling. Recent EU initiatives have introduced measures targeting pellet loss prevention, requiring operators handling ≥ 5 tons/year of pellets to implement best-practice procedures to minimize spillage during production, transport, and storage, representing an important preventive action targeting one relevant pathway of unintentional microplastic release (European Commission, REACH 2023). The EU has also advanced broader strategies to reduce plastic pollution. Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment addresses the proliferation of single-use plastics, particularly in the marine environment [241]. By targeting items such as cutlery, plates, straws, and expanded polystyrene containers, this directive aims to reduce plastic litter entering aquatic ecosystems. In addition, Directive 94/62/EC regulates packaging waste, emphasizing recycling and recovery obligations for plastic packaging materials [242]. Fishing gear is a significant source of marine litter, including MPs originating from lost or abandoned nets and ropes. The EU has acknowl-

edged this problem in the Waste Framework Directive (2008/98/EC), the Port Reception Facilities Directive (2000/59/EC), and the Control Regulation (1224/2009/EC), all of which encourage the collection and proper disposal of fishing gear to reduce inputs to the marine environment. Monitoring requirements under the Marine Strategy Framework Directive (2008/56/EC) require Member States to periodically assess and report on the abundance, composition, and properties of marine litter, including plastics. However, differences in sampling strategies, particle-size thresholds, and analytical protocols across Member States continue to limit data comparability, reinforcing the need for harmonized monitoring standards [243–246].

Table 8. Overview of key regulatory instruments addressing microplastic pollution and their relevance for aquatic systems.

Level	Regulatory Instrument	Year	Main Scope	Key Features
EU	ECHA RAC Opinion (REACH)	2020	Chemicals regulation	Basis for REACH restriction; threshold $\geq 0.01\%$ w/w; strict criteria for biodegradability
EU	Commission Regulation (EU) 2023/2055 (REACH Annex XVII)	2023	Chemicals, consumer & industrial products	Binding restriction; phased bans; labelling, reporting, and information obligations
EU	Plastic Pellet Loss Prevention Regulation	2025	Industrial handling & transport	Mandatory best practices for operators; targets unintentional releases at source
EU	Directive (EU) 2019/904 (Single-Use Plastics)	2019	Marine litter prevention	Reduces upstream plastic inputs through bans and consumption reduction
EU	Packaging and Packaging Waste Regulation (PPWR)	2025	Packaging waste	Mandatory recyclability and recycled content; indirect MP mitigation
EU	Marine Strategy Framework Directive (2008/56/EC)	2008	Marine environmental monitoring	Requires assessment of the abundance and composition of marine litter
EU	Environmental Quality Standards Directive (2008/105/EC)	2008	Chemical pollution in waters	Regulates POPs adsorbed onto MPs (PAHs, PCBs)
International	UNEA Resolution 5/14-Global Plastics Treaty (INC)	2022–ongoing	Global plastics life cycle	Legally binding treaty under negotiation; lifecycle approach
International	OECD Policy Guidance on Microplastics	2019–2023	Policy support	Best-practice mitigation strategies; non-binding
Canada	Microbeads Regulations (CEPA)	2018	Consumer products	Ban on the manufacture, import, and sale of microbeads
USA	Microbead-Free Waters Act	2015	Cosmetics	Federal ban on rinse-off cosmetics with microbeads
UK	Environment Act	2021	Environmental governance	Enables future targets, monitoring, and chemical controls
Other countries	National microbead bans (e.g., Australia, South Korea, Italy)	2016–2022	Consumer products	Sector-specific bans; heterogeneous implementation

Chemical pollution linked to MPs is also addressed under the Environmental Quality Standards Directive (2008/105/EC), which sets limits for priority hazardous substances in surface waters [247]. While the directive does not explicitly regulate MPs, it covers many persistent organic pollutants (POPs), such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), which adsorb onto plastic particles, thereby increasing ecological and health risks [248]. Collectively, these legislative efforts reflect a multi-layered policy approach aimed at restricting intentional MP uses, reducing plastic waste generation, improving waste management, and strengthening environmental monitoring. Nevertheless, challenges remain regarding enforcement, harmonization of monitoring methods, and integration of MPs into existing chemical and waste-management frameworks.

Beyond the EU, international and national initiatives further reinforce microplastic governance. At the international level, the United Nations Environment Assembly (UNEA) Resolution 5/14 established an intergovernmental negotiating committee (INC) to develop a legally binding global plastics treaty addressing plastic pollution, including microplastics, across the life cycle of plastics (UNEP, 2022) [249]. The Organisation for Economic Co-operation and Development (OECD) has published policy guidance on reducing microplastic emissions, providing member countries with strategies to mitigate both intentional and unintentional microplastic releases, including from textiles and tire wear (OECD 2019) [250]. At the national level, several countries have implemented microplastic-specific legislation. Canada's Microbeads Regulations prohibit the manufacture, import, and sale of toiletries containing plastic microbeads under the Canadian Environmental Protection Act (Microbeads Regulations (CEPA, 2018) [251]. In the United States, the Microbead-Free Waters Act bans rinse-off cosmetics containing plastic microbeads and has set a precedent for source-based microplastic restrictions (USA, Microbead-Free Waters Act 2015), [252]. Other countries, such as Australia, South Korea, Italy, New Zealand, and Sweden, have adopted or proposed similar bans on microbeads and intentional microplastics in consumer products. The United Kingdom's Environment Act 2021 establishes a framework for environmental targets and regulatory strategies applicable to microplastic monitoring and reduction initiatives (UK, Environment Act 2021) [253]. Additional subnational initiatives, including state-level risk assessments and strategies targeting tire-wear and textile-fiber emissions, further demonstrate increasing political commitment to microplastic mitigation.

Based on current environmental evidence, future regulatory priorities should include harmonized monitoring protocols, improved assessment of major emission pathways (particularly wastewater effluents, stormwater runoff, atmospheric deposition, textile fibers, tire wear, and plastic pellets), and stronger integration of MPs into environmental quality and chemical-risk frameworks through standardized reporting systems and catchment-scale assessments.

7. Research Gaps and Future Perspectives

Despite substantial advances in microplastic (MP) research, this review highlights several knowledge gaps that directly limit the effectiveness of environmental monitoring and regulatory action. The interpretation of existing evidence remains constrained by variability in study quality and methodological rigor. Many studies differ substantially in sampling design, particle-size thresholds, contamination control measures, polymer confirmation procedures, and reporting units, limiting cross-study comparability and increasing uncertainty in global assessments. In several cases, reliance on visual identification without spectroscopic confirmation, inconsistent use of field or procedural blanks, and limited reporting of methodological details reduce confidence in reported abundances and distribution patterns.

A major challenge remains the absence of standardized methodologies for MP sampling, separation, and identification across environmental compartments. Current inconsistencies in mesh sizes, analytical techniques, and reporting units hinder comparability between studies and prevent reliable large-scale assessments needed for policy implementation. A second critical gap concerns incomplete size coverage. Most monitoring efforts focus on particles larger than tens of micrometers, while smaller MPs and nano plastics remain largely excluded due to analytical limitations. This omission likely leads to systematic underestimation of environmental MP loads and compromises the development of robust emission inventories. MP transport is governed by interconnected pathways involving wastewater discharge, atmospheric deposition, terrestrial runoff, and riverine transfer; however, these pathways are frequently studied in isolation. The absence of integrated, multi-compartment monitoring frameworks restricts the ability to quantify relative source contributions and to evaluate the effectiveness of mitigation measures targeting specific emission pathways. River systems and soils emerge as priority compartments for policy-relevant research. Rivers function both as transport corridors and temporary sinks, while soils act as long-term reservoirs with episodic remobilization potential. Yet, long-term and catchment-scale datasets remain scarce, limiting predictive modeling and risk-based management. From a regulatory perspective, these gaps underscore the need for harmonized monitoring protocols, agreed size classifications, and coordinated reporting systems that can be incorporated into existing water and environmental quality directives.

Future studies would particularly benefit from greater methodological transparency, routine polymer confirmation, harmonized contamination-control procedures, and standardized reporting metrics to improve confidence in evidence synthesis and policy translation. Addressing these priorities will be essential to translating scientific evidence into effective policies that reduce microplastic emissions and mitigate their long-term environmental accumulation.

Although ecological and human-health implications of MPs remain highly relevant, a detailed evaluation of trophic transfer, bioaccumulation, and microplastic-contaminant interactions were beyond the primary scope of this review, which focused on sources, transport pathways, environmental distribution, and policy perspectives. These topics have been extensively discussed in recent dedicated reviews and remain a priority area for future interdisciplinary research integrating environmentally realistic exposure scenarios and long-term risk assessment [254].

8. Conclusions

Microplastics (MPs) are now recognized as pervasive and persistent contaminants across aquatic environments, with consistent evidence of their presence in rivers, lakes, estuaries, and marine systems worldwide. This review demonstrates that MP pollution is driven by a combination of point and diffuse sources, including wastewater effluents, atmospheric deposition, terrestrial runoff, and inadequate waste management. Rivers emerge as critical connectors between land and sea, functioning not only as transport pathways but also as dynamic systems where retention, sedimentation, and episodic remobilization strongly influence microplastic fluxes.

A central outcome of this synthesis is the recognition that MP distribution is controlled by tightly interconnected environmental compartments. Atmospheric transport enables long-range dispersal, soils act as long-term reservoirs with secondary release potential, and sediments represent temporary sinks within freshwater systems. These coupled processes challenge compartment-specific assessments and underscore the need for integrated, multi-pathway frameworks to accurately quantify sources, transport, and accumulation of MPs. Methodological heterogeneity—particularly in sampling strategies, size thresholds, and

analytical techniques—remains a major obstacle to robust comparisons and large-scale environmental assessments.

Unlike previous reviews that frequently address individual environmental compartments or specific aspects of MP pollution in isolation, this review provides an integrated perspective linking sources, transport pathways, environmental redistribution, and policy dimensions across interconnected aquatic systems. Particular emphasis was placed on the role of retention–remobilization processes, cross-compartment interactions, and methodological variability as key factors shaping environmental distribution and uncertainty in MP assessments. By explicitly connecting environmental evidence with regulatory and monitoring implications, this review further identifies practical priorities for harmonized monitoring, source-oriented mitigation, and evidence-based policymaking.

From a regulatory and management perspective, the findings of this review highlight the urgency of harmonizing monitoring protocols and incorporating microplastics into existing environmental quality frameworks. While recent policy initiatives, especially within the European Union, represent important progress, effective mitigation will require improved quantification of diffuse sources and better integration of scientific evidence into regulatory practice. Advancing standardized monitoring and cross-compartment assessments is essential to support evidence-based policies and reduce the long-term accumulation of microplastics in aquatic ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/microplastics5020130/s1>, Figure S1: Flow diagram of the literature selection process used in this review on microplastics in aquatic ecosystems; Figure S2 Prisma checklist; Table S1. Qualitative methodological appraisal criteria used to interpret cross-study comparability of MP studies. Reference [255] is cited in Supplementary Materials.

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