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MICROPLASTIC CONTAMINATION IN FRESHWATER ECOSYSTEMS: A SYSTEMATIC REVIEW OF DISTRIBUTION, ECOLOGICAL IMPACTS, AND MITIGATION STRATEGIES

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ABSTRACT

Microplastic (MP) pollution has emerged as one of the most pervasive environmental challenges of the twenty-first century, yet freshwater ecosystems—despite functioning as both transport conduits and long-term sinks for MPs—have historically received less research attention than marine environments. This paper presents a systematic literature review (SLR) framework and synthesis examining the distribution, ecological impacts, and mitigation strategies associated with MP contamination in freshwater rivers, lakes, reservoirs, wetlands, and groundwater systems, drawing on peer-reviewed literature indexed in Scopus, Web of Science, Google Scholar, and PubMed. Following PRISMA 2020 guidelines, the review protocol specifies explicit search strategies, inclusion and exclusion criteria, and a structured data extraction and thematic coding process. Synthesis of the available evidence indicates that MP distribution is shaped primarily by urban proximity, hydrological retention characteristics, and land-use intensity, with contamination arising from the concurrent operation of point sources—principally wastewater treatment plant effluent—and diffuse sources, including agricultural and urban runoff, atmospheric deposition, and tire wear particles. Ecotoxicological evidence documents consistent physiological, behavioral, and reproductive effects across freshwater trophic levels, from zooplankton to fish, with plausible cumulative implications for ecosystem functioning and food web stability. Human health and socioeconomic implications, while not yet fully characterized in quantitative risk terms, extend to drinking water security, fishery-dependent economies, and public health governance. Mitigation strategies spanning technological, regulatory, community-based, and circular-economy approaches each demonstrate partial effectiveness but require integrated, multi-pronged application to meaningfully reduce freshwater MP loading. The review concludes that freshwater MP contamination constitutes a distinct, cross-cutting sustainability challenge requiring coordinated scientific monitoring, technological investment, and policy action across watershed, national, and international scales.

Keywords: *microplastics; freshwater ecosystems; plastic pollution; ecological impacts; systematic literature review; mitigation strategies; water contamination; ecotoxicology*

1. INTRODUCTION

Plastic production has expanded at an extraordinary rate over the past seven decades, rising from approximately two million metric tons in 1950 to several hundred million metric tons annually in the present decade. This exponential growth has been driven by the material's low cost, versatility, and durability, properties that have made plastics indispensable across packaging, construction, textiles, agriculture, and consumer goods industries. However, the same durability that makes plastic economically attractive also renders it environmentally persistent, as most conventional plastics resist microbial degradation and instead fragment gradually into smaller particles under the influence of ultraviolet radiation, mechanical abrasion, and hydrolysis (Ahmed et al., 2021; Bhardwaj et al., 2024).

Among the emerging classes of plastic pollutants, microplastics—commonly defined as plastic particles smaller than five millimeters in diameter—have attracted heightened scientific and regulatory attention over the last decade. Microplastics are broadly categorized into primary microplastics, which are manufactured at microscopic size for use in cosmetics, industrial abrasives, and pre-production pellets, and secondary microplastics, which result from the fragmentation of larger plastic debris such as bottles, packaging film, fishing gear, and synthetic textiles. Their small size, chemical stability, and capacity to adsorb and transport co-occurring pollutants such as heavy metals and persistent organic pollutants have made microplastics a subject of growing concern among environmental scientists, toxicologists, and policymakers (Ahmed et al., 2021; Zhang et al., 2022).

While the bulk of early microplastic research concentrated on marine environments, a growing body of scholarship has recognized freshwater ecosystems—rivers, lakes, reservoirs, wetlands, and groundwater systems—as equally significant, and in many respects more immediately consequential, receptors of microplastic contamination (Bhardwaj et al., 2024; Zhao et al., 2024). Freshwater ecosystems provide indispensable services to human and ecological communities alike: they supply potable water, support agricultural irrigation, sustain fisheries that underpin food security for millions of people, regulate hydrological cycles, and harbor disproportionately high levels of biodiversity relative to their limited global surface area. The degradation of these systems through plastic contamination therefore carries consequences that extend well beyond the aquatic environment itself, implicating public health, food systems, and regional economies (Al Mamun et al., 2023; Jamal et al., 2025).

Advances in analytical detection methods—including Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, and increasingly standardized sampling protocols—have enabled researchers to document the presence of microplastics across a widening range of freshwater compartments. Reports of microplastic particles in major river systems, urban and rural lakes, drinking water reservoirs, constructed and natural wetlands, and even subsurface groundwater have proliferated in the scientific literature since 2020, suggesting that freshwater microplastic contamination is both geographically widespread and compartmentally pervasive (Zhao et al., 2024; Cha et al., 2023; Su et al., 2022).

Freshwater systems occupy a unique position in the global plastic pollution cycle: they function simultaneously as conduits that transport terrestrial plastic debris toward marine environments and as sinks in which microplastics accumulate within sediments, biota, and hydrological dead zones. Understanding the dynamics of microplastic distribution, transport, and ecological impact within freshwater ecosystems is therefore essential not only for characterizing a distinct and consequential contamination pathway, but also for informing the broader, cross-boundary strategies needed to mitigate plastic pollution at its source. It is within this context that the present study undertakes a systematic literature review of microplastic contamination in freshwater ecosystems, synthesizing evidence on its distribution, ecological impacts, and mitigation strategies published between 2020 and 2025.

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1.2 Review of Related Literature

Theme 1: Distribution of Microplastics in Freshwater Ecosystems

A substantial body of research has documented the occurrence of microplastics across the full spectrum of freshwater compartments. This section synthesizes reported findings across five ecosystem types: rivers, lakes, reservoirs, wetlands, and groundwater systems.

Rivers. Studies examining riverine systems have generally reported that microplastic concentrations increase with proximity to urban centers, wastewater discharge points, and industrial zones, with fibrous and fragment-type particles predominating in surface water and sediment samples (Range et al., 2023). Al-Zawaidah et al. (2021) similarly emphasized that macroplastic and microplastic loading in rivers is closely tied to catchment-scale land use and hydro-geomorphic characteristics, noting that river systems function simultaneously as contamination pathways and temporary storage compartments depending on channel morphology and flow regime.

Lakes. Lake systems, particularly those situated near densely populated watersheds, have been shown to accumulate microplastics through both direct surface runoff and atmospheric deposition, with concentrations often correlating with lake morphometry, retention time, and surrounding land use (Zhao et al., 2024). A configurative synthesis of water-body studies further found that lake water constitutes the second-largest share of published freshwater microplastic research after rivers, accounting for approximately 24% of studies reviewed, underscoring the comparatively higher retention of particles in lentic, low-turbulence systems.

Reservoirs. Reservoirs used for drinking water supply and irrigation have been identified in recent studies as sites of measurable microplastic accumulation, raising concerns regarding downstream transfer into treated water systems. Bhardwaj et al. (2024) reported that microplastic concentrations in freshwater bodies, including reservoirs such as those within the Yangtze River basin, can span several orders of magnitude, from fractions of a particle per cubic meter to tens of thousands of particles per square meter, reflecting both genuine variation in contamination and inconsistency in measurement protocols across studies.

Wetlands. Wetlands, owing to their hydrological function as natural filters, have been found to trap and retain substantial quantities of microplastics within vegetation and sediment matrices, positioning them as both mitigators and long-term reservoirs of contamination. Su et al. (2022) documented the co-occurrence and migration of microplastics alongside microplastic-carrying organic pollutants in both natural and constructed wetlands, concluding that wetlands represent an enlarging, though still insufficiently quantified, ecological risk within the freshwater microplastic cycle.

Groundwater Systems. Although comparatively understudied relative to surface waters, emerging research has begun to detect microplastic particles in groundwater and karst aquifer systems, suggesting that subsurface transport pathways—via infiltration through soil and fractured rock—warrant further investigation. Cha et al. (2023) detected microplastic contamination in agricultural groundwater in the Haean Basin of Korea, attributing particle presence to infiltration from surface agricultural activity, and argued that groundwater monitoring remains a substantially underdeveloped component of freshwater microplastic research relative to surface water studies.

Across these ecosystem types, comparative synthesis suggests that urban proximity, hydrological connectivity, and land-use intensity are recurring determinants of microplastic abundance (Zhao et al., 2024; Bhardwaj et al., 2024). Methodological heterogeneity in sampling protocols and size-detection thresholds, however, complicates direct cross-study comparison and represents a persistent limitation noted throughout the literature (Zhao et al., 2024). Studies focusing on lentic systems (lakes, reservoirs) remain more numerous than those addressing groundwater, indicating an important compartmental gap (Cha et al., 2023).

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Theme 2: Sources and Transport Pathways of Microplastics

Understanding the pathways through which microplastics enter freshwater systems is essential to designing effective interventions. The literature identifies several principal source categories and transport mechanisms.

Urban Runoff. Stormwater runoff from urban and peri-urban areas has been consistently identified as a major non-point source, transporting tire wear particles, degraded packaging, and synthetic fibers into adjacent waterways during precipitation events (Al-Zawaidah et al., 2021).

Wastewater Treatment Plant Effluents. Despite partial removal efficiency in conventional treatment processes, wastewater treatment plants have been repeatedly identified as point sources of microplastic discharge, owing to the high volume of effluent released continuously into receiving waters. Acarer (2023) noted that conventional wastewater and drinking water treatment plants cannot completely remove microplastics using standard treatment trains, and that advanced membrane technologies—including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis—represent the most effective, though not yet universally deployed, removal options.

Textile Fibers. Synthetic textile laundering has been highlighted as a dominant source of microfiber contamination. Ahmed et al. (2023) identified textile-derived fibers as a persistent and difficult-to-remove class of aquatic microplastic contaminant, noting that their high length-to-diameter ratio complicates both filtration-based removal and analytical quantification relative to fragment- or bead-shaped particles.

Tire Wear Particles. Vehicular tire abrasion generates substantial quantities of rubber-polymer particulates that are transported via road runoff into freshwater systems, a source increasingly recognized as significant in urbanized watersheds. Kole et al. (2017) estimated that tire wear constitutes one of the largest sources of microplastic release into the environment on a global mass basis, entering water bodies via both surface runoff and atmospheric transport.

Agricultural Runoff. The use of plastic mulching films, coated fertilizers, and polymer-based soil amendments has been linked to microplastic transfer from agricultural land into adjacent surface waters via irrigation return flow and surface runoff. Cha et al. (2023) directly linked agricultural land use to microplastic contamination of adjacent groundwater in the Haean Basin of Korea, implicating both surface infiltration and irrigation-related pathways.

Industrial Discharges. Direct discharges from plastic manufacturing and processing facilities, including pre-production pellet ('nurdle') spillage, constitute a further documented point-source pathway, compounding the loading already contributed by wastewater and urban runoff sources (Ahmed et al., 2023).

Atmospheric Deposition. Recent research has demonstrated that airborne microplastic particles, transported over variable distances, settle onto freshwater surfaces, indicating that atmospheric deposition constitutes a non-negligible, and previously underappreciated, contamination pathway. Brahney et al. (2021) quantified atmospheric microplastic transport and deposition at a continental scale, demonstrating that particles can be transported far beyond their point of origin and subsequently deposited into remote aquatic systems with no direct anthropogenic contact.

Synthesis of source-pathway literature indicates that point sources (wastewater effluent, industrial discharge) and diffuse sources (urban and agricultural runoff, atmospheric deposition) operate concurrently, complicating source-apportionment efforts (Ahmed et al., 2023; Brahney et al., 2021). Few studies have attempted to quantify the relative contribution of each pathway within a single watershed, representing a methodological gap addressed further below.

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Theme 3: Ecological Impacts of Microplastics

Microplastic exposure has been associated with a range of physiological, behavioral, reproductive, and ecosystem-level effects across freshwater taxa.

Fish. Ingestion studies in freshwater fish species have reported gastrointestinal tract accumulation, oxidative stress responses, and, in some cases, altered feeding behavior and growth trajectories following microplastic exposure. Banaee et al. (2024) reviewed the environmental toxicology of microplastic particles in fish and found consistent evidence of oxidative stress, disrupted antioxidant signaling pathways, and histopathological damage across multiple freshwater and marine species. Subaramaniyam et al. (2023) further demonstrated that combined exposure to microplastics and other aquatic pollutants, such as pesticides, compounds oxidative stress and impairs antioxidant defense mechanisms in fish beyond the effect of microplastics alone.

Zooplankton. As primary consumers occupying a foundational trophic position, zooplankton have been shown to ingest microplastic particles readily, with documented effects on feeding efficiency, reproduction, and population-level dynamics that may propagate impacts up the food web. Ziajahromi et al. (2017) demonstrated that microplastic polyester fibers and polyethylene beads produced dose-dependent reductions in survival, growth, and reproduction in the freshwater zooplankton Ceriodaphnia dubia under both acute and chronic exposure conditions. Zhang et al. (2022) additionally showed that the formation of an ecological corona—biomolecules and pollutants adsorbing to the microplastic surface—can further modify particle toxicity to aquatic organisms including zooplankton.

Macroinvertebrates. Benthic macroinvertebrates, owing to their close association with sediment-bound microplastics, have exhibited altered burrowing behavior, tissue accumulation, and, in select taxa, reduced survivorship under experimental exposure conditions. Prata et al. (2023) examined uptake dynamics and adverse effects of microplastics on the freshwater benthic invertebrate Chironomus riparius, reporting measurable physiological effects linked to both particle ingestion and prolonged sediment contact.

Aquatic Plants. Emerging evidence suggests that microplastic presence in sediment and water column can impair nutrient uptake, root development, and photosynthetic efficiency in submerged and emergent aquatic macrophytes, though this remains one of the less extensively studied taxa groups relative to fish and zooplankton within the freshwater ecotoxicological literature (Bhardwaj et al., 2024).

Freshwater Biodiversity. At the community level, cumulative and chronic exposure to microplastics has been hypothesized to contribute to shifts in species composition and reductions in overall biodiversity indices. Huang et al. (2021) reviewed the ecotoxicological effects and trophic transfer of microplastics and associated contaminants in aquatic environments, concluding that while individual-organism effects are well documented, translating this evidence into confident community- and biodiversity-level conclusions remains an ongoing scientific challenge due to the confounding influence of co-occurring environmental stressors.

Taken together, the ecotoxicological literature demonstrates consistent, though variably severe, sub-lethal effects across trophic levels (Banaee et al., 2024; Ziajahromi et al., 2017; Prata et al., 2023), with laboratory-based exposure studies substantially outnumbering field-based or mesocosm studies capable of capturing ecosystem-level and chronic-exposure dynamics (Huang et al., 2021)—an imbalance identified as a recurring methodological gap.

Theme 4: Human Health and Socioeconomic Implications

Beyond direct ecological effects, microplastic contamination of freshwater systems carries implications for human health and regional economies.

Food Chain Contamination. Trophic transfer of microplastics from lower to higher organisms, including species consumed by humans, has raised concern regarding bioaccumulation and potential biomagnification along freshwater food chains. Al Mamun et al. (2023) reviewed evidence of microplastics entering human food chains,

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concluding that dietary exposure via contaminated fish and other aquatic food products represents a plausible, if not yet fully quantified, human exposure pathway. Jamal et al. (2025) further documented microplastic contamination in seafood species harvested from the northern Bay of Bengal, with implications for consumer risk assessment in fishery-dependent coastal and riverine communities.

Drinking Water Concerns. Detection of microplastic particles in both raw source water and, in some cases, treated tap water has prompted investigation into the adequacy of conventional water treatment processes for microplastic removal (Acarer, 2023). Zuri et al. (2023) reviewed human biomonitoring evidence for microplastics, noting that drinking water constitutes one of several confirmed human exposure routes alongside food and inhalation.

Public Health Implications. Although the toxicological significance of chronic low-dose human microplastic exposure remains an active area of investigation, researchers have raised concerns regarding potential inflammatory, endocrine-disrupting, and particle-associated chemical exposure risks. Vethaak and Legler (2021) argued in a widely cited perspective that significant knowledge gaps remain regarding the human health risks of microplastics and called for urgent, coordinated research to close this gap. Subsequent studies have detected microplastic particles directly in human blood (Leslie et al., 2022), lung tissue (Jenner et al., 2022), and placental tissue (Ragusa et al., 2021), while Alijagic et al. (2024) emphasized that human health risk should be assessed as a 'triple exposure nexus' incorporating microplastic particles, their associated chemical additives, and co-occurring environmental pollutants simultaneously.

Economic Impacts on Fisheries and Water Resources. Contamination-related declines in fish stock health and consumer confidence, as well as increased costs associated with water treatment upgrades, have been identified as tangible economic burdens on fishery-dependent and water-utility-dependent communities. Jamal et al. (2025) linked microplastic contamination in commercially important seafood species to potential downstream economic and food-safety consequences for fishery-dependent economies in the Bay of Bengal region.

The human health and socioeconomic literature remains comparatively nascent relative to ecological studies (Vethaak & Legler, 2021), with most human-health-oriented research still confined to hazard identification (Leslie et al., 2022; Ragusa et al., 2021; Jenner et al., 2022) rather than quantitative risk assessment (Alijagic et al., 2024)—an important gap given the direct policy relevance of this theme.

Theme 5: Mitigation and Management Strategies

A range of mitigation and management strategies have been proposed and, in some cases, implemented to reduce microplastic loading into freshwater systems.

Plastic Waste Reduction. Upstream interventions, including single-use plastic bans and extended producer responsibility schemes, have been examined for their potential to reduce the overall volume of plastic entering waste streams and, subsequently, waterways (Ahmed et al., 2023).

Wastewater Treatment Technologies. Advanced tertiary treatment technologies, including membrane filtration and coagulation-based processes, have demonstrated improved microplastic removal efficiency relative to conventional primary and secondary treatment. Acarer (2023) found that membrane-based technologies, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, are among the most effective and promising approaches currently available for microplastic removal from water and wastewater.

Biodegradable Alternatives. The development and adoption of biodegradable and bio-based polymers has been proposed as a longer-term substitution strategy, though questions regarding degradation conditions and unintended ecological effects remain under investigation (Ahmed et al., 2023).

Circular Economy Approaches. Circular economy frameworks emphasizing plastic redesign, reuse, and closed-loop recycling have been advanced as systemic alternatives to the prevailing linear production-consumption-disposal model. Mehinto et al. (2022) proposed a risk-based management framework for microplastics in aquatic ecosystems intended to guide the prioritization of monitoring and mitigation resources within a broader circular-

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economy-oriented management strategy. Gao et al. (2023) additionally demonstrated the feasibility of microalgae-based bioremediation as an emerging, low-cost biological technique for removing microplastics from wastewater.

Policy Interventions. National and subnational regulatory measures, ranging from plastic bag levies to watershed-specific discharge standards, have been evaluated for their effectiveness in reducing freshwater plastic loading (Mehinto et al., 2022).

Community-Based Initiatives. Grassroots and community-led interventions, including river clean-up programs and citizen science monitoring networks, have been documented as complementary, participatory approaches to plastic pollution management, contributing valuable long-term monitoring data at comparatively low cost (Zhao et al., 2024).

The mitigation literature reveals a general progression from downstream, reactive measures (clean-up, treatment upgrades) (Acarer, 2023) toward upstream, preventive strategies (circular economy design, policy regulation) (Mehinto et al., 2022; Gao et al., 2023), though implementation and evaluation studies—particularly those assessing real-world effectiveness at watershed scale—remain limited.

1.3 Theoretical Foundation

This study is anchored in four complementary theoretical perspectives that collectively explain both the occurrence and the management of microplastic pollution in freshwater ecosystems.

Pollution Theory provides a foundational framework for understanding the generation, transport, and accumulation of pollutants within environmental media, conceptualizing microplastics as a persistent contaminant class subject to source-pathway-receptor dynamics. This theory supports the present study's organization of source and transport-pathway literature under Theme 2.

Ecosystem Theory, which conceptualizes freshwater bodies as interconnected systems of biotic and abiotic components bound by energy and material flows, informs the study's treatment of ecological impacts (Theme 3), framing microplastic contamination as a stressor capable of disrupting trophic interactions and ecosystem functioning.

Environmental Systems Theory extends this framework by situating freshwater ecosystems within broader hydrological, atmospheric, and anthropogenic systems, thereby supporting the study's integration of distribution (Theme 1), source pathways (Theme 2), and human health/socioeconomic implications (Theme 4) as interconnected rather than isolated phenomena.

Circular Economy Theory, finally, underpins the study's discussion of mitigation strategies (Theme 5), offering a systemic alternative to the linear 'produce–use–dispose' model of plastic consumption and providing a normative framework against which current and proposed interventions can be evaluated.

Collectively, these four theoretical lenses allow the present review to move beyond a purely descriptive cataloguing of empirical findings toward an integrated, systems-based synthesis of microplastic contamination dynamics and management options.

1.4 Conceptual Framework

The conceptual framework guiding this review posits a sequential yet cyclical relationship among four core constructs. Sources of Microplastics—encompassing urban, agricultural, industrial, and atmospheric origins—generate particles that enter freshwater systems through identifiable Distribution and Transport Mechanisms, including surface runoff, effluent discharge, and atmospheric deposition. Once introduced, microplastics accumulate within freshwater compartments (rivers, lakes, reservoirs, wetlands, groundwater) and interact with biotic communities, producing measurable Ecological Impacts spanning physiological, behavioral, reproductive,

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and ecosystem-level effects, which in turn generate downstream Human Health and Socioeconomic Implications. This chain of effects creates the impetus for Mitigation Strategies, which act recursively upon the initial sources and transport pathways, thereby closing the conceptual loop. The framework emphasizes that effective mitigation cannot be evaluated in isolation from an understanding of source dynamics and ecological consequences, reinforcing the rationale for the integrated, thematic structure adopted in this review.

1.5 Research Gap

Empirical Gap: Considerable inconsistency persists regarding quantitative microplastic concentration thresholds associated with measurable ecological harm, as findings across studies vary substantially due to differences in exposure duration, particle characteristics, and species sensitivity, leaving dose-response relationships inconclusive.

Contextual Gap: Geographic and ecosystem-type coverage in the existing literature remains uneven, with groundwater systems, tropical and archipelagic freshwater contexts, and small-to-medium urban watersheds in developing regions comparatively underrepresented relative to large temperate-zone rivers and lakes.

Methodological Gap: The absence of standardized sampling, extraction, and particle-identification protocols across studies constrains cross-study comparability and meta-analytic synthesis, while field-based and long-term monitoring studies remain scarce relative to short-term laboratory exposure experiments.

Theoretical Gap: Few studies explicitly integrate ecological and circular-economy theoretical perspectives within a single analytical framework, resulting in a literature that addresses ecological impacts and mitigation strategies as largely separate rather than interdependent lines of inquiry.

The present study addresses these gaps by systematically synthesizing findings across all five thematic areas within a single integrative framework, explicitly documenting methodological variation across studies, and applying an explicit theoretical lens that connects ecological outcomes to circular-economy-informed mitigation strategies.

1.6 Significance of the Study

This study is expected to contribute meaningfully to the following areas:

- Environmental Science: This review consolidates a fragmented body of empirical evidence into a coherent, thematically organized synthesis, providing a reference point for future primary research on freshwater microplastic dynamics.
- Freshwater Ecology: By systematically mapping ecological impacts across trophic levels and ecosystem types, the study contributes to a more integrated understanding of microplastic-mediated ecosystem stress.
- Environmental Policy: The identification of source-pathway and mitigation-strategy evidence offers a synthesized evidentiary basis to inform regulatory and watershed-management decision-making.
- Waste Management: Findings regarding treatment technology effectiveness and circular economy interventions provide practical reference points for waste and wastewater management practitioners.
- Sustainable Development: The study's integration of ecological, health, and socioeconomic dimensions aligns with the multidimensional character of the Sustainable Development Goals, particularly those concerning clean water, life below water, and sustainable production and consumption.
- Future Research: By explicitly articulating empirical, contextual, methodological, and theoretical gaps, the review provides a structured research agenda for scholars seeking to advance the field.

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1.7 Research Questions

Central Research Question:

What does the peer-reviewed literature published between 2020 and 2025 reveal about the distribution, ecological impacts, and mitigation strategies of microplastic contamination in freshwater ecosystems?

Specific Research Questions:

1. What distribution patterns of microplastics have been documented across freshwater rivers, lakes, reservoirs, wetlands, and groundwater systems?
2. What are the principal sources and transport pathways through which microplastics enter freshwater ecosystems?
3. What ecological impacts of microplastic contamination have been documented across freshwater fish, zooplankton, macroinvertebrates, aquatic plants, and biodiversity?
4. What human health and socioeconomic implications have been associated with freshwater microplastic contamination?
5. What mitigation and management strategies have been proposed or implemented, and what gaps remain in the current body of research?

2. METHODOLOGY

2.1 Research Design

This study employs a Systematic Literature Review (SLR) design, utilizing secondary data derived exclusively from peer-reviewed journal articles. The SLR approach was selected over alternative review methodologies (e.g., narrative review, scoping review) because it applies an explicit, replicable, and pre-specified protocol for study identification, screening, and synthesis, thereby minimizing selection bias and enhancing methodological transparency. The use of secondary data is justified on several grounds: it enables comprehensive geographic and temporal coverage that would be unattainable through primary data collection alone; it allows for the synthesis of findings across diverse ecosystem types and methodological approaches; and it is consistent with established practice in environmental science reviews seeking to consolidate a rapidly expanding evidence base. The principal advantages of this design include reproducibility, transparency of the selection process, capacity to identify patterns and gaps across a large body of literature, and suitability for informing evidence-based policy and future research directions.

2.2 Review Protocol

This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure methodological rigor and reporting transparency. The PRISMA framework structures the review process into four sequential stages—identification, screening, eligibility assessment, and inclusion—each of which is documented with explicit criteria and, where applicable, a PRISMA flow diagram indicating the number of records identified, screened, excluded, and ultimately included at each stage. Adherence to PRISMA guidelines ensures that the review process is auditable and replicable by future researchers.

2.3 Data Sources

This review draws upon four major bibliographic databases: Scopus, Web of Science, Google Scholar, and PubMed. Scopus and Web of Science were selected for their extensive, quality-controlled coverage of peer-reviewed environmental science and ecology journals, and their widely recognized standing as primary databases for systematic reviews in the natural sciences. Google Scholar was included to broaden coverage and capture

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relevant studies that may not be indexed in the subscription-based databases, including regionally published or open-access journals. PubMed was incorporated specifically to ensure adequate coverage of the human health and toxicological dimensions of microplastic exposure, given its specialization in biomedical and life-science literature. The combined use of these four databases is intended to maximize both the comprehensiveness and the disciplinary breadth of the retrieved literature.

2.4 Search Strategy

Search Keywords

- "microplastic contamination"
- "freshwater ecosystems"
- "rivers"
- "lakes"
- "reservoirs"
- "wetlands"
- "groundwater"
- "ecological impacts"
- "plastic pollution"
- "mitigation strategies"
- "human health microplastics"

Boolean Operators and Sample Search Strings

The search strategy combines keywords using Boolean operators (AND, OR) and truncation (*) to maximize sensitivity while maintaining topical relevance. Representative search strings applied across the four databases include:

- ("microplastic*" AND "freshwater ecosystem*") AND ("distribution" OR "occurrence")
- ("microplastic*" AND ("river*" OR "lake*" OR "reservoir*" OR "wetland*" OR "groundwater"))
- ("microplastic*" AND "ecological impact*" AND ("fish" OR "zooplankton" OR "macroinvertebrate*" OR "aquatic plant*"))
- ("microplastic*" AND ("human health" OR "food chain" OR "drinking water"))
- ("microplastic*" AND ("mitigation" OR "management strateg*" OR "circular economy" OR "wastewater treatment"))

2.5 Inclusion Criteria

Studies are included if they meet all of the following criteria:

- Peer-reviewed journal articles
- Published between January 2020 and 2025
- Written in the English language
- Focused specifically on freshwater ecosystems (rivers, lakes, reservoirs, wetlands, or groundwater)
- Address at least one of the study's core themes: distribution, sources/transport, ecological impacts, human health/socioeconomic implications, or mitigation strategies

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2.6 Exclusion Criteria

Studies are excluded if they meet any of the following criteria:

- Studies focused exclusively on marine or estuarine environments
- Conference abstracts without full-text peer-reviewed publication
- Editorials, commentaries, and opinion pieces lacking original data or systematic synthesis
- Duplicate publications or studies substantially overlapping in dataset and findings with an already-included study
- Publications not available in the English language

2.7 Study Selection Process

The study selection process follows the four-stage PRISMA sequence. During the Identification stage, records are retrieved from all four databases using the search strings specified above, and duplicate records are removed using reference management software. During the Screening stage, titles and abstracts are reviewed against the inclusion and exclusion criteria to exclude clearly irrelevant records. During the Eligibility stage, full-text articles of the remaining records are retrieved and assessed in detail against the complete set of inclusion and exclusion criteria, with reasons for exclusion documented for transparency. In the final Inclusion stage, the remaining studies constitute the final corpus subjected to data extraction and thematic synthesis. This process is documented using a PRISMA 2020 flow diagram indicating the number of records at each stage (identification, screening, eligibility, inclusion), together with the corresponding number and stated reasons for exclusions.

2.8 Data Extraction

For each included study, the following data elements are systematically extracted and recorded in a structured extraction matrix: author(s) and year of publication; country or region of study; ecosystem type investigated (river, lake, reservoir, wetland, or groundwater); reported microplastic concentration and measurement units; identified sources of contamination; documented ecological impacts; and mitigation strategies discussed or evaluated. This structured extraction process ensures consistency across studies and facilitates subsequent thematic and descriptive synthesis.

Sample Data Extraction Matrix

Author(s) & Year	**Country**	**Ecosystem Type**	**MP Concentration**	**Sources Identified**	**Ecological Impacts**	**Mitigation Strategies**
[Author, Year]	[Country]	[River/Lake/etc.]	[e.g., particles/L or particles/kg]	[e.g., urban runoff]	[e.g., reduced fish growth]	[e.g., WWTP upgrade]
[Author, Year]	[Country]	[Ecosystem type]	[Value]	[Source category]	[Impact observed]	[Strategy discussed]
[Author, Year]	[Country]	[Ecosystem type]	[Value]	[Source category]	[Impact observed]	[Strategy discussed]

2.9 Quality Assessment

The methodological quality of included studies is assessed using four criteria adapted for environmental science systematic reviews: methodological rigor, evaluated by the appropriateness and clarity of sampling and analytical procedures; data completeness, evaluated by the extent to which studies report sufficient quantitative and contextual detail to permit extraction; reliability of findings, evaluated by the use of appropriate controls, replication, and validated analytical techniques (e.g., FTIR or Raman confirmation of polymer identity); and

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relevance to research objectives, evaluated by the directness of a study's contribution to one or more of the review's five thematic areas. Studies are not excluded solely on the basis of quality scores but are contextualized accordingly during synthesis, with lower-quality studies discussed with appropriate caveats.

2.10 Data Analysis

Descriptive Analysis

Descriptive analysis is conducted to characterize overall patterns in the included literature, including publication trends over the 2020–2025 period, geographic distribution of study sites across regions and countries, and the relative frequency of studies addressing each ecosystem category (rivers, lakes, reservoirs, wetlands, groundwater). These descriptive patterns provide context for interpreting the thematic findings and for identifying underrepresented geographic or ecosystem contexts.

Thematic Analysis

Thematic analysis is employed to synthesize qualitative and quantitative findings across the five core themes: distribution patterns, sources and transport pathways, ecological impacts, human health implications, and mitigation strategies. Coding proceeds in three stages: initial open coding of extracted data to identify recurring concepts and findings within each theme; axial coding to group related codes into sub-themes (e.g., grouping specific ecosystem findings under the broader distribution theme); and selective synthesis, in which sub-themes are integrated into a coherent narrative for each theme, highlighting points of convergence, divergence, and gaps across studies. This coding process is conducted iteratively, with the extraction matrix serving as the primary data source for theme development.

2.11 Ethical Considerations

As this study relies exclusively on secondary data derived from publicly available, peer-reviewed publications, no direct human or animal subjects are involved, and no primary data collection requiring institutional ethical clearance is undertaken. Nonetheless, the review adheres to established ethical standards for secondary research, including accurate and complete representation of source findings, rigorous adherence to APA 7th Edition citation practices to ensure proper attribution of original authors' work, avoidance of selective or misleading interpretation of source data, and transparent documentation of the review's search, screening, and synthesis procedures to uphold academic integrity and enable independent verification by future researchers.

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4. DISCUSSION

4.1 Distribution of Microplastics in Freshwater Ecosystems

Synthesis of the reviewed literature indicates that microplastic (MP) contamination in freshwater systems is not randomly distributed but instead follows patterns closely tied to human economic activity, hydrological connectivity, and sampling methodology. Zhao et al. (2024) found that MPs are widely distributed across global freshwater systems, with higher abundances consistently reported in regions of intense human economic activity such as the United States, Europe, and China, and noted that abundance figures vary substantially across rivers, lakes, estuaries, and wetlands depending on sampling method and size-range selection. This pattern is corroborated by a configurative synthesis of water-body studies, which found that river water accounted for the largest share of published MP research (30%), followed by lakes (24%), with China alone accounting for approximately 19% of global MP research output.

Regionally, this concentration of research effort in industrialized and densely populated watersheds raises an important interpretive caveat: apparent 'hotspots' of MP contamination may partly reflect where scientists have looked rather than where contamination is objectively most severe. Bhardwaj et al. (2024) reported MP concentrations spanning several orders of magnitude across different freshwater systems—from fractions of a particle per cubic meter in some lake systems to tens of thousands of particles per square meter in heavily impacted reservoirs such as the Yangtze River basin in China—a range that reflects both genuine variation in contamination and the lack of a harmonized global measurement protocol.

Lentic systems such as lakes and reservoirs, particularly those situated in low-turbulence, high-retention-time settings, appear disproportionately prone to MP accumulation, consistent with the general principle that reduced hydrodynamic energy favors particle settling and retention rather than downstream flushing. Wetlands, by virtue of their vegetative structure and hydrological function as natural filters, likewise emerge in the literature as compartments of long-term MP retention, effectively acting as both sinks and secondary sources should sediments be disturbed. Groundwater and subsurface systems remain markedly underrepresented in the literature relative to surface waters, a gap consistent with the methodological difficulty of subsurface sampling rather than any inherent resistance of aquifers to contamination.

These distributional findings align closely with, and extend, Pollution Theory's source-pathway-receptor framework: freshwater bodies proximal to urban, industrial, and agricultural sources function as receptors accumulating the cumulative pollutant loading of their watersheds. The persistent methodological heterogeneity identified across studies—differing size thresholds, extraction protocols, and detection technologies—has direct implications for environmental monitoring: without standardized protocols, cross-jurisdictional comparison of contamination levels, and therefore evidence-based prioritization of remediation resources, remains fundamentally constrained. This reinforces calls in the literature for internationally harmonized MP monitoring frameworks and open-source datasets to enable meaningful comparison across regions and over time.

4.2 Sources and Transport Pathways

The reviewed literature converges on the view that freshwater MP contamination arises from the interaction of multiple, concurrently operating source categories rather than any single dominant pathway. Wastewater treatment plants (WWTPs) have been repeatedly identified as a major point source: despite achieving substantial removal efficiencies for larger debris, conventional secondary treatment processes are not specifically engineered to capture MPs, and the sheer volume of effluent discharged continuously means that even a small residual fraction of particles translates into a large absolute loading of MPs into receiving waters. This helps explain why WWTP-adjacent river reaches are consistently identified in the literature as zones of elevated MP concentration.

Diffuse, non-point sources operate in parallel with these point sources. Urban stormwater runoff transports tire wear particles, synthetic fibers, and fragmented packaging debris accumulated on impervious surfaces into

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receiving waters during precipitation events, while agricultural runoff introduces MPs through plastic mulching film degradation, coated fertilizers, and land application of biosolids and sewage sludge—the latter itself a downstream consequence of WWTP operations, illustrating how source pathways are frequently interlinked rather than independent. Industrial discharges, including pre-production pellet loss, constitute a further point-source pathway, while atmospheric deposition has emerged in recent literature as a previously underappreciated pathway capable of transporting MPs—including tire wear particles and synthetic fibers—over considerable distances before settling onto both terrestrial and aquatic surfaces, even reaching remote lakes and reservoirs far from obvious contamination sources.

Tire wear particles specifically warrant emphasis given the scale of the estimated global release—approximately 5,918 kilotonnes annually, equivalent to roughly 0.81 kilograms per capita per year—and their capacity to enter water bodies via both surface runoff and atmospheric transport. Taken together, these findings suggest that human activity influences freshwater MP accumulation through a layered combination of continuous point-source discharge and episodic, precipitation-driven diffuse-source pulses, with hydrological connectivity (rainfall intensity, impervious surface cover, drainage density) acting as the key mediating variable determining how efficiently land-based MPs are transported into receiving waters.

Comparing across the reviewed sources, an emerging trend is the increasing recognition that source apportionment cannot be reduced to a single dominant contributor; rather, source contributions are watershed-specific, varying with land-use composition, population density, industrial activity, and precipitation regime. This has practical implications for the design of source-control interventions, which the literature increasingly suggests must be tailored to local source profiles rather than adopting a uniform, one-size-fits-all mitigation approach.

4.3 Ecological Impacts on Freshwater Organisms

Physiological Effects

Physiological effects of MP exposure are among the most consistently documented outcomes across the reviewed ecotoxicological literature. Meta-analytic evidence indicates that MP exposure significantly increases oxidative damage in fish, with freshwater fish showing greater sensitivity in terms of growth and reproductive impairment compared to marine fish. Mechanistically, MP-induced oxidative stress has been linked to disruption of the Keap1-Nrf2 antioxidant signaling pathway, with downstream consequences including apoptosis, tissue damage, and altered energy allocation as organisms divert metabolic resources toward stress response and detoxification rather than growth or reproduction. Subaramaniyam et al. (2023) similarly documented that combined exposure to microplastics and other pollutants such as pesticides compounds oxidative stress and antioxidant defense disruption in fish, underscoring the ecological relevance of MP co-exposure with other anthropogenic stressors.

Behavioral Effects

Behavioral effects, while comparatively less studied than physiological endpoints, are reported with reasonable consistency: reduced feeding capacity and altered energy budgets have downstream consequences for movement patterns and predator-avoidance capacity, since organisms with impaired energy reserves are generally less able to sustain the metabolic demands of escape responses. Neurotoxic effects have also been documented in zebrafish following MP accumulation, with implications for locomotor activity and broader nervous system function.

Reproductive Effects

Reproductive effects appear particularly pronounced in freshwater zooplankton. Ziajahromi et al. (2017) exposed the freshwater cladoceran Ceriodaphnia dubia to microplastic polyester fibers and polyethylene beads under both acute and chronic conditions and documented dose-dependent reductions in survival, growth, and reproductive output, illustrating that even short-lived, rapidly reproducing organisms occupying foundational trophic positions are not insulated from MP-induced reproductive harm. Testicular apoptosis has similarly been documented in zebrafish following polystyrene MP exposure, suggesting that reproductive impacts extend across both invertebrate and vertebrate freshwater taxa.

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Biodiversity Consequences

At the community and biodiversity level, the evidence is more circumstantial than direct, reflecting the practical difficulty of establishing causal links between MP exposure and population-level or community-level decline under real-world, multi-stressor field conditions. Nonetheless, the consistency of sub-lethal effects documented across trophic levels—from zooplankton through macroinvertebrates to fish—provides a plausible mechanistic basis for inferring that chronic, low-dose MP exposure could contribute cumulatively to altered community structure and reduced ecosystem resilience over time, even where individual laboratory studies cannot capture this emergent, ecosystem-scale outcome.

These findings can be productively interpreted through Ecosystem Theory, which conceptualizes stressors as propagating through interconnected trophic and functional relationships rather than remaining confined to the individual organisms initially exposed. The observed pattern—sub-lethal but consistent physiological and reproductive impairment at lower trophic levels—is precisely the kind of stressor that ecosystem theory would predict to generate diffuse, difficult-to-detect, but ultimately consequential impacts on higher-order ecosystem functioning and stability.

4.4 Ecosystem-Level Impacts

Beyond effects on individual organisms and populations, the reviewed literature points toward broader ecosystem-level consequences of MP contamination that are less easily quantified but arguably more consequential for long-term ecosystem functioning. Trophic transfer of MPs—from zooplankton and other primary consumers upward through the food web—raises the possibility of food web disruption extending well beyond the initially exposed organisms, particularly where MP-associated chemical additives and adsorbed pollutants biomagnify alongside particle transfer.

Sediment interactions represent a further significant, if underexamined, pathway of ecosystem-level impact. Because a substantial proportion of freshwater MPs ultimately settle into benthic sediments, MP accumulation in this compartment has the potential to alter sediment biogeochemistry, including nutrient cycling processes mediated by benthic microbial communities. The biofilm colonization phenomenon documented on MP surfaces further complicates this picture: MPs act as novel substrates for microbial colonization, potentially altering local microbial community composition and, by extension, the biogeochemical processes those communities mediate, including nitrogen and carbon cycling.

Habitat degradation constitutes an additional ecosystem-level concern, particularly in benthic and interstitial habitats where accumulated MPs may physically alter substrate characteristics relevant to macroinvertebrate colonization and reproduction. Collectively, these findings suggest that MP contamination should be understood not merely as a discrete toxicological stressor acting on individual organisms, but as a diffuse perturbation capable of altering fundamental ecosystem processes—nutrient cycling, sediment biogeochemistry, and habitat structure—that underpin overall ecosystem functioning. This ecosystem-level framing is consistent with Environmental Systems Theory's emphasis on the interconnectedness of hydrological, biological, and biogeochemical processes within freshwater systems, and reinforces the argument that MP contamination cannot be fully understood through single-species toxicological studies alone.

4.5 Human Health and Socioeconomic Implications

The human health and socioeconomic implications of freshwater MP contamination, while less mechanistically established than ecological impacts, are nonetheless substantial enough to warrant serious governance attention. MPs have been detected not only in raw source water but, in some documented cases, in treated drinking water, prompting scrutiny of the adequacy of conventional treatment trains for MP removal. Evidence of MP presence in human tissues, including reports of placental detection, alongside associations with oxidative stress, gut microbiome disruption, and chronic inflammation, has elevated microplastic exposure from a purely

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environmental concern to a matter of direct public health relevance—even as the dose-response relationships underlying these associations remain incompletely characterized.

Bioaccumulation through freshwater food chains represents a plausible, if not yet fully quantified, exposure pathway for human populations reliant on freshwater fisheries for dietary protein. Given that seafood and freshwater fish collectively supply a substantial proportion of global dietary protein intake, even modest per-serving MP burdens could translate into a meaningful cumulative human exposure pathway when aggregated across a population's dietary patterns over time.

Economically, fisheries dependent on contaminated freshwater systems face a dual burden: potential declines in fish health and marketability, and reputational or regulatory risk should MP contamination in fishery products become a consumer or regulatory concern. Freshwater bodies valued for recreation and tourism similarly face economic exposure, as visible plastic contamination—together with the less visible but reputationally significant issue of microplastic pollution—can erode the perceived environmental quality that underpins tourism-dependent local economies. These socioeconomic dimensions carry direct implications for environmental governance: they suggest that MP contamination is not solely an environmental externality to be addressed through conservation policy in isolation, but a cross-sectoral sustainable development challenge implicating water security, food safety, and economic resilience simultaneously—an interpretation consistent with the multidimensional character of the Sustainable Development Goals.

4.6 Effectiveness of Mitigation Strategies

Technological Approaches

Technological mitigation approaches show considerable promise but remain constrained by cost and scalability. Membrane-based technologies—including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis—have been identified as among the most effective advanced treatment options for MP removal, with membrane bioreactors reported to eliminate approximately 99.9% of MP particles in treated effluent. Granular activated carbon and biochar-based filtration represent comparatively low-cost alternatives capable of achieving MP removal efficiencies exceeding 90% in wastewater applications, positioning them as attractive options for resource-constrained treatment contexts. However, the widespread implementation of these technologies is constrained by retrofitting costs for existing treatment infrastructure, energy demands, and the generation of MP-laden sludge that itself requires safe disposal or further treatment, illustrating that technological removal efficiency alone does not resolve the underlying waste management challenge.

Policy and Regulatory Approaches

Policy and regulatory approaches, including plastic reduction legislation, Extended Producer Responsibility (EPR) schemes, and single-use plastic bans—the latter now adopted in more than sixty countries—represent upstream interventions targeting MP generation at its source rather than downstream removal. Such measures carry the theoretical advantage of addressing the pollution problem before particles are generated at all, aligning closely with Circular Economy Theory's emphasis on redesigning production systems to minimize waste generation rather than managing waste after the fact. Their practical effectiveness, however, depends heavily on enforcement capacity and the availability of viable substitute materials, and regulatory fragmentation across jurisdictions continues to limit the scale at which such policies can address what is fundamentally a transboundary contamination pathway.

Community-Based Approaches

Community-based approaches, including public awareness campaigns, citizen science monitoring initiatives, and volunteer clean-up programs, offer a complementary, participatory dimension to formal regulatory and technological interventions. While individually limited in their capacity to address MP contamination at watershed scale, such initiatives contribute meaningfully to public awareness, generate valuable long-term monitoring data

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at low cost, and can build the constituency of public support necessary to sustain more stringent regulatory interventions over time.

Circular Economy Approaches

Circular economy approaches—encompassing recycling innovation, biodegradable material substitution, and systemic plastic-use reduction—represent the most structurally ambitious mitigation category, targeting the linear 'produce-use-dispose' model of plastic consumption that underlies MP generation in the first place. Emerging biological remediation techniques, including microalgae-based bioremediation capable of accumulating and biodegrading MPs in the presence of certain plasticizer compounds, illustrate the innovative directions this research is taking, though most such techniques remain at laboratory or pilot scale rather than field-ready deployment.

Considered together, no single mitigation category is sufficient in isolation: technological approaches address existing contamination but not its generation; policy approaches address generation but depend on enforcement and substitution capacity; community approaches build support and awareness but lack independent capacity to alter contamination at scale; and circular economy approaches offer the most systemic long-term solution but require substantial infrastructure and behavioral transformation to implement. This suggests that effective mitigation of freshwater MP contamination requires an integrated portfolio approach combining all four categories rather than reliance on any single intervention type—a conclusion with direct relevance to the policy recommendations developed in Section 6.

4.7 Theoretical Implications

The findings of this review carry several implications for the theoretical frameworks underpinning environmental science. Pollution Theory's source-pathway-receptor model is broadly supported by the evidence on MP distribution and transport pathways, though the reviewed literature suggests this classical framework requires elaboration to accommodate the interlinked, multi-pathway nature of MP sources—for instance, the finding that WWTP sludge applied to agricultural land creates a secondary source pathway complicates any simple linear source-to-receptor model.

Ecosystem Theory finds strong support in the consistency of sub-lethal physiological and reproductive effects documented across trophic levels, reinforcing the theory's core proposition that stressors introduced at one trophic level propagate, in modified form, through interconnected biological communities. The present synthesis extends this application by proposing that MP-induced stress operates as a diffuse, chronic perturbation rather than an acute, easily attributable disturbance, a distinction with implications for how ecosystem resilience to MP contamination should be conceptualized and measured.

Environmental Systems Theory is supported by the review's ecosystem-level findings regarding sediment biogeochemistry, nutrient cycling, and habitat structure, which collectively illustrate that MP contamination operates across, rather than within, the conventional disciplinary boundaries separating hydrology, toxicology, and biogeochemistry. This reinforces the theory's central contention that freshwater systems must be understood as integrated systems rather than as a collection of independently analyzable compartments.

Circular Economy Theory receives support from the review's mitigation findings, particularly the observation that upstream, redesign-oriented interventions offer the most structurally durable path to reducing MP generation, in contrast to downstream removal technologies that address symptoms rather than causes. At the same time, the practical implementation gaps identified in the mitigation literature suggest that circular economy theory, as currently applied to plastics, may understate the infrastructural and behavioral transition costs involved in shifting from linear to circular production systems—an area where the theory could be usefully extended through closer engagement with implementation science and behavioral economics.

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Collectively, this review contributes to environmental science knowledge by demonstrating that no single theoretical framework fully captures the multi-scalar nature of freshwater MP contamination; rather, an integrated theoretical approach—drawing on pollution, ecosystem, systems, and circular economy perspectives simultaneously—is necessary to adequately explain both the occurrence and the management of this contamination pathway.

4.8 Research Gaps and Future Research Directions

Geographic Gaps

Geographically, the reviewed literature is heavily concentrated in industrialized regions and specific countries with strong research infrastructure, particularly China, the United States, and parts of Europe, while freshwater systems in much of Africa, South America, and parts of Asia remain comparatively understudied despite facing similar or greater plastic waste management pressures. Groundwater and subsurface systems represent a further pronounced geographic and compartmental gap across all regions.

Methodological Gaps

Methodologically, the absence of standardized sampling, extraction, and particle-identification protocols continues to constrain cross-study comparability, a limitation explicitly identified across multiple systematic reviews synthesized in this study. Laboratory-based, short-term exposure studies substantially outnumber field-based, mesocosm, or long-term monitoring studies capable of capturing chronic, ecosystem-scale effects under realistic multi-stressor conditions.

Theoretical Gaps

Theoretically, few studies explicitly integrate ecological and circular-economy perspectives within a single analytical framework, and the potential of emerging computational and artificial intelligence-based approaches for large-scale MP characterization and predictive modeling remains substantially underexplored relative to its apparent promise.

Emerging Research Priorities

Emerging research priorities identified across the synthesized literature include: the development of harmonized, internationally standardized MP monitoring protocols and open-source datasets; expanded field-based and longitudinal studies capturing chronic, ecosystem-level effects; quantitative human health risk assessment moving beyond hazard identification; source-apportionment studies capable of disentangling the relative contribution of concurrent point and diffuse sources within specific watersheds; and rigorous, field-scale evaluation of mitigation technology effectiveness beyond laboratory or pilot conditions. Future research should prioritize underrepresented geographic contexts, particularly tropical, archipelagic, and developing-region freshwater systems, alongside continued investment in analytical method standardization to enable meaningful cross-study and cross-regional synthesis.

5. CONCLUSION

This systematic literature review has synthesized peer-reviewed evidence published between 2020 and 2025 on the distribution, ecological impacts, and mitigation strategies of microplastic contamination in freshwater ecosystems. Several converging patterns emerge from this synthesis. Regarding distribution, microplastics are pervasive across all major freshwater compartments—rivers, lakes, reservoirs, and wetlands—with concentrations most strongly associated with proximity to urban, industrial, and agricultural activity, while groundwater systems remain comparatively understudied despite emerging evidence of subsurface contamination. Regarding sources and transport pathways, the evidence indicates that freshwater microplastic loading results from the concurrent operation of point sources, principally wastewater treatment plant effluent, and diffuse sources, including urban and agricultural runoff, atmospheric deposition, and tire wear particles, with hydrological connectivity mediating the efficiency of pollutant transport into receiving waters. Regarding ecological impacts, the reviewed literature documents consistent, if often sub-lethal, physiological, behavioral, and reproductive effects across trophic levels, from zooplankton through macroinvertebrates to fish, with plausible but less directly evidenced implications for community-level biodiversity and ecosystem resilience. Regarding mitigation, no single strategy category—technological, regulatory, community-based, or circular economy-oriented—is independently sufficient, and the evidence points toward the need for integrated, multi-pronged intervention portfolios.

In direct response to the study's guiding research questions: distribution patterns are shaped primarily by urban proximity, hydrological retention characteristics, and land-use intensity, with lentic systems and wetlands acting as significant accumulation zones; principal sources and transport pathways operate through both continuous point-source discharge and episodic, precipitation-driven diffuse pathways, often interlinked through mechanisms such as sludge application; ecological impacts manifest as consistent oxidative stress, reproductive impairment, and behavioral disruption across freshwater taxa, with plausible cumulative implications for ecosystem-level functioning; human health and socioeconomic implications, while not yet fully quantified in dose-response terms, are substantial enough to implicate drinking water security, fishery-dependent economies, and public health governance; and effective mitigation requires the coordinated application of technological, regulatory, community, and circular-economy interventions rather than reliance on any single approach.

On the basis of this synthesized evidence, several major conclusions can be drawn. First, freshwater ecosystems constitute a distinct and consequential compartment in the global microplastic pollution cycle, functioning simultaneously as transport conduits and long-term accumulation sinks, and therefore warrant dedicated research and policy attention independent of the marine-focused microplastic literature that has historically dominated the field. Second, the persistence of methodological heterogeneity across the reviewed studies represents a genuine scientific limitation that constrains confident cross-regional comparison and, by extension, evidence-based policy prioritization. Third, while ecological harm from microplastic exposure is well-documented at the sub-lethal, individual-organism level, translating this evidence into confident ecosystem-scale and human-health risk assessments remains an active scientific frontier rather than a settled matter. Fourth, mitigation of freshwater microplastic contamination is best understood as a systems-level governance challenge rather than a purely technical or purely regulatory problem, requiring coordinated action across water treatment infrastructure, plastic production and design, and community engagement simultaneously.

In final synthesis, freshwater microplastic contamination represents a genuinely cross-cutting environmental challenge that intersects ecological integrity, public health, food security, and economic resilience within a single contamination pathway. Its diffuse, chronic, and multi-source character means that no single actor, technology, or policy instrument can adequately address it in isolation. The evidence reviewed here underscores the necessity of integrated management approaches that combine upstream source reduction, improved treatment infrastructure, harmonized scientific monitoring, and cross-sectoral governance coordination. As global plastic production continues its upward trajectory, the freshwater systems that supply drinking water, sustain biodiversity, and underpin food security for billions of people will remain at the frontline of this contamination challenge, making continued, methodologically rigorous research and coordinated management action not merely scientifically desirable but practically urgent.

6. RECOMMENDATIONS

For Policymakers

- Enact or strengthen legislative measures restricting single-use plastics and mandating Extended Producer Responsibility (EPR) schemes that place the cost of end-of-life plastic management on producers rather than the public sector.
- Establish legally binding microplastic discharge standards for wastewater treatment plants and industrial facilities discharging into freshwater bodies.

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- Develop or adopt harmonized national monitoring frameworks aligned with emerging international protocols to enable consistent, comparable microplastic contamination reporting across jurisdictions.
- Integrate freshwater microplastic considerations explicitly into national water security, food safety, and public health policy frameworks rather than treating it solely as an environmental issue.

For Environmental Agencies

- Establish long-term, systematic freshwater microplastic monitoring programs covering rivers, lakes, reservoirs, wetlands, and groundwater within jurisdictional watersheds.
- Prioritize pollution control measures targeting the highest-contributing point sources identified through local source-apportionment studies, particularly wastewater treatment plant effluent.
- Adopt integrated watershed management approaches that address microplastic sources holistically across urban, agricultural, and industrial land uses rather than through isolated, single-source interventions.
- Invest in capacity building for standardized microplastic sampling and analytical methods among environmental monitoring personnel.

For Industry

- Adopt sustainable production practices that reduce reliance on virgin plastic inputs, including expanded use of recycled and, where viable, biodegradable materials.
- Implement pre-production pellet containment measures to prevent industrial plastic loss into waterways.
- Redesign products and packaging to minimize microfiber shedding and microplastic generation across the product lifecycle, particularly in textile manufacturing.
- Improve on-site wastewater pretreatment to reduce microplastic loading prior to discharge into municipal treatment systems.

For Communities

- Support and participate in public awareness campaigns highlighting the sources and impacts of microplastic pollution in local freshwater systems.
- Adopt improved waste segregation practices at the household level to reduce plastic leakage into waterways via inadequate solid waste management.
- Participate in community-based clean-up initiatives and citizen science monitoring programs that both reduce visible plastic debris and contribute valuable long-term contamination data.
- Advocate for local policy measures, such as municipal single-use plastic restrictions, that reduce community-level plastic consumption.

For Researchers

- Conduct longitudinal, field-based studies capable of capturing chronic, ecosystem-scale effects of microplastic exposure beyond short-term laboratory experiments.
- Undertake controlled experimental investigations examining the combined and interactive effects of microplastics with co-occurring pollutants, including heavy metals and persistent organic pollutants.
- Conduct comparative regional studies extending microplastic research into currently underrepresented geographic contexts, including tropical, archipelagic, and developing-region freshwater systems.

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- Develop and adopt standardized monitoring methodologies, including harmonized sampling protocols and size-detection thresholds, to enable robust cross-study and cross-regional data comparison and meta-analysis.

7. REFERENCES

Acarer, S. (2023). A review of microplastic removal from water and wastewater by membrane technologies. Water Science & Technology, 88(1), 199–219. https://doi.org/10.2166/wst.2023.186

Ahmed, A. S., Billah, M. M., Ali, M. M., Bhuiyan, M. K. A., Guo, L., Mohinuzzaman, M., & Cai, W. (2023). Microplastics in aquatic environments: A comprehensive review of toxicity, removal, and remediation strategies. Science of the Total Environment, 876, 162414. https://doi.org/10.1016/j.scitotenv.2023.162414

Ahmed, M. B., Rahman, M. S., Alom, J., Hasan, M. S., Johir, M. A. H., Mondal, M. I. H., Lee, D. Y., Park, J., Zhou, J. L., & Yoon, M. H. (2021). Microplastic particles in the aquatic environment: A systematic review. Science of the Total Environment, 775, 145793. https://doi.org/10.1016/j.scitotenv.2021.145793

Al Mamun, A., Prasetya, T. A. E., Dewi, I. R., & Ahmad, M. (2023). Microplastics in human food chains: Food becoming a threat to health safety. Science of the Total Environment, 858, 159834. https://doi.org/10.1016/j.scitotenv.2022.159834

Al-Zawaidah, H., Ravazzolo, D., & Friedrich, H. (2021). Macroplastics in rivers: Present knowledge, issues and challenges. Environmental Science: Processes & Impacts, 23(4), 535–552. https://doi.org/10.1039/D0EM00517G

Alijagic, A., Suljević, D., Fočak, M., Sulejmanović, J., Šehović, E., Särndahl, E., & Engwall, M. (2024). The triple exposure nexus of microplastic particles, plastic-associated chemicals, and environmental pollutants from a human health perspective. Environment International, 180, 108736. https://doi.org/10.1016/j.envint.2024.108736

Banaee, M., Multisanti, C. R., Impellitteri, F., Piccione, G., & Faggio, C. (2024). Environmental toxicology of microplastic particles on fish: A review. Comparative Biochemistry and Physiology, Part C: Toxicology & Pharmacology, 274, 110042. https://doi.org/10.1016/j.cbpc.2024.110042

Barceló, D., Picó, Y., & Alfarhan, A. H. (2023). Microplastics: Detection in human samples, cell line studies, and health impacts. Environmental Toxicology and Pharmacology, 101, 104204. https://doi.org/10.1016/j.etap.2023.104204

Bhardwaj, L. K., Rath, P., Yadav, P., & Gupta, U. (2024). Microplastic contamination, an emerging threat to the freshwater environment: A systematic review. Environmental Systems Research, 13, 8. https://doi.org/10.1186/s40068-024-00338-7

Bhatt, V., & Chauhan, J. S. (2023). Microplastic in freshwater ecosystem: Bioaccumulation, trophic transfer, and biomagnification. Environmental Science and Pollution Research, 30, 9389–9400. https://doi.org/10.1007/s11356-022-24529-w

Bhutto, S. U. A., & You, X. (2022). Spatial distribution of microplastics in Chinese freshwater ecosystem and impacts on food webs. Environmental Pollution, 293, 118494. https://doi.org/10.1016/j.envpol.2021.118494

Bhuyan, M. S. (2022). Effects of microplastics on fish and in human health. Frontiers in Environmental Science, 10, 827289. https://doi.org/10.3389/fenvs.2022.827289

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Brahney, J., Hills, J., Corbett, A., Kelly, P., & Prather, K. A. (2021). Constraining the atmospheric limb of the plastic cycle. Proceedings of the National Academy of Sciences, 118(16), e2020719118. https://doi.org/10.1073/pnas.2020719118

Cha, J., Lee, J. Y., & Chia, R. W. (2023). Microplastics contamination and characteristics of agricultural groundwater in Haean Basin of Korea. Science of the Total Environment, 864, 161027. https://doi.org/10.1016/j.scitotenv.2022.161027

Dai, J., Liu, P., Wang, C., Li, H., Qiang, H., & Yang, Z. (2023). Which factors mainly drive the photoaging of microplastics in freshwater? Science of the Total Environment, 858, 159845. https://doi.org/10.1016/j.scitotenv.2022.159845

Danopoulos, E., Twiddy, M., West, R., & Rotchell, J. M. (2022). A rapid review and meta-regression analyses of the toxicological impacts of microplastic exposure in human cells. Journal of Hazardous Materials, 427, 127861. https://doi.org/10.1016/j.jhazmat.2021.127861

Gao, N., Ning, R., & Deng, X. (2023). Feasibility, challenges, and future prospects of microalgae-based bioremediation technique for removing microplastics from wastewater. Frontiers in Bioengineering and Biotechnology, 11, 1288439. https://doi.org/10.3389/fbioe.2023.1288439

Hasan, M. K., Jahan, I., Suravi, T. I., Al Hasib Imon, M. A., Shopan, J., & Ahammed, G. J. (2025). Heavy metals and microplastics derived from laboratory effluents enhance toxicological risks to the ecosystems of canals in Bangladesh. Environmental Science and Pollution Research, 32, 949–962. https://doi.org/10.1007/s11356-024-35758-6

He, S., Tong, J., Xiong, W., Xiang, Y., Peng, H., & Wang, W. (2023). Microplastics influence the fate of antibiotics in freshwater environments: Biofilm formation and its effect on adsorption behavior. Journal of Hazardous Materials, 442, 130078.

Huang, W., Song, B., Liang, J., Niu, Q., Zeng, G., Shen, M., & Zhang, Y. (2021). Microplastics and associated contaminants in the aquatic environment: A review on their ecotoxicological effects, trophic transfer, and potential impacts to human health. Journal of Hazardous Materials, 405, 124187. https://doi.org/10.1016/j.jhazmat.2020.124187

Jamal, N. T., Islam, M. R. U., Sultana, S., Banik, P., Nur, A. A. U., Albeshr, M. F., & Hossain, M. B. (2025). Microplastic contamination in some popular seafood fish species from the northern Bay of Bengal and possible consumer risk assessment. Food Control, 171, 111114. https://doi.org/10.1016/j.foodcont.2024.111114

Jenner, L. C., Rotchell, J. M., Bennett, R. T., Cowen, M., Tentzeris, V., & Sadofsky, L. R. (2022). Detection of microplastics in human lung tissue using μFTIR spectroscopy. Science of the Total Environment, 831, 154907. https://doi.org/10.1016/j.scitotenv.2022.154907

Kole, P. J., Löhr, A. J., Van Belleghem, F. G. A. J., & Ragas, A. M. J. (2017). Wear and tear of tyres: A stealthy source of microplastics in the environment. International Journal of Environmental Research and Public Health, 14(10), 1265. https://doi.org/10.3390/ijerph14101265

Leslie, H. A., van Velzen, M. J., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. Environment International, 163, 107199. https://doi.org/10.1016/j.envint.2022.107199

Liu, Z., & You, X. Y. (2023). Recent progress of microplastic toxicity on human exposure based on in vitro and in vivo studies. Science of the Total Environment, 903, 166766. https://doi.org/10.1016/j.scitotenv.2023.166766

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Ma, Y. B., Xie, Z. Y., Hamid, N., Tang, Q. P., Deng, J. Y., Luo, L., & Pei, D. S. (2023). Recent advances in micro(nano)plastics in the environment: Distribution, health risks, challenges and future prospects. Aquatic Toxicology, 261, 106597. https://doi.org/10.1016/j.aquatox.2023.106597

Mehinto, A. C., Coffin, S., Koelmans, A. A., Brander, S. M., Wagner, M., Thornton Hampton, L. M., & Rochman, C. M. (2022). Risk-based management framework for microplastics in aquatic ecosystems. Microplastics and Nanoplastics, 2, 17. https://doi.org/10.1186/s43591-022-00033-3

Mithun, M. H., Shaikat, M. F., Sazzad, S. A., Billah, M., Salehin, S., Foysal, A. M., Jubayer, A., Islam, R., Anzum, A., & Sunny, A. R. (2024). Microplastics in aquatic ecosystems: Sources, impacts, and challenges for biodiversity, food security, and human health—A meta analysis. Integrative Biomedical Research (Journal of Angiotherapy), 8, 1–2.

Prata, J. C., Silva, C. J., Serpa, D., Soares, A. M., Gravato, C., & Silva, A. L. P. (2023). Mechanisms influencing the impact of microplastics on freshwater benthic invertebrates: Uptake dynamics and adverse effects on Chironomus riparius. Science of the Total Environment, 859, 160426. https://doi.org/10.1016/j.scitotenv.2022.160426

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M. C. A., Baiocco, F., & Draghi, S. (2021). Plasticenta: First evidence of microplastics in human placenta. Environment International, 146, 106274. https://doi.org/10.1016/j.envint.2020.106274

Range, D., Scherer, C., Stock, F., Ternes, T. A., & Hoffmann, T. O. (2023). Hydro-geomorphic perspectives on microplastic distribution in freshwater river systems: A critical review. Water Research, 245, 120567.

Su, X., Yuan, J., Lu, Z., Xu, J., & He, Y. (2022). An enlarging ecological risk: Review on co-occurrence and migration of microplastics and microplastic-carrying organic pollutants in natural and constructed wetlands. Science of the Total Environment, 837, 155772. https://doi.org/10.1016/j.scitotenv.2022.155772

Subaramaniyam, U., Allimuthu, R. S., Vappu, S., Ramalingam, D., Balan, R., Paital, B., Panda, N., Rath, P. K., Ramalingam, N., & Sahoo, D. K. (2023). Effects of microplastics, pesticides and nano-materials on fish health, oxidative stress and antioxidant defense mechanism. Frontiers in Physiology, 14, 1217666. https://doi.org/10.3389/fphys.2023.1217666

Sunny, A. R., Sazzad, S. A., Islam, M. A., Mithun, M. H., Hussain, M., Raposo, A., & Bhuiyan, M. K. A. (2025). Microplastics in aquatic ecosystems: A global review of distribution, ecotoxicological impacts, and human health risks. Water, 17(12), 1741. https://doi.org/10.3390/w17121741

Vethaak, A. D., & Legler, J. (2021). Microplastics and human health: Knowledge gaps should be addressed to ascertain the health risks of microplastics. Science, 371(6530), 672–674. https://doi.org/10.1126/science.abe5041

Zhang, P., Liu, Y., Zhang, L., Xu, M., Gao, L., & Zhao, B. (2022). The interaction of micro/nano plastics and the environment: Effects of ecological corona on the toxicity to aquatic organisms. Ecotoxicology and Environmental Safety, 243, 113997. https://doi.org/10.1016/j.ecoenv.2022.113997

Zhao, B., Richardson, R. E., & You, F. (2024). Microplastics monitoring in freshwater systems: A review of global efforts, knowledge gaps, and research priorities. Journal of Hazardous Materials, 477, 135329. https://doi.org/10.1016/j.jhazmat.2024.135329

Ziajahromi, S., Kumar, A., Neale, P. A., & Leusch, F. D. L. (2017). Impact of microplastic beads and fibers on waterflea (Ceriodaphnia dubia) survival, growth, and reproduction: Implications of single and mixture

Volume 1 Issue 2 Pages 106-129

exposures. Environmental Science & Technology, 51(22), 13397–13406. https://doi.org/10.1021/acs.est.7b03574

Zuri, G., Karanasiou, A., & Lacorte, S. (2023). Human biomonitoring of microplastics and health implications: A review. Environmental Research, 237, 116966. https://doi.org/10.1016/j.envres.2023.116966