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Microplastic pollution in lakes: Sources, impact, and solutions

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Abstract

Microplastic pollution has become a critical environmental concern in freshwater ecosystems, especially lakes. These particles, less than 5 mm in size, originate from various sources including urban runoff, wastewater, atmospheric deposition, recreational use, and the degradation of larger plastic debris. Once in lakes, microplastics can be ingested by aquatic organisms, leading to physical and toxicological impacts, bioaccumulation, and potential transfer to humans through drinking water and seafood. This paper provides a comprehensive overview of the sources and pathways of microplastic contamination in lakes, their environmental and ecological impacts, and potential mitigation strategies. Proposed solutions include source control, stormwater and wastewater management, advanced purification technologies, regulatory action, and public engagement. A multifaceted, collaborative approach is essential to prevent and remediate microplastic pollution in freshwater environments.

Keywords: Microplastics; Lakes; Pollution Sources; Ecological Impact; Microplastic Pollution; Environmental Policy

1. Introduction

Microplastic pollution has emerged as one of the most pressing environmental challenges of the 21st century. These plastic fragments, defined as particles less than 5 millimeters in diameter, are generated either as small particles (primary microplastics) or through the breakdown of larger plastic debris (secondary microplastics) [1]. Once introduced into the environment, microplastics are nearly impossible to remove completely due to their minuscule size, chemical stability, and ability to disperse widely across air, water, and soil [2]. Originally identified as a threat primarily to marine environments, microplastics have now been detected in freshwater ecosystems including rivers, streams, and notably, lakes raising alarm among scientists, environmentalists, and public health officials alike [3,4].

Lakes are particularly vulnerable to microplastic pollution for several reasons. First, they often serve as endpoints for a range of human activities, including urban runoff, industrial discharge, recreational use, and wastewater effluent, all of which contribute to plastic waste [5]. Second, lakes, unlike oceans, are typically closed or semi-closed systems with limited water exchange, which means that pollutants, including microplastics, can accumulate over time [6]. Many lakes also serve as critical sources of drinking water and are central to regional biodiversity, making the consequences of contamination more direct and potentially hazardous to human health and aquatic ecosystems [7].

Recent studies have found microplastics not only in lake surface waters, but also in sediments, aquatic organisms, and even in remote, high-altitude freshwater lakes, suggesting that no environment is immune to plastic infiltration [8,9].

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The global nature of this pollution underscores the need for a better understanding of its origin, movement, and consequences. Moreover, the ingestion of microplastics by aquatic organisms can lead to a cascade of biological effects, disrupting food webs and ecological functions [10,11]. Concerns are also mounting about the potential transfer of microplastics and their associated toxic chemicals to humans through the consumption of contaminated fish and drinking water [12].

Despite growing awareness of microplastic pollution in marine contexts, freshwater bodies—especially lakes—remain relatively understudied and under-regulated in global plastic pollution frameworks [13]. This knowledge gap hinders the development of effective strategies for prevention, monitoring, and mitigation. Addressing microplastic pollution in lakes requires an interdisciplinary approach that incorporates scientific research, technological innovation, regulatory action, and public participation.

This article aims to provide a comprehensive overview of microplastic pollution in lakes. It begins by identifying the key sources and pathways through which microplastics enter lake systems. It then examines the ecological and environmental impacts on lake ecosystems and aquatic life. Finally, it outlines a range of solutions—from policy reforms and technological interventions to community-based efforts—that can help curb the growing threat of microplastics in freshwater environments. By focusing on lakes, this discussion emphasizes the urgent need for targeted action to protect these vital ecosystems from an emerging and pervasive pollutant.

2. Sources of Microplastic Pollution in Lakes

Microplastics enter lake environments through a diverse and dynamic set of pathways that can be broadly categorized as either direct or indirect. These inputs originate from both human activities and environmental processes and are influenced by regional variables such as population density, land use, and the intensity of industrial and urban development (Figure 1). Microplastics are generally classified into two main types based on their origin:

- Primary microplastics are deliberately manufactured in microscopic form, typically less than 5 mm in diameter. These include microbeads found in personal care products, cleaning agents, and industrial abrasives, as well as pre-production plastic pellets (also known as nurdles) used in the plastics industry.
- Secondary microplastics result from the fragmentation of larger plastic materials such as bottles, bags, fishing gear, and packaging. These plastics degrade over time through physical abrasion, UV-induced photodegradation, and chemical or microbial breakdown, releasing microscopic plastic fragments into the aquatic environment [1,14].

The relative contribution of each source is context-specific. For instance, urban and industrial regions may release high levels of primary microplastics through wastewater effluent, while rural or recreational lake environments may see higher contributions of secondary microplastics from littering and environmental weathering of discarded plastic items. Understanding these distinctions is critical for identifying pollution hotspots and designing effective mitigation strategies.

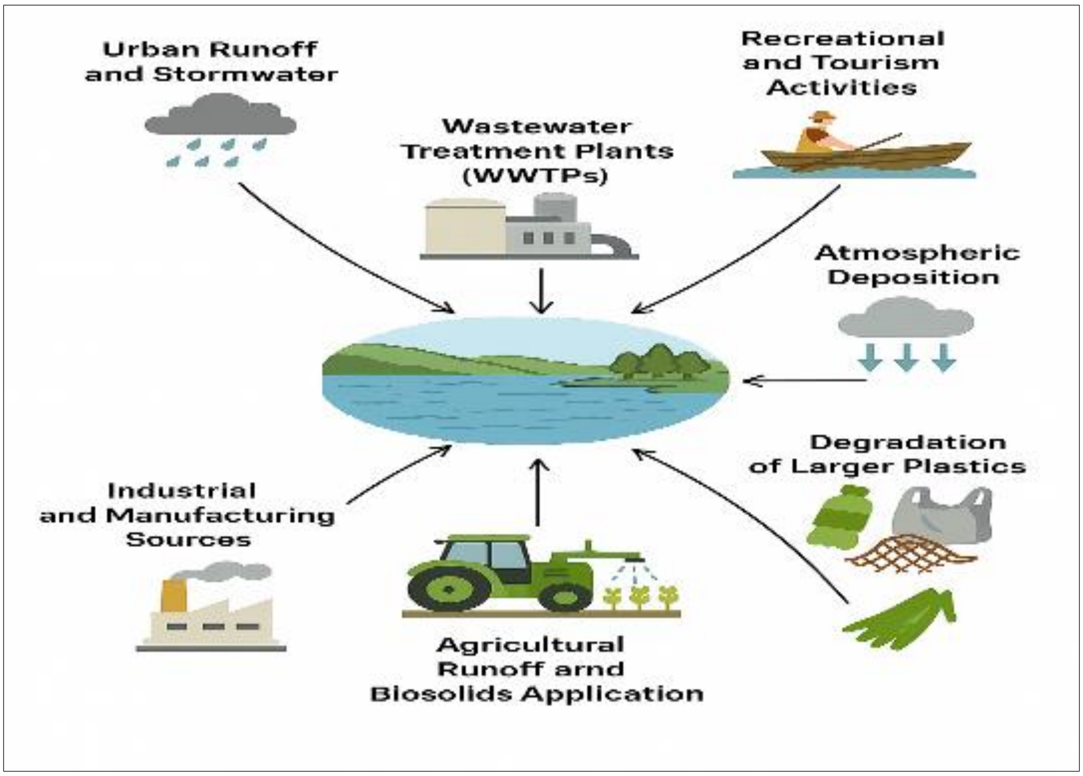

Figure 1 Sources of Microplastic Pollution in Lakes

2.1. Urban Runoff and Stormwater

Urban runoff and stormwater drainage are major non-point sources of microplastics in lake environments. As rainwater flows over impermeable surfaces like roads, sidewalks, and rooftops, it accumulates microplastics from various materials, including

- Synthetic textile fibers from clothes and carpets,
- Tire wear particles composed of synthetic rubber,
- Plastic litter such as fragments from packaging, wrappers, and cigarette butts.

This contaminated water is often directed into storm drains that discharge untreated into lakes or tributaries. Research in Chinese urban lakes demonstrated that stormwater drains carried substantial loads of tire-derived microplastics and synthetic fibers, particularly after heavy rainfall events [15]. Globally, tire wear particles alone account for 5–10% of total microplastic pollution in aquatic environments [16].

2.2. Wastewater Treatment Plants (WWTPs)

WWTPs are important point sources of microplastics, particularly in urbanized watersheds. Although tertiary treatment facilities can remove 95–99% of microplastics, the sheer volume of water processed means that billions of particles may still be released daily [17].

The primary contributors include

- Synthetic microfibers, released during laundering of polyester, nylon, and acrylic fabrics,
- Microbeads, once common in facial scrubs and toothpaste (now banned in many countries),
- Industrial microplastic waste, from manufacturing and commercial cleaning operations.

Browne et al. (2011) found that microfibers dominate effluents from WWTPs and can persist in freshwater ecosystems for years, accumulating in sediments and biota [18]. Sludge removed during treatment also contains high microplastic concentrations and may re-enter the environment when used as agricultural fertilizer.

2.3. Recreational and Tourism Activities

Recreational use of lakes such as boating, fishing, camping, and swimming can directly introduce plastics into the water. Common sources include

- Fishing lines, nets, and bait containers,
- Single-use plastics, such as food wrappers, beverage bottles, and cutlery,
- Polyethylene foam from boat parts and docks.

With constant exposure to UV radiation, wave action, and microbial activity, these items gradually degrade into secondary microplastics [19]. For heavily trafficked lakes, especially during peak tourism seasons, local plastic input can spike dramatically, exacerbating pollution levels in shallow and nearshore areas.

2.4. Atmospheric Deposition

Airborne microplastics, primarily synthetic fibers and fragmented particles, can be transported long distances and deposited onto lake surfaces or surrounding catchment areas through rainfall and dry fallout. This pathway contributes even to remote or alpine lakes that are far from direct anthropogenic sources.

Allen et al. (2019) found that microplastics are deposited at rates of 365 particles/m^2/day in mountainous regions of France, highlighting the significance of long-range atmospheric transport [8]. Similarly, Free et al. (2014) reported microplastic contamination in lakes located in U.S. national parks, attributing it largely to atmospheric deposition [6].

Sources of airborne microplastics include

- Clothing fibers released during drying or wear,
- Construction dust from insulation, paint, and composite materials,
- Industrial emissions, such as those from plastic manufacturing plants.

2.5. Agricultural Runoff and Biosolids Application

Agricultural practices contribute microplastics to lakes via

- Surface runoff, especially from fields treated with plastic mulch or containing plastic waste,
- Biosolids application, where treated sewage sludge is used as fertilizer on farmland.

Biosolids are known to contain high concentrations of microfibers, microbeads, and synthetic particles originating from urban WWTPs [20]. During rainfall events or irrigation, these particles can be mobilized and transported into nearby lakes and streams. Over time, microplastic accumulation in agricultural soils may also result in their leaching into groundwater and adjacent surface water bodies.

2.6. Industrial and Manufacturing Sources

Industrial sectors involved in plastic production, recycling, transportation, and packaging are direct contributors to microplastic contamination. Key sources include

- Pre-production plastic pellets (nurdles), often spilled during transport or storage,
- Shredded plastics from recycling operations,
- Wastewater discharge from polymer processing plants.

Yonkos et al. (2014) observed significantly elevated microplastic concentrations in rivers and lakes located downstream of industrial zones, particularly where plastic recycling or packaging facilities were clustered [21]. Inadequate containment and weak regulations can result in persistent, localized microplastic hotspots in sediments and biota.

2.7. Degradation of Larger Plastics

Another significant pathway for microplastics entering lake ecosystems is the environmental degradation of larger plastic debris. Items such as plastic bags, bottles, containers, packaging, fishing nets, and other consumer or industrial plastic waste often end up in or near lakes. Over time, these larger plastic materials undergo fragmentation due to photodegradation, mechanical abrasion, and chemical weathering.

Photodegradation occurs when ultraviolet (UV) radiation from sunlight weakens plastic polymers, making them brittle and prone to cracking. Mechanical processes, such as wave action, sediment abrasion, and seasonal freeze-thaw cycles, further break down these weakened plastics into smaller pieces. In combination, these forces can generate microplastic particles that persist in the aquatic environment for decades [1].

Furthermore, biofouling where organisms like algae and bacteria colonize the plastic surfaces—can alter the density of plastic debris, causing them to sink and contribute to benthic microplastic pollution. This process expands the range of ecological compartments impacted, including sediments and bottom-dwelling species [22].

This pathway is particularly concerning because even remote lakes, far from urban sources, can accumulate microplastics through legacy plastic waste introduced years or decades ago. The persistence of plastics and their continued fragmentation highlight the importance of addressing plastic pollution at the source and removing existing debris from the environment.

3. Impact of Microplastic Pollution in Lakes

The infiltration of microplastics into lake ecosystems has both immediate and long-term consequences, affecting aquatic organisms, ecosystem functionality, and potentially human health. Microplastics interact with biological and physical processes in complex ways, exacerbating existing environmental pressures such as eutrophication, invasive species, and climate change.

3.1. Impact on Aquatic Organisms

Freshwater organisms across trophic levels ranging from zooplankton and insect larvae to mollusks, amphibians, and fish have been shown to ingest microplastics [3]. The effects on these organisms include

- Physical blockage of the digestive tract, leading to starvation,
- Reduced feeding and energy uptake, due to a false sense of satiation,
- Stunted growth, reproductive dysfunction, and altered behaviors.

For example, Oehlmann et al. (2009) found that invertebrates exposed to microplastics experienced hormonal disruption and reproductive anomalies, indicating endocrine interference [23]. Lusher et al. (2013) observed altered swimming behaviors and growth reductions in fish exposed to polyethylene microplastics, suggesting both physiological and behavioral stress responses. Microplastic ingestion is not limited to direct consumption particles can also adhere to the gills and skin, causing abrasions and inflammation [10,24].

3.2. Toxicological Effects

Microplastics act as vectors for environmental contaminants, including persistent organic pollutants (POPs) like PCBs, PAHs, and heavy metals, which adsorb onto plastic surfaces due to their hydrophobic properties [25]. Once ingested, these pollutants may desorb in the gut of organisms, potentially leading to internal exposure and toxicity.

Laboratory studies have demonstrated that zebrafish (Danio rerio) exposed to microplastics develop liver inflammation, oxidative stress, and lipid metabolism disorders [11]. Over time, these toxic effects could compromise immune function, fertility, and survival rates, affecting entire aquatic populations. Microplastics may also release additives used in plastic production, such as bisphenol A (BPA) and phthalates, which are known endocrine disruptors.

3.3. Food Chain Contamination

Microplastics pose a risk of bioaccumulation and trophic transfer. Once consumed by plankton or small invertebrates, microplastics can ascend the food chain to predatory fish, birds, and mammals. Studies have found microplastic particles in the gut contents of freshwater fish such as perch and roach [26], raising concerns about bioavailability to humans who consume these fish.

Smith et al. (2018) argue that the potential for human exposure through drinking water, seafood, and even table salt warrants further toxicological and epidemiological studies [12]. Though the full health implications remain uncertain, microplastics have already been detected in human stool samples [27], indicating widespread exposure.

3.4. Habitat and Water Quality Degradation

Microplastics also influence non-biotic components of freshwater systems. They alter the physical and chemical properties of sediments and water columns

- Microplastics in sediment can change porosity and microbial community structure, affecting biogeochemical cycles [28].
- Suspended microplastics reduce light penetration, impeding photosynthesis by submerged plants and phytoplankton [29].
- Particle accumulation in shallow zones can smother benthic habitats, disrupting the lifecycles of invertebrates and spawning grounds for fish.

These changes may reduce biodiversity and impair the resilience of freshwater ecosystems, making them more vulnerable to stressors like invasive species, hypoxia, and climate change-induced temperature fluctuations [3,27].

4. Solutions to Microplastic Pollution in Lakes

Microplastic pollution has emerged as a pressing environmental issue due to its pervasive presence in freshwater, marine, and terrestrial ecosystems. Addressing this multifaceted problem requires a comprehensive approach that combines technological, policy-driven, and behavioral solutions. The following strategies highlight key areas where interventions can effectively mitigate the release, transport, and accumulation of microplastics in the environment.

4.1. Source Control

4.1.1. Reduce plastic production

Reducing the manufacture and use of single-use plastics is a critical step toward controlling microplastic pollution at its source. Governments and industries should prioritize the development and adoption of biodegradable or compostable materials as alternatives. For example, policies like plastic bag bans and restrictions on microbeads have already shown effectiveness in some regions [30,31].

4.1.2. Improve waste management

Enhancing waste collection, separation, and recycling systems can significantly reduce the leakage of plastic waste into the environment. Effective waste management, especially in developing countries, is vital to minimizing plastic entering freshwater systems [32].

4.1.3. Promote sustainable agricultural practices

Agricultural use of plastic, such as polyethylene mulching films, contributes to microplastic contamination in soils and runoff. Encouraging alternatives like biodegradable films or natural mulches, and reducing overall plastic inputs in agriculture, can lower microplastic emissions from this sector [33,34].

4.1.4. Control wastewater discharge

Municipal wastewater treatment plants are known pathways for microplastics entering freshwater environments. Upgrading these facilities with advanced treatment technologies such as tertiary filtration and membrane bioreactors—can increase microplastic retention rates [16,35].

4.2. Prevention of Microplastic Transport

4.2.1. Establish buffer zones

Constructed or natural vegetative buffer strips between land-use areas (e.g., farms and urban zones) and aquatic systems can act as physical filters to trap microplastics in runoff before they reach water bodies (Figure 2). The Interstate Technology and Regulatory Council (ITRC) states that when vegetated strips or riparian buffer areas are placed alongside water bodies; they are highly effective in removing suspended solids including microplastics through settling within the vegetation. Constructed wetlands in a treatment train can achieve microplastic removal rates up to 100% [36]. A University of Mississippi study found that using treated plant-based biochar as a filter in agricultural runoff reduced microplastic content by 86.6–92.6% [37]. Research on highway stormwater showed that bioretention systems with vegetation removed significantly more microplastics (20–100 μm) than non-vegetated sand filters median effluent concentrations dropped from 121 to 26.5 particles per liter [38].

4.2.2. Implement stormwater management

Stormwater drains can carry large amounts of plastic debris directly into lakes and rivers. Incorporating best management practices (BMPs), such as constructed wetlands, retention basins, and litter traps (Figure 3), can significantly reduce microplastic loads in stormwater [39].

Figure 2 Constructed Wetland

Figure 3 Stormwater Interceptor

4.3. Water Purification Technologies

4.3.1. Advanced oxidation, bioremediation, and membrane filtration

A slate of innovative technologies membrane filtration (e.g., ultrafiltration, nanofiltration, reverse osmosis, and membrane bioreactors) offers high microplastic removal efficiencies, often exceeding 90% due to pore-size exclusion [40]. Advanced oxidation processes (photocatalysis, Fenton, ozonation) have shown potential to degrade plastic polymers with reported removal/degradation rates of ~30–95% [41]. Bioremediation, including membrane bioreactors, combines sorption and biodegradation; microbial biofilms have demonstrated partial ingestion and breakdown of microplastics, though conventional systems still leave some residual particle [42].

4.4. Policy and Awareness

4.4.1. Enact stricter regulations

Regulatory frameworks that limit plastic use, enhance recycling mandates, and implement Extended Producer Responsibility (EPR) systems can drive systemic change. Countries that have enforced producer accountability and plastic reduction strategies have demonstrated reductions in plastic leakage [24,29]. In the U.S., multiple states (Maine, California, New York, Oregon, New Jersey) have introduced EPR bills obligating producers to fund recycling infrastructure and phase out non-recyclable packaging showing momentum toward producer accountability [43]. A Pew Charitable Trusts and SYSTEMIQ report projected that global implementation of EPR could reduce ocean plastic pollution by up to 80% by 2040, highlighting its potential for large-scale impact [44].

4.4.2. Increase public awareness

Public education campaigns are essential to reduce littering and increase recycling participation. Awareness of microplastics' impacts on health and ecosystems can foster behavioral changes in consumption and waste disposal habits [1,18]. A pre/post study in Turkey showed that a four-session environmental health program significantly raised ninth-graders' awareness about microplastic pollution (*Microplastic Pollution Awareness Scale*, MPAS) compared to a control group, demonstrating that targeted education can shift knowledge and attitudes significantly [45]. At Sapienza University in Rome, a pilot study found that providing an informative brochure on microplastics significantly increased public health students' concern and knowledge 25% had never heard of microplastics before [46].

5. Conclusion

Microplastic pollution in freshwater ecosystems, particularly lakes, poses a significant and growing environmental threat. This pollution stems from diverse sources, including wastewater effluent, urban and agricultural runoff, atmospheric deposition, recreational activities, and the breakdown of larger plastic debris. Once introduced into lake environments, microplastics can accumulate in sediments, bioaccumulate in aquatic organisms, and ultimately impact ecosystem health and human well-being.

Addressing this challenge requires a comprehensive, multi-faceted approach. Source control through improved waste management, sustainable agriculture, and advanced wastewater treatment is essential. Preventive measures, such as stormwater management and vegetative buffer zones, can significantly reduce microplastic transport into aquatic systems. Technological solutions, including membrane filtration and bioremediation, offer promising avenues for remediation, while policy enforcement and public awareness are crucial for long-term behavioral and systemic change.

Tackling microplastic pollution will require coordinated efforts from policymakers, researchers, industries, and communities to develop and implement practical solutions. By integrating scientific understanding with effective management and education, we can mitigate microplastic pollution and protect the ecological integrity of freshwater systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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