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REVIEW ARTICLE

Microplastics in Aquatic Ecosystems: Sources, Transport Mechanisms, and Ecological Impacts

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Abstract. Microplastics have emerged as one of the most pervasive contaminants in aquatic ecosystems, posing significant environmental and ecological challenges worldwide. These plastic particles, generally smaller than 5 mm, originate from both primary sources, such as industrial microbeads and synthetic pellets, and secondary sources resulting from the degradation of larger plastic debris. Rivers, lakes, estuaries, coastal waters, and marine environments act as major reservoirs and transport pathways, facilitating the widespread distribution of microplastics across diverse ecosystems. Their persistence, buoyancy, and resistance to degradation enable long-distance transport through hydrological processes, atmospheric deposition, and biological interactions. The increasing accumulation of microplastics has raised concerns regarding their impacts on aquatic organisms, biodiversity, food webs, and ecosystem functioning. Numerous studies have demonstrated that microplastics can be ingested by organisms at different trophic levels, causing physical injury, physiological stress, altered feeding behavior, reproductive impairment, and reduced growth. Furthermore, microplastics act as carriers of toxic chemicals, heavy metals, and pathogenic microorganisms, amplifying their ecological risks through bioaccumulation and trophic transfer. Recent advances in analytical techniques, remote sensing, numerical modelling, and artificial intelligence have improved the detection, monitoring, and prediction of microplastic pollution, providing valuable insights into their environmental dynamics. This review summarizes the major sources of microplastics, their transport mechanisms within aquatic environments, and their ecological consequences. It also highlights current monitoring approaches, emerging mitigation strategies, and future research directions aimed at reducing microplastic contamination and protecting aquatic ecosystems.

Keywords: Microplastics, aquatic ecosystems, plastic pollution, transport mechanisms, ecological impacts, marine environment, freshwater systems.

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1. Introduction

Plastic materials have become indispensable in modern society because of their durability, lightweight nature, versatility, and low production cost. Global plastic production has increased exponentially over the past several decades, supporting applications in packaging, construction, agriculture, healthcare, transportation, and consumer products. However, inadequate waste management, excessive consumption of single-use plastics, and improper disposal practices have resulted in the widespread accumulation of plastic debris in natural environments. As larger plastic materials undergo fragmentation through physical, chemical, and biological weathering processes, they generate microscopic plastic particles commonly known as microplastics, which have emerged as contaminants of growing environmental concern [1–3].

Microplastics are generally defined as plastic particles measuring less than 5 mm in diameter and are broadly categorized into primary and secondary microplastics. Primary microplastics are intentionally manufactured at microscopic sizes for industrial applications, cosmetics, pharmaceuticals, and personal care products, whereas secondary microplastics originate from the degradation of larger plastic items exposed to ultraviolet radiation, mechanical abrasion, temperature fluctuations, and microbial activity. Because these particles are highly resistant to natural degradation, they persist in aquatic environments for extended periods, allowing continuous accumulation within freshwater and marine ecosystems [4,5].

Aquatic ecosystems serve as the ultimate recipients of a substantial proportion of global plastic waste. Rivers transport plastic debris from urban, industrial, and agricultural regions toward estuaries and oceans, while lakes, reservoirs, wetlands, and coastal environments function as temporary storage zones where microplastics accumulate within surface waters, sediments, and biological communities. Ocean currents, tides, wind-driven circulation, and seasonal hydrological variations further redistribute microplastics over long distances, resulting in their detection even in remote regions such as polar seas and deep-ocean sediments [6–8].

The environmental significance of microplastics extends beyond their widespread distribution. Their small size allows them to be readily ingested by plankton, benthic invertebrates, mollusks, crustaceans, fish, seabirds, marine mammals, and other aquatic organisms. Once ingested, microplastics may obstruct digestive systems, reduce feeding efficiency, alter energy allocation, impair reproduction, and induce physiological stress. In addition, plastic particles possess hydrophobic surfaces capable of adsorbing persistent organic pollutants, heavy metals, antibiotics, and pathogenic microorganisms, thereby acting as vectors that facilitate the transport of hazardous substances throughout aquatic food webs [9–11].

The complexity of microplastic pollution has stimulated considerable interdisciplinary research involving environmental science, hydrology, ecology, chemistry, materials science, and computational modelling. Recent technological developments have substantially improved the ability to detect and characterize microplastics using spectroscopic techniques, microscopy, machine learning algorithms, and numerical transport models. Geographic Information Systems (GIS), remote sensing technologies, and hydrodynamic simulations are increasingly employed to investigate the spatial distribution and transport pathways of microplastics across river basins, estuaries, and coastal environments, providing valuable information for environmental management and pollution mitigation.

Despite growing scientific understanding, several uncertainties remain regarding the long-term environmental fate of microplastics, their interactions with emerging contaminants, and their cumulative ecological effects under changing climatic conditions. Differences in particle size, polymer composition, density, morphology, and environmental conditions influence transport behavior and biological interactions, making comprehensive risk assessment particularly challenging. Furthermore, the increasing production of plastic materials suggests that microplastic contamination will continue to intensify unless effective waste management strategies, regulatory policies, and sustainable material alternatives are widely implemented [12–15].

This review provides a comprehensive assessment of microplastic pollution in aquatic ecosystems by examining their sources, transport mechanisms, environmental distribution, and ecological impacts. The paper also reviews current monitoring techniques, discusses emerging mitigation strategies, identifies major research gaps, and outlines future directions for improving scientific understanding and environmental management of microplastic contamination.

attacks, and autonomously adapt defensive responses [8].

Adaptive cybersecurity is becoming increasingly important as cyber threats evolve in complexity and frequency. Unlike static security mechanisms, adaptive cybersecurity systems continuously monitor network behavior, identify emerging attack patterns, evaluate system vulnerabilities, and dynamically modify defense strategies in response to changing threat conditions [9]. Such capabilities are particularly valuable in critical infrastructure environments where uninterrupted operation, low latency, and high reliability are essential.

The integration of neuromorphic intelligence with Digital Twin architectures also supports sustainable cybersecurity. Event-driven processing significantly reduces power consumption compared with conventional deep learning systems, making neuromorphic hardware suitable for edge computing, autonomous sensors, and battery-powered devices deployed across smart infrastructure [10]. Combined with real-time Digital Twin simulations, these energy-efficient architectures provide scalable cybersecurity solutions capable of protecting complex distributed systems while minimizing computational costs.

Understanding the principles of neuromorphic Digital Twin architectures is therefore essential for developing the next generation of intelligent cybersecurity systems. The combination of brain-inspired computation, virtual system modeling, adaptive learning, and real-time threat analysis provides a comprehensive framework for enhancing cyber resilience across smart infrastructure.

This paper reviews the fundamental concepts of neuromorphic computing and Digital Twin architectures for adaptive cybersecurity. It discusses neuromorphic principles, Digital Twin technologies, adaptive threat detection, enabling computational frameworks, and the role of these integrated systems in securing future smart infrastructure against evolving cyber threats.

2. Literature Review

2.1. Classification and Characteristics of Microplastics

Microplastics exhibit considerable diversity in terms of origin, size, morphology, chemical composition, density, and surface characteristics, all of which influence their environmental behavior and ecological impacts. Based on their origin, microplastics are classified into primary and secondary microplastics. Primary microplastics are intentionally manufactured at microscopic dimensions for applications such as cosmetic exfoliants, industrial abrasives, resin pellets, and synthetic fibers. In contrast, secondary microplastics are generated through the fragmentation of larger plastic products exposed to ultraviolet radiation, mechanical abrasion, thermal degradation, and biological weathering. Owing to the continuous breakdown of plastic waste, secondary microplastics constitute the dominant fraction of environmental microplastic pollution [16–18].

Microplastics also differ in their physical appearance. They commonly occur as fibres, fragments, films, foams, pellets, and microbeads, each exhibiting distinct transport characteristics and biological interactions. Fibres released from synthetic textiles dominate wastewater discharges, whereas fragments are typically produced by the degradation of packaging materials and household plastics. Expanded polystyrene contributes lightweight foam particles that remain suspended near the water surface, while polyethylene and polypropylene films are easily transported by wind and surface currents. Particle size influences residence time, settling velocity, and the likelihood of ingestion by aquatic organisms, making size distribution an important parameter in ecological risk assessments [19,20].

The chemical composition of microplastics further determines their environmental persistence. Common polymers include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyvinyl chloride (PVC), and nylon. These materials exhibit varying densities, degradation rates, and affinities for contaminants. Plastics with densities lower than water generally remain buoyant, whereas denser polymers tend to accumulate within bottom sediments. As weathering progresses, surface roughness and oxidation increase, enhancing the adsorption of heavy metals, persistent organic pollutants, and microbial biofilms. Consequently, aged microplastics often present greater ecological risks than newly released particles [21–23].

2.2. Major Sources of Microplastics in Aquatic Ecosystems

The widespread occurrence of microplastics in aquatic environments is attributed to numerous anthropogenic activities that release plastic particles directly or indirectly into freshwater and marine systems. Urbanization, industrial development, population growth, and increasing plastic consumption have significantly accelerated the generation of microplastic pollutants during recent decades.

Municipal wastewater treatment plants represent one of the major pathways through which microplastics enter rivers and coastal waters. Domestic washing of synthetic textiles releases millions of microscopic fibres during each washing cycle. Although wastewater treatment facilities remove a substantial proportion of these particles, complete removal remains difficult because of their extremely small size. Consequently, treated effluents continue to discharge considerable quantities of microplastics into receiving water bodies [24,25].

Road transportation has emerged as another important source of microplastic contamination. Continuous abrasion of vehicle tyres produces synthetic rubber particles that accumulate on road surfaces before being transported into drainage systems during rainfall events. Similarly, wear of road markings, brake linings, and vehicle components contributes additional polymer particles that ultimately reach nearby rivers and lakes through stormwater runoff.

Agricultural activities also contribute significantly to microplastic pollution. Plastic mulching films, greenhouse coverings, irrigation pipes, fertilizer coatings, and sewage sludge applications gradually degrade under environmental exposure, releasing plastic fragments into agricultural soils. Surface runoff subsequently transports these particles into adjacent streams and reservoirs, particularly during periods of intense rainfall. Aquaculture facilities, fishing gear, and maritime activities further introduce ropes, nets, floats, and packaging materials that progressively fragment within aquatic environments [26–28].

Industrial processes provide additional pathways for microplastic release. Plastic manufacturing plants, resin pellet transportation, recycling facilities, and construction activities may accidentally discharge raw polymer materials into nearby drainage networks if appropriate containment measures are not implemented. In developing regions where waste management infrastructure remains inadequate, open dumping and uncontrolled disposal substantially increase the quantity of plastic waste entering aquatic ecosystems.

Atmospheric transport has recently been recognized as an additional mechanism contributing to microplastic contamination. Airborne fibres and fine plastic particles can travel considerable distances before being deposited onto rivers, lakes, reservoirs, and coastal waters through precipitation or dry deposition. This pathway partly explains the presence of microplastics in remote mountain lakes, Arctic environments, and other regions located far from direct pollution sources [29–31].

2.3. Transport Mechanisms in Freshwater and Marine Environments

After entering aquatic systems, microplastics are transported through a combination of hydrodynamic, atmospheric, and biological processes. Their movement depends not only on environmental conditions but also on particle characteristics such as size, density, shape, and surface properties. Consequently, transport pathways differ considerably among freshwater rivers, estuaries, lakes, and marine environments.

River systems constitute the principal conduits connecting terrestrial plastic pollution with coastal ecosystems. Stream velocity, discharge, channel morphology, sediment characteristics, and seasonal flooding strongly influence downstream transport. During high-flow events, suspended microplastics may remain within the water column for extended periods before eventually settling in low-energy zones such as reservoirs, wetlands, floodplains, and estuaries. Sediment resuspension during floods may subsequently remobilize previously deposited particles, creating repeated transport cycles [32–34].

In marine environments, tides, wave action, coastal circulation, and large-scale ocean currents govern the distribution of floating microplastics. Buoyant polymers can travel thousands of kilometres across ocean basins before accumulating within subtropical gyres or being stranded along coastlines. Dense particles gradually settle onto the seabed where they become incorporated into marine sediments, while biological fouling may alter particle density and accelerate sinking processes. Seasonal variations in temperature, salinity, and biological productivity further influence the vertical movement and environmental residence time of microplastics.

Biological transport also contributes to microplastic redistribution. Aquatic organisms ingest plastic particles during feeding and subsequently excrete them at different locations, facilitating movement across habitats and trophic levels. Migratory fish, seabirds, marine mammals, and benthic organisms may therefore act as biological vectors, extending the spatial distribution of microplastics beyond purely hydrodynamic transport mechanisms [35–37].

Recent advances in hydrodynamic modelling, Geographic Information Systems (GIS), remote sensing, and machine learning have improved the ability to predict microplastic transport pathways. Numerical models increasingly integrate river discharge, meteorological variables, particle characteristics, and ocean circulation data to identify pollution hotspots and estimate long-term accumulation patterns. Such predictive tools support environmental monitoring programmes and provide valuable information for designing targeted pollution mitigation strategies [38–40].

2.4. Global Distribution and Environmental Occurrence

Microplastics have now been detected in nearly every aquatic environment investigated, demonstrating the global extent of plastic contamination. Elevated concentrations are commonly reported in densely populated urban rivers, estuaries, industrial harbours, and coastal regions where anthropogenic activities are concentrated. However, the occurrence of microplastics in deep-sea sediments, polar ice, alpine lakes, and remote islands indicates that long-range transport mechanisms have extended plastic pollution far beyond its original sources.

Freshwater ecosystems frequently function as temporary storage zones before transporting microplastics to marine environments. River basins draining large metropolitan areas often exhibit the highest contamination levels because they receive wastewater discharges, stormwater runoff, industrial effluents, and agricultural drainage. Estuaries serve as transitional environments where freshwater mixing, tidal processes, and sediment deposition influence particle retention and redistribution. Consequently, many estuarine ecosystems act as important accumulation zones that regulate the transfer of microplastics from rivers to coastal waters [41–43].

Marine ecosystems contain diverse microplastic reservoirs distributed across surface waters, the water column, beaches, coral reefs, mangrove forests, and deep-ocean sediments. Floating plastics are frequently concentrated within subtropical ocean gyres by large-scale circulation patterns, whereas denser particles accumulate on the seabed through sedimentation processes. Continuous fragmentation of larger debris further increases the abundance of smaller particles, including nanoplastics, which remain difficult to detect using conventional analytical techniques.

Long-term monitoring programmes indicate that global microplastic contamination continues to increase despite growing environmental awareness and regulatory interventions. Differences in sampling methods, analytical protocols, and reporting units currently limit direct comparison among studies, highlighting the need for internationally standardized monitoring frameworks. Improved harmonization of sampling strategies and laboratory methodologies will enable more reliable assessment of temporal trends, facilitate global data sharing, and strengthen future ecological risk assessments [44,45].

3. Ecological Impacts of Microplastics

The ecological significance of microplastics is primarily associated with their widespread availability, persistence, and ability to interact with organisms across different trophic levels. Because their size overlaps with the feeding range of many aquatic organisms, microplastics can be mistaken for natural food particles and subsequently enter biological systems. The severity of their effects depends on particle size, polymer type, concentration, exposure duration, shape, surface properties, and the physiological characteristics of the exposed organism.

3.1. Effects on Plankton and Microorganisms

Planktonic organisms occupy a fundamental position in aquatic food webs and are among the earliest biological receptors of microplastic contamination. Phytoplankton may experience changes in photosynthetic activity and cellular growth following exposure to suspended plastic particles. Microplastics can also modify the physical and chemical conditions surrounding microorganisms by providing artificial surfaces for microbial attachment and biofilm formation.

Zooplankton can ingest microplastics because of their similarity in size to naturally occurring food particles. Ingestion may reduce feeding efficiency and energy availability while increasing physiological stress. Since plankton constitute an important food source for fish and other aquatic organisms, their exposure may provide an initial pathway for the transfer of plastic particles and associated contaminants to higher trophic levels [46–48].

Microplastic surfaces can develop a microbial community known as the plastisphere. This biofilm may differ considerably from microbial communities naturally associated with surrounding water and sediments. Consequently, plastic particles can potentially transport microorganisms between geographically separated environments. The ecological consequences of these microbial associations remain an active area of research, particularly concerning the movement of opportunistic or pathogenic organisms.

3.2. Impacts on Fish and Aquatic Fauna

Fish and aquatic invertebrates can ingest microplastics either directly from the surrounding environment or indirectly through contaminated prey. Following ingestion, particles may accumulate temporarily within the gastrointestinal tract and, depending on their characteristics, may subsequently be eliminated or translocated into other tissues. Exposure has been associated with physical irritation, altered feeding behaviour, oxidative stress, inflammation, and changes in metabolic activity in several experimental studies [49–51].

The effects of microplastics are not restricted to the digestive system. Very small particles may cross biological barriers and interact with tissues and cells. Laboratory investigations have reported changes in antioxidant activity, immune responses, reproductive performance, and gene expression following exposure to particular microplastic concentrations. However, extrapolation from laboratory experiments to natural ecosystems remains challenging because environmental concentrations, exposure durations, particle mixtures, and ecological conditions are often substantially different from controlled experimental conditions.

Aquatic invertebrates such as mussels, oysters, crustaceans, and benthic worms are particularly important in microplastic research because their feeding mechanisms expose them to particles suspended in water and deposited within sediments. Filter-feeding organisms may accumulate considerable quantities of particles from contaminated water, while sediment-dwelling organisms encounter microplastics incorporated into bottom deposits. These organisms can therefore serve both as ecological receptors and as indicators of environmental contamination.

3.3. Bioaccumulation and Trophic Transfer

Microplastics have the potential to move through aquatic food webs when contaminated organisms are consumed by predators. The concept of trophic transfer is particularly important because even if individual organisms eliminate a substantial proportion of ingested particles, repeated exposure can maintain a continuous flow of microplastics through ecosystems. Predatory fish, seabirds, and marine mammals may therefore encounter particles indirectly through their prey [52–54].

Microplastics may also interact with other environmental contaminants. Hydrophobic organic pollutants can accumulate on plastic surfaces, while metals may associate with weathered particles containing chemically active functional groups. Biofilms developing on microplastics can further modify their adsorption properties. Consequently, ecological exposure may involve not only the physical effects of plastic particles but also combined effects arising from chemicals and microorganisms associated with them.

However, the magnitude of contaminant transfer through microplastics remains dependent on environmental conditions and competing exposure pathways. In many natural environments, organisms are simultaneously exposed to contaminants present in water, sediments, and food. Therefore, the contribution of microplastics to total contaminant exposure requires further quantitative assessment rather than being assumed to be the dominant pathway.

3.4. Ecosystem-Level Consequences

At the ecosystem level, microplastic pollution may influence ecological processes extending beyond individual organisms. Changes in feeding behaviour, growth, reproduction, and survival can potentially affect population dynamics and predator–prey relationships. Accumulation within sediments may also modify sediment structure and influence organisms responsible for nutrient cycling and decomposition.

The ecological consequences are particularly important in coastal wetlands, mangrove ecosystems, coral reefs, estuaries, and freshwater wetlands because these environments combine high biological productivity with strong particle retention. Microplastic accumulation within such habitats may create persistent exposure conditions and increase the probability of interactions with benthic organisms.

Nevertheless, considerable uncertainty remains regarding the long-term ecosystem-scale effects of environmentally realistic microplastic concentrations. Much of the available evidence is based on laboratory experiments using controlled concentrations and selected polymer types. Future research should therefore increasingly integrate field observations, long-term ecological experiments, food-web modelling, and environmentally realistic exposure scenarios to determine whether observed individual-level effects translate into measurable changes in ecosystem structure and functioning [55–57].

4. Detection and Monitoring of Microplastics

Reliable monitoring is essential for understanding the spatial distribution, environmental fate, and ecological risks associated with microplastics. Conventional visual identification methods can provide preliminary information about particle abundance and morphology but cannot reliably determine polymer composition, particularly for particles below the millimetre scale. Modern monitoring therefore combines physical separation with spectroscopic and chemical analytical techniques.

Fourier Transform Infrared (FTIR) spectroscopy is widely used for polymer identification because different plastic materials exhibit characteristic infrared absorption patterns. Micro-FTIR systems can analyse relatively small particles and provide information on both particle morphology and polymer composition. Raman spectroscopy provides complementary capabilities and is particularly useful for smaller particles because of its high spatial resolution. However, fluorescence from organic material and difficulties associated with dark or weathered particles can affect analytical performance [58–60].

For complex environmental samples, Pyrolysis-Gas Chromatography/Mass Spectrometry (Py-GC/MS) provides a chemical approach for identifying and quantifying polymer types. Unlike particle-counting techniques, which generally report the number or size of individual particles, Py-GC/MS can estimate polymer mass and detect mixtures that may be difficult to identify visually. Combining spectroscopic and thermal analytical methods can therefore provide a more comprehensive assessment of microplastic contamination.

Sampling design remains equally important. Water samples, sediments, biological tissues, and atmospheric deposition require different collection and preparation procedures. Contamination from synthetic clothing, laboratory equipment, and airborne fibres can introduce substantial analytical bias. Standardized sampling protocols, procedural blanks, contamination controls, and harmonized reporting units are consequently necessary for reliable comparison among studies [61,62].

Emerging computational approaches are beginning to improve monitoring efficiency. Machine learning and computer vision can automatically classify particles according to shape, colour, size, and spectral characteristics, reducing the time required for manual analysis. GIS-based mapping can integrate sampling results with land use, drainage networks, hydrology, population density, and industrial activity to identify probable pollution sources and spatial hotspots. Remote sensing has also shown potential for detecting larger floating plastic accumulations in coastal and marine environments, although its ability to directly detect small microplastics remains limited.

The integration of analytical chemistry, GIS, remote sensing, hydrodynamic modelling, and Artificial Intelligence offers a promising pathway toward large-scale microplastic monitoring. Such multidisciplinary systems could eventually support near-real-time pollution assessment and predictive mapping, enabling environmental agencies to identify major sources and prioritize intervention areas more efficiently.

5. Mitigation and Management Strategies

The management of microplastic pollution requires interventions across the entire plastic lifecycle, from production and consumption to waste collection, treatment, and environmental remediation. Because microplastics originate from numerous diffuse and point sources, a single mitigation measure cannot adequately address the problem. Effective management therefore requires a combination of source reduction, improved wastewater treatment, sustainable product design, improved waste management, and ecosystem-based interventions.

Source reduction represents the most effective long-term approach because preventing plastic particles from entering aquatic environments is generally more practical than removing them after widespread dispersion. Restrictions on unnecessary single-use plastics, improved textile design, reduction of plastic additives, and development of biodegradable or recyclable materials can reduce future particle generation. Particular attention should be given to synthetic textile fibres, tyre wear, plastic packaging, fishing equipment, and agricultural plastics because these represent important pathways of environmental release [63–65].

Wastewater treatment facilities can substantially reduce the quantity of microplastics discharged into receiving waters. Screening, sedimentation, filtration, membrane technologies, and advanced treatment processes can capture a large proportion of particles. However, captured microplastics are frequently transferred to sewage sludge rather than completely destroyed. If sludge is subsequently applied to agricultural land, the particles may re-enter terrestrial environments and potentially reach aquatic systems through runoff. Consequently, microplastic management should consider the complete treatment chain rather than focusing exclusively on effluent quality [66,67].

Stormwater management is particularly important in urban environments because road runoff can transport tyre-derived particles, synthetic fibres, and fragmented plastic waste into drainage networks. Permeable surfaces, retention ponds, constructed wetlands, sediment traps, and filtration systems can reduce particle transport before stormwater reaches natural water bodies. Similarly, improved collection and recycling systems can prevent larger plastic waste from entering rivers and coastal environments and subsequently becoming a source of secondary microplastics.

Aquatic remediation approaches, including floating barriers, filtration systems, sediment removal, and shoreline clean-up, can help reduce localized contamination. However, large-scale removal of microplastics from natural ecosystems remains technically difficult and potentially disruptive to aquatic habitats. Remediation should therefore be regarded as a complementary strategy rather than a substitute for source reduction.

6. Research Gaps and Future Directions

Despite rapid progress in microplastic research, major uncertainties remain regarding their environmental fate and ecological significance. One of the most important limitations is the lack of standardized definitions, sampling procedures, analytical techniques, and reporting units. Studies may use different particle-size thresholds, sampling volumes, digestion procedures, and identification methods, making comparisons among locations and time periods difficult.

The detection of particles below approximately 100 μm and the identification of nanoplastics remain particularly challenging. Conventional microscopy and spectroscopy may not adequately characterize the smallest particles, while analytical procedures can introduce contamination or particle loss. Development of sensitive, standardized, and cost-effective analytical techniques is therefore an important research priority [68–70].

Another major gap concerns the long-term ecological consequences of environmentally realistic exposure. Future investigations should move beyond short-duration laboratory experiments using high concentrations and instead incorporate field observations, chronic exposure experiments, multiple polymer types, weathered particles, and naturally occurring contaminant mixtures. Greater attention should also be given to interactions between microplastics and climate-driven changes in temperature, salinity, precipitation, river discharge, and ocean circulation.

Artificial Intelligence and advanced modelling provide promising opportunities for future research. Machine learning can integrate large environmental datasets to predict microplastic hotspots, identify probable sources, and estimate transport pathways. Coupling AI models with hydrodynamic simulations and GIS can provide dynamic pollution maps that account for changing rainfall, river discharge, wind, tides, and ocean currents. Such systems could support early-warning mechanisms and help environmental authorities prioritize monitoring and mitigation activities.

Future research should also investigate the transition from microplastics to nanoplastics, whose smaller dimensions may enable greater mobility and interaction with biological tissues. Improved understanding of particle ageing, biofilm development, chemical adsorption, trophic transfer, and degradation processes will be essential for developing realistic ecological risk assessments.

International cooperation is equally important. Microplastic pollution crosses administrative and national boundaries through rivers, atmospheric transport, and ocean circulation. Harmonized monitoring protocols and open environmental databases would allow researchers to compare contamination patterns globally and identify large-scale trends. Policies should increasingly address the complete plastic lifecycle rather than focusing exclusively on visible plastic waste.

7. Conclusion

Microplastic pollution represents a complex and persistent environmental challenge affecting freshwater, estuarine, coastal, and marine ecosystems. Microplastics originate from diverse sources, including plastic degradation, synthetic textiles, tyre wear, wastewater, agriculture, industrial activities, and atmospheric deposition. Once introduced into aquatic systems, their movement is controlled by hydrological conditions, particle characteristics, sediment interactions, biological processes, and ocean circulation.

Their ecological effects range from ingestion and physiological stress in individual organisms to potential changes in food-web interactions and ecosystem functioning. However, significant uncertainties remain regarding long-term impacts under natural exposure conditions. Improved analytical methods, standardized monitoring, field-based research, and integrated ecological modelling are therefore required.

Effective management should prioritize prevention and source reduction while improving wastewater treatment, stormwater management, plastic waste collection, recycling, and environmental monitoring. Emerging applications of GIS, remote sensing, hydrodynamic modelling, and Artificial Intelligence provide new opportunities for predicting pollution pathways and developing targeted interventions. Ultimately, controlling microplastic contamination will require coordinated action among researchers, industries, governments, and communities, supported by scientifically robust monitoring and sustainable plastic-management policies.

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