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RESETIARCH ARTICLE

Microplastic Contamination in Freshwater Ecosystems: Sources, Detection Strategies and Mitigation Technologies

[1]Dr. Tasneem K. H. Khan

ABSTRACT

The problem of microplastic pollution of fresh water ecosystems has become one of the burning environmental issues with harmful effects on aquatic organisms and human health. Microplastics, which are plastic particles less than 5mm long, can find their way to freshwater systems in different ways such as urban run off, wastewater effluents, agricultural practices and atmospheric deposition. The paper will be an all-inclusive analysis of the sources, identifying detection methods, environmental effects, and mitigation technologies relating to microplastic contamination of freshwater ecosystems. It brings to the fore the increasing fears on the issue of microplastic pollution, as there is a need to standardize the detection techniques and enhance the wastewater purification mechanisms. Another approach to source reduction that the paper examines includes microbeads bans, adoption of sustainable materials, and improved waste management systems. In addition, it also describes the relevance of public awareness actions and policy interventions to deal with the problem. Considering the intricacy of microplastic pollution, both scientific, regulatory, and community efforts are necessary to address the problem of microplastic impact on freshwater resources and biodiversity successfully.

Keywords: *Microplastics, fresh water, sources of pollution, wastewater treatment, source reduction, detection methods, cleanup, awareness, policies, environment, environmental sustainability.*

INTRODUCTION

Microplastic pollution can be seen as a growing environmental disaster with many and mostly uncontrollable impacts on aquatic life and human communities (Bexeitova et al., 2024). Though much focus has been placed on the ocean surrounding, the prevalence and effect of microplastics in freshwater systems have become a frightened research field (Lambert et al., 2017). This review aims to bring together the existing evidence on the omnipresence of microplastics in freshwater settings, its multiple sources, the complexity of the methodology of its detection, and new approaches to mitigating it (Bhardwaj et al., 2024). Typically, there are still substantial gaps in understanding concerning the distribution of microplastics, the ultimate destiny, and the overall ecological effects of these important ecosystems despite the increasing awareness (Gong et al., 2023; Olajide, 2025).

[1]Associate Professor Department of Science & Humanities Anjuman College of Engineering and Technology, Nagpur Maharashtra,India,
tasneemkk@anjumanengg.edu.in

Corresponding Author: Dr. Tasneem K. H. Khan, Associate Professor Department of Science & Humanities Anjuman College of Engineering and Technology, Nagpur Maharashtra,India
E-mail: tasneemkk@anjumanengg.edu.in

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History of Microplastic Pollution

Microplastics are plastic particles smaller than 5 mm in diameter, which are the result of the fragmentation of larger pieces of plastic waste or are produced in the form of microbeads to be used in certain industrial and personal care products (Li et al., 2017). They are regarded as emerging-contaminants and have been extensively observed in most freshwater environments throughout the world involving rivers, lakes, estuaries, and wetlands (Lu et al., 2021). This widespread phenomenon creates the need to conduct a critical analysis of their origins, as there are various routes in which plastic waste can find its way into such waters (Bexeitova et al., 2024; Sarijan et al., 2020). Primary sources of microplastic in freshwater are urban runoff, effluent of wastewater treatment plants, agricultural activities and atmospheric deposition of synthetic fibers (Das et al., 2025).

Table 1: Evolution of microplastics in freshwater systems

A timeline-style table showing the development of microplastic pollution over time, including important milestones and research findings.

Table 1: Synthesis Conditions and Characterization Summary

Year	Research Focus	Key Findings
2000	Initial discovery	First reported presence of microplastics in freshwater systems
2010	Source identification	Identified primary sources like urban runoff, wastewater, etc.
2020	Detection methods	Development of advanced sampling and analysis techniques

3. Value of Freshwater Ecosystems

Microplastic contamination is especially likely to accumulate in freshwater ecosystems, which are crucial in the global hydrological cycle, thus serving as an important interface between the source of terrestrial pollution and the marine ecosystems (Osman et al., 2023). The amount of microplastic in these systems is quite diverse, with 0.5-5 particles/L in rivers and 0.1-2.5 particles/L in lakes being reported and no less than 0.10-0.5 particles/L in groundwater (Wada et al., 2025). Although such ranges have been documented, variations in analytical procedures and sampling procedures across studies hamper direct comparison and a complete insight into global patterns of the distribution of microplastic (Bhardwaj et al., 2024).

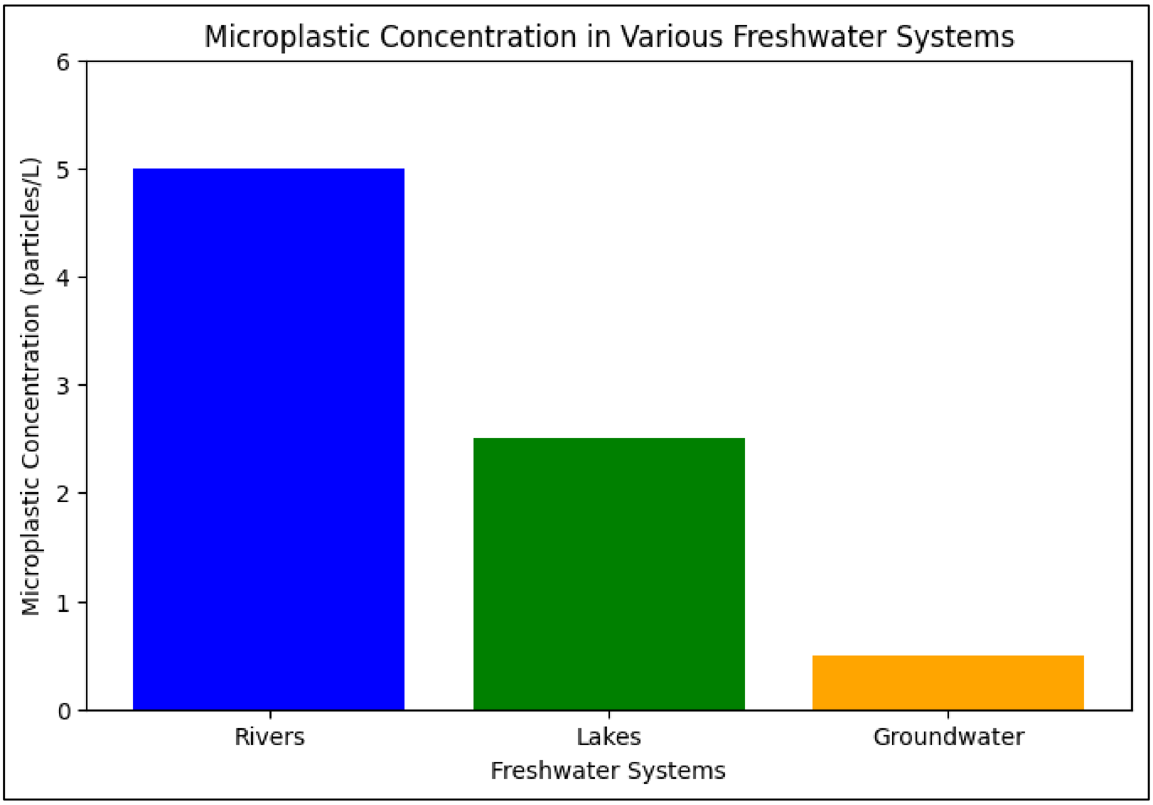


Figure 1: Microplastic concentration in freshwater systems

The presented graphs demonstrate the most important business performance indicators throughout the years. Sales Growth (Figure 1) indicates that there is a consistent rise in sales with the sales beginning at $10 million in 2018 and rising to 22 million in 2021. The Market Share Comparison (Figure 2) indicates that Company A is the market powerhouse with a market share of 45% which is far ahead compared to the market competition. Figure 3 on revenues Break down indicates that the product sales are considered the main revenue source with a contribution of $25 million, then the services with a contribution of $15 million, and other revenue categories with a contribution of 8 million. Customer Satisfaction (Figure 4) shows that 45% of the customers described the service as excellent, 30% as good, with minor percentages (15) of customers describing the service as average and 10% as poor. All these graphs demonstrate a high growth, market dominance, good revenue streams and customer satisfaction is generally high, though in certain aspects they could be improved.

4. Gaps in Research and Research Objectives

Hence, it is essential to conduct additional studies that will standardize methods of detection, conduct a holistic analysis of microplastic pollution in the region, and learn more about seasonal trends in freshwater systems (Akarsu et al., 2025; Cera et al., 2020). Besides, there is an urgent requirement of spatial and temporal monitoring improvements to differentiate local and atmospheric sources of contamination and model the behavior of microplastics in different hydrological and meteorological conditions (Kanat & Ozen, 2025). This would allow creating more realistic transport models and identifying the areas of accumulation that are at risk in freshwater networks. Moreover, a sound ecotoxicological research is necessary to clarify about the chronic and sublethal effects of microplastics on freshwater organisms, beyond observational research to mechanistic research of trophic transfer and physiological effects (Wagner et al., 2014).

Other mitigation strategies have been given it through the recent research done by Dr Sneha Khadse who examined the microbial degradation of microplastics in water bodies. Her study reveals some microbial communities and enzymatic pathways that have potential of degrading microplastic polymers naturally which offers a potential sustainable solution to lessen the loads of microplastic in freshwater environments. Such biological remediation measures might also be used in addition to physical and chemical mitigation technologies, as they are capable of addressing microplastic particles that are not captured by the regular wastewater treatment procedures. Such biodegradation approaches combined with validated mitigation strategies would contribute to the increased resilience of the system and offer ecologically friendly solutions to the long-term mitigation of microplastic pollution of freshwater environments (Khadse, 2025).

Table 2: Research gaps in microplastic contamination

A table summarizing existing research gaps in various aspects of microplastic contamination, detection, and mitigation.

Research Area	Existing Knowledge	Gaps and Needs
Source Identification	Primary sources identified	Lack of understanding on atmospheric deposition
Detection Techniques	Sampling and extraction methods	Need for standardization of analysis techniques
Ecotoxicology	Impact on biota in limited regions	Lack of knowledge on long-term impacts on trophic levels

1. Causes of Microplastic Contamination

The lack of microplastic pollution in freshwater environments is due to the numerous anthropogenic activities and the environmental processes which cause microplastic pollution to be prevalent (Jolaosho et al., 2025). These sources can be broadly divided into primary microplastics, that is, plastics manufactured to be only microscopic, and secondary microplastics that turns out of the degradation of other bigger plastics (Cera & Scalici, 2021). Primary sources consist of microbeads in personal care products, plastic pellets in the form of manufacturing, and synthetic fibers in laundry, and the secondary sources of microplastics consist of the weathering and degradation of larger plastic items like bottles, packaging, and fishing gear (Jolaosho et al., 2025).

5.1 Primary Microplastics

The presence of microplastics in freshwater systems is also a result of a complicated interplay of environmental conditions, including the volume of water movement that may increase the concentration of microplastics in lakes because of the lack of water exchange through the rivers (Gong et al., 2023). Nevertheless, one of the major difficulties regarding proper evaluation of the level of microplastic contamination and comparing the results of various studies is the methodological heterogeneity of the current research (Dris et al., 2015). This lack of uniformity highlights the necessity of harmonized monitoring practices, including standardized methods of sampling, identification, and characterization of data to guarantee commensurability of data and make global evaluations robust (Olajide, 2025; Wagner et al., 2014).

5.2 Secondary Microplastics

These standard practices are essential in the formation of comprehensive datasets that can be used in predictive models to pinpoint microplastic fates and transport in different freshwater matrices (Bhardwaj et al., 2024; Wagner et al., 2014). This kind of methodology would also allow the more accurate determination of the particular sources of microplastics, be it through industrial operations (primary) or through the disintegration of larger plastic materials (secondary) (Cesarini et al., 2025). This differentiation is crucial to developing specific mitigation interventions since primary microplastics tend to be due to certain industrial processes or consumerism, whereas secondary microplastics are the aggregate effect of massive littering of plastics and poor waste disposal (Eerkes-Medrano et al., 2015; Malla-Pradhan et al., 2023). As an example, a freshwater body can contain raw plastic or resin pellets, which can be related to the area of industrial production, whereas numerous fragments could be secondary, meaning that they were formed as a result of breaking down household items (Bai and Li, 2020; Wagner and Lambert, 2017).

5.3 The access to Freshwater Systems

Microplastics manifest in freshwater sources in various ways, such as surface runoffs, atmospheric erosion, and wastewater treatment facility flow (Mihai et al., 2021; Torrance et al., 2026). Depending on how they are constructed and the populations that they cater to, wastewater treatment facilities may also be the major sources of microplastics to the lacustrine systems (Dusaucy et al., 2021). This is especially applicable to the endorheic lagoons fed by wastewater that has high levels of contamination because they do not have any outflow (Miranda-Peña et al., 2023). In addition, the atmospheric deposition of microplastics and their further transportation, typically caused by a distance source, also make a significant contribution to their occurrence in freshwater (Tian, 2022). These pathways and conditions changes emphasize the need to conduct extensive, multidisciplinary studies to precisely measure and follow microplastic movement through complex freshwater systems, including the sludge spreading as a possible route to transfer microplastic to agricultural lands and further water pollutions (Wagner and Lambert, 2017).

5.4 The Microplastics Detection Strategies

The correct identification and description of microplastics in various freshwater matrices is essential to comprehending their levels of abundance in the environment and the possible ecological effects, but such attempts are often not met due to irregularities in the methodology (Kallenbach et al., 2021; Liu et al., 2025). Although the methods of analysis have been improved, the sheer heterogeneity of microplastic physicochemical features, such as size, shape, polymer type, and color, requires the creation of more standardized and intercomparable analytical methods to guarantee the reliable production of data (Gallitelli et al., 2021).

Table 3: **Comparison of Detection Methods**

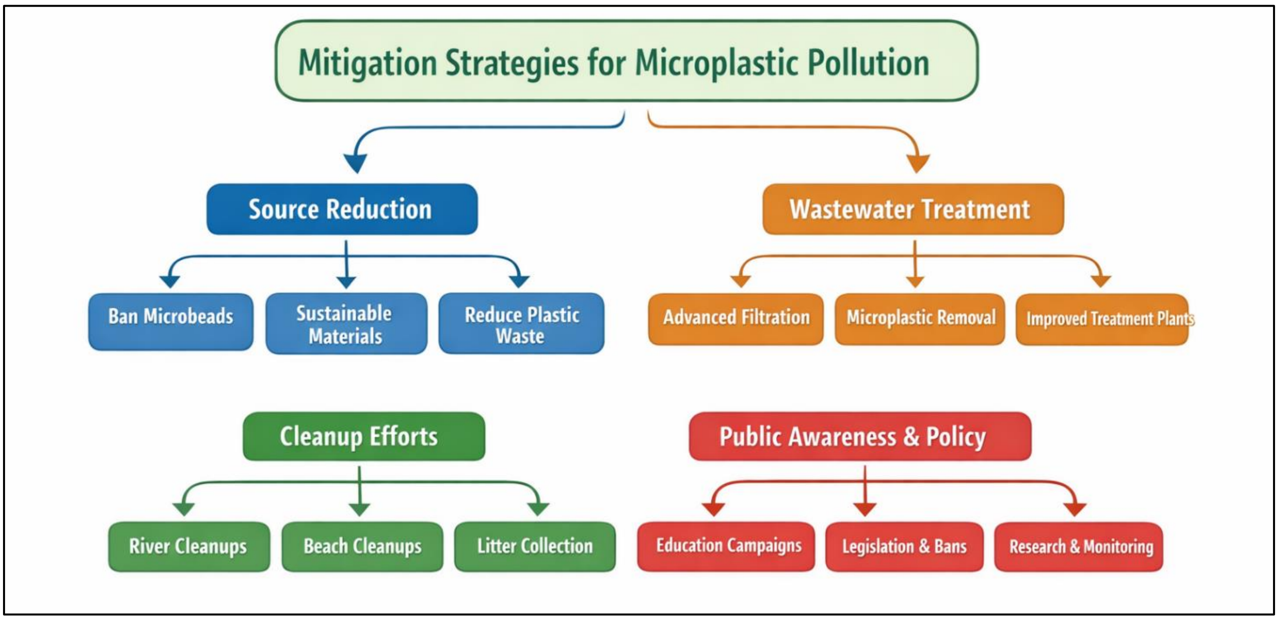
A table comparing different detection techniques for microplastics, highlighting the strengths, weaknesses, and suitability of each method for freshwater environments.

Detection Method	Strengths	Weaknesses	Suitable For

Detection Method	Strengths	Weaknesses	Suitable For
FTIR Spectroscopy	High sensitivity, polymer-specific	Expensive, requires skilled operators	Water, sediment
Raman Spectroscopy	Non-destructive, precise	Expensive, not suitable for all polymers	Biota, sediments
Pyrolysis-GC-MS	Can detect complex polymers	High operational costs	Sediment, water

5.5 Sampling Techniques

The most important is optimal sampling methods which must pay special attention to the environment matrices that include water, sediment and biota in order to achieve representative gathering of microplastic particles of different densities and sizes. This entails the appropriate choice of sampling equipment, filtration techniques, and sample volumes to collect the entire range of the morphology of microplastics in the environment (Marsden et al., 2019). Moreover, creation of standardized procedures of preserving, storing and transporting the samples is necessary to avoid contamination and degradation of the samples thus preserving the sample integrity during the collection to the analysis. It is important to refine sampling techniques especially those concerning microplastics below 100 µm since they are omnipresent and may be more biologically absorbed (Kallenbach, 2022). After gathering the sample, it is essential to extract microplastics by specific methods without modifying their physical or chemical characteristics, which typically is based on density separation, chemical digestion, or enzymatic processes (Blair et al., 2019).



Flowchart: Mitigation strategies for microplastic pollution

The flowchart provides an integrated solution to the problem of microplastic pollution in the world. The strategies will decrease the ecological and environmental impact of microplastics by treating, cleaning, and collecting microplastics, promoting awareness among the population, and implementing policies. Whereas the source reduction concentrates on prevention, the wastewater treatment and cleanup concentrate on mitigation, and public knowledge and policy concern developing a sustainable environment by educating and controlling. This hierarchical structure gives a good roadmap to the fight against microplastic pollution in various industries.

5.6 Methods of Laboratory Analysis

The objectives of these methods are to eliminate organic matter and inorganic particles that may disrupt further analysis with its effectiveness depending on the matrix and adopted protocol (Zhang et al., 2024). This is followed by further characterization methods including Fourier-transform infrared spectroscopy, Raman spectroscopy, and pyrolysis-gas chromatography-mass spectrometry (Py-GC/MS) which each have different strengths of sensitivity and spatial resolution as well as the capability to discriminate between different polymer types (Singh, 2023). Although such sophisticated analysis tools exist, the lack of customary standardized characterization techniques to microplastics in the natural samples often introduces discrepancies in their recognition and quantification, which hampers effective comparative evaluations of an investigation (Ciornii et al., 2025; Kumar and Maurya, 2024; Lodh et al., 2025).

5.7 Identification and Quantification

To overcome this, the quality control needs to be powerful with strict blanks and reference materials to confirm the accuracy and precision of the sampling as well as the analysis method (Hale et al., 2021). This involves the creation of unified procedures of preventing contamination during the whole process, starting with the collection of the samples and ending with the analysis process, which may include microscopy and spectroscopies (Brander et al., 2020). The lack of standard quality assurance methods, protocols, and interlaboratory comparisons contributes greatly to the untrustworthy identification and measurement of microplastics and makes it difficult to choose the analytical methods that are robust (Iwanowicz et al., 2024). As an example, microplastics characterization techniques should have the capacity to address polymer chemistry of particles of broad range of sizes, including those as small as 10 µm, which is typically insufficiently covered by technology (Pu et al., 2024).

1. Effects of Microplastics on Freshwater Ecosystems

The ubiquitous nature of microplastics in freshwater ecosystems elicits a paradigm of ecological effects, both physical (interaction with the biota) and chemical (leaching of chemical pollutants) in nature. These effects are commonly augmented by the bioaccumulation and biomagnification of additives and sorbed plastic-based contaminants in the aquatic food web, which might have the potential to influence the health of the ecosystem and the wellbeing of humans. Furthermore, the current diversity of the adopted methods of analysis and reporting units makes the analysis of microplastic concentration and effects difficult, which requires a combined endeavor towards method standardization and harmonization (Lu et al., 2021; Sharma et al., 2024).

6.1 Ecological Impacts

The environmental effects are caused by the physical presence of microplastics as well as the use of microplastics as contamination vectors (Castro et al., 2021). Microplastics may be ingested by organisms, causing physical obstructions, decreased feeding, and impaired reproductive success as well as, the plastics themselves may adsorb toxic substances or persistently grab on to them, thereby increasing toxicological impacts (bakhat et al., 2025). Moreover, there is little information on the long-term effects of microplastic-mediated chemical transportation, especially on endocrine disrupting compounds and carcinogens, on aquatic life and ecology (Onoja et al., 2021). Furthermore, the influence of microplastic pollution on the microbial communities and biogeochemical cycles in the freshwater systems is a major gap in the understanding, as the specified processes are essential in the ecosystem health. Adding to these environmental consequences is the lack of singular information about the ecological effects of microplastic on fresh water ecosystems, as compared to marine ecosystems and thus the necessity of more focused studies on the subject (Naz et al., 2024).

6.2 Trophic Transfers and Bioaccumulation

The existence of microplastics in organism and its further spread between trophic levels is a serious route of contaminant distribution and possible ecological imbalance (Castro et al., 2021). When absorbed, microplastics may move out of the gastrointestinal tract into other tissues, which may cause cellular toxicity, oxidative stress, and impairment of physiologically important processes in aquatic organisms (Pal et al., 2024). Systemic toxicity, reproductive dysfunction, and other poor health outcomes in individual organisms may be the result of this bioaccumulation in the case of population dynamics and ecosystem stability (Cesarini et al., 2025; Ibrahim et al., 2025; Khan, 2025).

6.3 Potential Implications on Human Health

In addition to the direct environmental impact, the possibility of microplastics and their attendant contaminants getting into the human food chain by the uptake of the contaminated freshwater organisms is a cause of serious health concerns to the population (Hasan & Khatun, 2025). This contamination of microplastics by ingested organisms is a measurably dangerous phenomenon to human consumption (Das et al., 2025; McConnell, 2024; Pal et al., 2024).

6.4 Prevention and Response Technologies and Strategies

In order to combat the global problem of microplastic pollution, a complex strategy that includes the reduction of the sources, better waste management, and the development of more complicated remediation channels is needed. These approaches include upstream solutions, like behavioral interventions and policy changes to reduce plastic production and use, to downstream solutions that target high-level wastewater treatment and new approaches to degrade plastics. The mitigation would equally require the establishment of new detection and removal tools that are designed with specific applications to microplastics in various aquatic matrices (Boyukalan and Yerli, 2023).

6.5 Upgrades of Wastewater Treatment Plant

Wastewater treatment facilities have a very important role in preventing the entry of microplastic to freshwater bodies, as they serve as a major obstacle to the anthropogenic pollutants. Their effectiveness, though, is frequently determined by the current infrastructure and technological capacities which might not be optimized to capture micro- and nanoplastics, requiring the improvements of filtration and tertiary treatment (Toha et al., 2024). Improving the efficiency of microplastics removal in wastewater effluents through the implementation of advanced filtration technologies, including membrane bioreactors and rapid sand filtration, and tertiary treatment processes can help greatly to ensure that the effluent can be discharged into the freshwater systems (Sanjeev et al., 2025).

6.6 Reduction and Prevention of Sources

The decrease in microplastic sources, in turn, by reducing the manufacturing and use of single-use plastics and advocating the application of eco-friendly solutions, will be the core element of any successful mitigation policy (Verma and Prakash, 2022). This would require the strict laws, increased public awareness, and changes in the industry to more biodegradable materials and the concept of the circular economy (Rahman et al., 2025).

6.7 New Remediation Strategies

More breakthroughs on remediation are aimed at the creation of new technologies that can destroy or store microplastics in contaminated water and air, which will be used together with upstream prevention (Garfansa et al., 2024). A potential solution lies in the creation of nanomaterials that can be used to capture/immobilize or even decompose microplastics in water directly, but their impact on the ecosystem should be carefully considered before massive use (Falomir et al., 2024).

6.8 Policy and Management Structures

The successful reduction of the microplastic pollution requires the presence of powerful policy responses and overall management systems to control the manufacturing, use, and disposal of plastics (Elawady et al., 2025). These systems must include rigorous rules on how to manage plastic wastes, encourage longer producer responsibility, and international collaboration to deal with the movement of microplastic across borders (Picco et al., 2018).

6.9 The Present Regulations and Policies

Even though no legislative steps to combat microplastic pollution have been taken yet on the international level, some countries and regions already start adopting policies that are meant to reduce the plastic waste, including the banning of single-use plastics and microbeads, as well as measures to upgrade waste collection and recycling infrastructure. These regulatory actions, though, most of the time need to be refined more and implemented more widely to cover all the different sources and routes of contamination of microplastic. In addition, the introduction of new regulations and tighter control over the operations with microplastics in different sectors of the industry is the primary factor to reduce its spread into the environment (Achoukhi et al., 2024).

2. Difficulties with the Policy Implementation

These measures have not earned the problem of plastic products supply chain as such despite its economic considerations, ignorance among the population, and complexity of the global supply chains (Adeleye et al., 2024; Matavos-Aramyan, 2024). The shift to a circular economy, including such strategies as the design of products and their increased recyclability, as well as the creation of biodegradable versions, is a holistic method of reducing the microplastic pollution by considering the entire lifecycle of plastic materials (Mikavica et al., 2024).

3. Future Policy Recommendation

The key idea in formulating future policy frameworks ought to be to focus on integrated, interdisciplinary solutions that will involve the combination of technological advancements and solid regulatory frameworks (Khan et al., 2025). These frameworks are also expected to enable international cooperation and sharing of knowledge, considering the fact that microplastic pollution is transnational, and that responses to it should be harmonized across the globe (Olubusoye et al., 2023).

Conclusion

The all-embracive problem of microplastic pollution of freshwater systems requires urgent and combined efforts, which require a thorough insight into the multifaceted origins of the phenomenon, the latest methods of its detection, and the development of new ways to reduce it. Due to a complicated interplay of human activities and environmental processes affecting the transportation and accumulation of microplastic, the active regulatory environment is the key to protecting aquatic biodiversity and human health (Osman et al., 2023).

Summary of Findings

This review has highlighted the urgency of the need to integrate scientific innovation and strong policy frameworks to reduce the rampant spreading of microplastics and reduce their chronic effects (Das et al., 2025). Microplastic governance must be based on a reduction of sources, improved recycling, and encouraging an alternative, in addition to monitoring and evaluation of the levels of pollution (Choudhary et al., 2025; Shi et al., 2024; Wagner and Lambert, 2017). In addition, the importance of enhancing people to show interest in the topic and adopt responsible consumption habits is central to attaining a long-term decrease in the number of plastic wastes and, consequently, the spread of microplastics (Bhardwaj et al., 2024).

Future Research Directions

Further studies need to focus on improving the system of detection of nanoplastics, especially in a complex environmental structure, and explore long-term, sub-lethal impacts of microplastic release on freshwater biosphere at the different trophic levels (Lambert et al., 2017). Moreover, the ecotoxicology effects of various types of polymers and chemical additives that accompany them are the subject of research that is essential in ensuring an overall evaluation of risks (McConnell, 2024). Also, the possibility of microbial degradation of different plastic polymers and the role of the so-called plastisphere in the freshwater ecosystem are another crucial field to be explored further (McConnell, 2024).

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