The Emerging Factor Causing Aquatic Pollution: Micro and Nano Plastics: An Updated Review.

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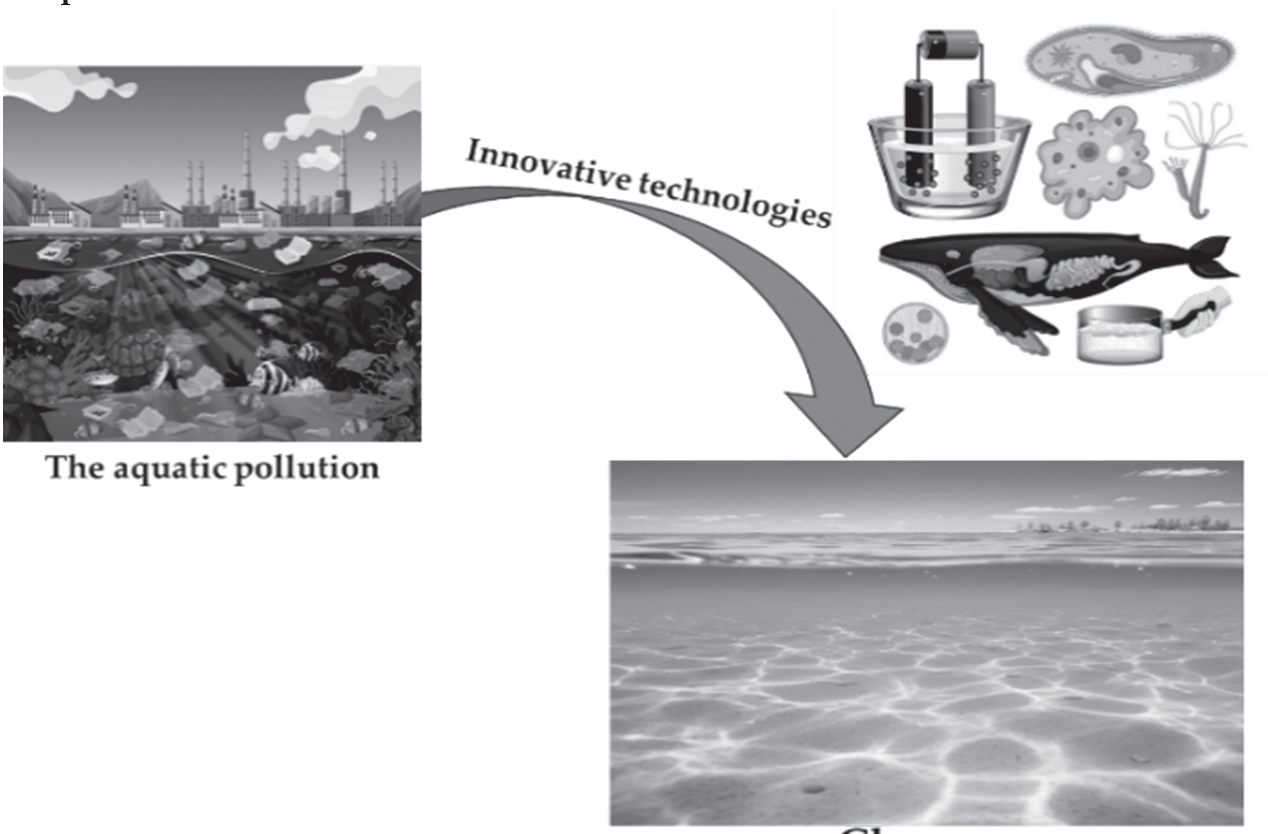
Graphical abstract



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Abstract:

The pervasive presence of micro/nano plastics in aquatic environments has emerged as a critical environmental challenge, necessitating a comprehensive understanding of their sources, behaviors, impacts, and removal strategies. This systematic review synthesizes recent advancements in the detection, impact assessment, and remediation of micro/nano plastics in water bodies. Through an in-depth analysis of contemporary studies, the review elucidates the multifaceted nature of plastic pollution, highlighting the efficacy of innovative technologies such as membrane bioreactors, electrocoagulation, biochar adsorption, advanced oxidation processes, magnetic nanoparticles, and bioremediation. These methodologies demonstrate varying degrees of success in mitigating the environmental and health risks associated with micro/nano plastics. The review underscores the importance of integrating technological innovations with policy measures to enhance the efficacy of water treatment processes and safeguard aquatic ecosystems. Future research directions are identified to address existing gaps and improve the scalability and implementation of these promising solutions.

Keywords: *microplastics, water pollution, wastewater treatment, environmental impact, remediation technologies*

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Nomenclature

AMBRT	advanced membrane bioreactor technology
AOP	advanced oxidation processes
OPs	Organic pollutants

Overview of general issue

In recent years, the pervasive issue of micro/nano plastics infiltrating our water systems has emerged as a critical environmental challenge, garnering significant attention from the scientific community. These minuscule plastic particles, often less than 5 millimeters in size, originate from a myriad of sources, including the degradation of larger plastic debris, synthetic textiles, and personal care products. (Geyer et al., 2017) Once they enter aquatic environments, their diminutive size and buoyant nature allow them to disperse widely, contaminating oceans, rivers, and even remote freshwater systems. (Lebreton et al., 2017) (Figure 1)

The environmental and health implications of micro/nano plastics are profound. These particles act as vectors for toxic pollutants, including persistent POPs and heavy metals, which adhere to their surfaces and can be ingested by marine organisms, leading to bioaccumulation and biomagnification through the food web. (Rochman et al., 2016; Wang et al., 2016) Moreover, the ingestion of microplastics by aquatic fauna can cause physical harm, such as gastrointestinal blockages and reduced feeding efficiency, ultimately affecting biodiversity and ecosystem health. (Cole et al., 2011)

Despite the growing recognition of the problem, the removal of micro/nano plastics from water bodies remains a formidable challenge. Traditional water treatment methods are often inadequate for capturing these tiny particles, necessitating the development of innovative technologies and strategies. (Mintenig et al., 2017; Prata et al., 2020) This systematic review aims to synthesize recent advancements in the detection, impact assessment, and removal of micro/nano plastics from aquatic environments, providing a comprehensive overview of current research and identifying gaps that warrant further investigation.

By examining ten recent studies published within the last five years, this review seeks to elucidate the multifaceted nature of micro/nano plastic pollution and explore potential solutions to mitigate its impact on water quality and ecosystem health. The findings will contribute to a deeper understanding of this pressing environmental issue and inform future research and policy development to safeguard our water resources.

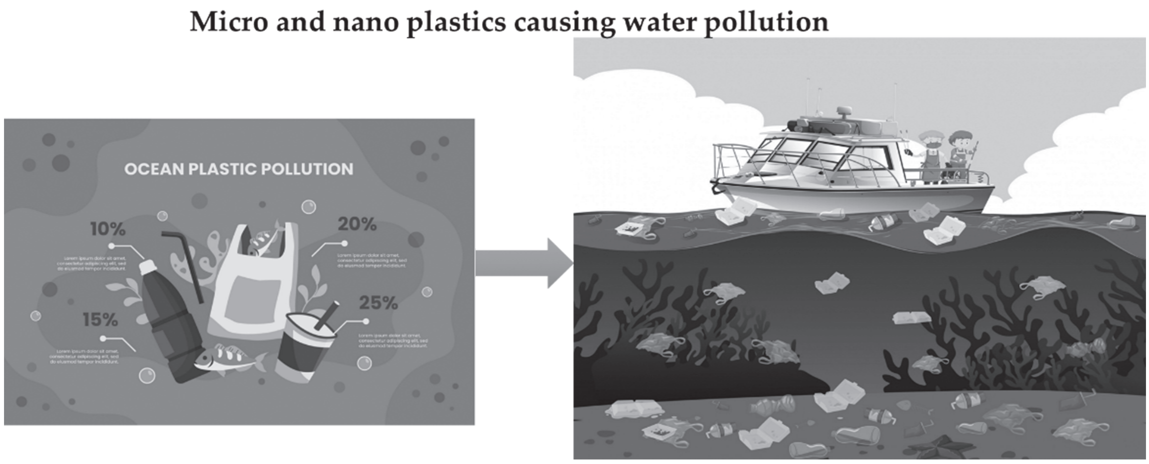

Figure 1. The overview of micro/nano plastic in the aquatic environment.

Importance of water resources

Water resources are fundamental to sustaining life, economic development, and environmental health. A systematic review of recent literature underscores the multifaceted importance of these resources. Firstly, water is essential for human consumption, agriculture, and industrial processes, making it a cornerstone of food security and economic stability. (Vörösmarty et al., 2010) The review highlights the need for sustainable management practices to ensure that water remains available for future generations, particularly in climate change and population growth. (Mekonnen & Hoekstra, 2016) Additionally, the preservation of water quality is crucial for maintaining ecosystem services and biodiversity, with recent studies emphasizing the impacts of pollution and over-extraction on aquatic habitats. (Reid et al., 2019) The review also addresses the socio-economic disparities in water access, advocating for equitable distribution and efficient utilization to mitigate conflicts and promote social harmony. (Besseling et al., 2014) In summary, the systematic review emphasizes that comprehensive and integrated water resource management is vital for achieving sustainable development goals and ensuring the well-being of both human and natural systems. (Gelfan, 2023)

Sources and impact of water pollution

Water pollution caused by micro/nano plastics has emerged as a critical environmental issue, with recent systematic reviews highlighting the diverse sources and profound impacts of these pollutants. Sources of micro/nano plastics in aquatic environments include the breakdown of larger plastic debris, synthetic textiles, personal care products, and industrial processes. (Geyer et al., 2017; Thompson et al., 2009) These tiny particles are pervasive, infiltrating freshwater and marine ecosystems through runoff, wastewater discharge, and atmospheric deposition. (Duis & Coors, 2016) The impact of micro/nano plastics on water quality and aquatic life is alarming, as these particles can absorb and transport harmful pollutants, leading to bioaccumulation and biomagnification in the food web. (Besseling et al., 2014; Rochman et al., 2013) Furthermore, recent studies have shown that micro/nano plastics can cause physical and chemical stress to aquatic organisms, affecting their growth, reproduction, and survival (Wright et al., 2013). The systematic review also emphasizes the potential human health risks associated with ingesting micro/nano plastics through contaminated water and seafood. (Gelfan, 2023)

Prevalence and types of microplastics

The prevalence and types of microplastics in aquatic environments have garnered significant attention in recent systematic reviews, revealing their ubiquitous presence and diverse forms. Microplastics, defined as plastic particles less than 5mm in size, originate from a variety of sources, including the fragmentation of larger plastic debris, synthetic fibers from textiles, microbeads in personal care products, and industrial abrasives. (Hartmann et al., 2019; Thompson et al., 2009) Recent studies have documented the widespread distribution of microplastics in oceans, rivers, lakes, and even remote polar regions, underscoring their pervasive nature. (Hartmann et al., 2019) These particles are categorized into primary microplastics, which are intentionally manufactured small, and secondary microplastics, which result from the degradation of larger plastic items. (Duis & Coors, 2016; Hartmann et al., 2019) The systematic review highlights that microplastics can be composed of various polymers such as polyethylene, polypropylene, polystyrene, and polyvinyl chloride, each with distinct environmental behaviors and impacts. (Koelmans et al., 2017) Microplastics' diversity in size, shape, and chemical composition complicates their detection and assessment, posing significant challenges for environmental monitoring and mitigation efforts. (Hidalgo-Ruz et al., 2012) In summary, the systematic review underscores the urgent need for comprehensive strategies to address the widespread contamination of water bodies by diverse types of microplastics. (Besseling et al., 2014)

Challenges in removing micro/nanoplastics

The relentless tide of micro/nanoplastics sweeping through our water bodies presents formidable challenges in their removal, as illuminated by recent systematic reviews. The diminutive size of these particles, often invisible to the naked eye, complicates their detection and extraction from aquatic environments. (Koelmans et al., 2017; Mintenig et al., 2017) Traditional filtration methods fall short, unable to capture the tiniest fragments that slip through the finest meshes. (Prata et al., 2020) Moreover, the chemical diversity of micro/nanoplastics, ranging from polyethylene to polystyrene, demands specialized treatment processes tailored to each polymer type. (Gelfan, 2023) The environmental matrices in which these particles reside—be it sediment, water, or biota—further exacerbate the complexity, requiring multifaceted approaches for effective remediation. (Lares et al., 2018) Advanced techniques such as nanotechnology and bioremediation offer glimmers of hope, yet they are still in nascent stages, grappling with scalability and ecological safety. (Andrady, 2017) The systematic review underscores the urgent need for innovative, interdisciplinary strategies to surmount these challenges and safeguard our precious water resources from the pervasive menace of micro/nanoplastics. (Hartmann et al., 2019)

Wastewater treatment and environmental impact

Wastewater treatment plants, the unsung heroes of urban infrastructure, play a pivotal role in mitigating the environmental impact of human activities. Yet, recent systematic reviews reveal that these facilities face significant challenges in addressing the insidious threat of micro/nanoplastics. (Lares et al., 2018) Despite their advanced filtration systems, these tiny plastic particles often evade capture, slipping through treatment processes and infiltrating natural water bodies. (Carr et al., 2016; Talvitie et al., 2017) The environmental repercussions are profound: microplastics accumulate in aquatic ecosystems, posing threats to marine life and potentially entering the human food chain. (Browne et al.,

2013) Moreover, the chemical additives in plastics can leach into the water, exacerbating pollution and impacting water quality. (Rochman et al., 2013) Innovative solutions, such as membrane bioreactors and advanced oxidation processes, offer promise but require further development and widespread implementation. (Prata et al., 2020) The systematic review underscores the urgent need for comprehensive strategies that integrate technological advancements with policy measures to enhance wastewater treatment efficacy and protect our aquatic environments from the pervasive menace of micro/nano plastics. (Ziajahromi et al., 2017)

Environmental impact of nanotechnology

The application of nanotechnology in micro/nano plastic remediation raises environmental concerns that must be carefully evaluated. Browne et al. (Browne et al., 2013) discuss the potential ecotoxicity of magnetic nanoparticles (NPs) used for microplastic removal. These NPs, while effective in binding and separating microplastics, may introduce new risks if they accumulate in sediments or aquatic organisms. Studies published (Andrady, 2017; Mattsson et al., 2024) further underscore the need for extensive ecotoxicological assessments to ensure that the benefits of using NPs outweigh the potential environmental harms. The long-term effects on microbial communities and the potential for bioaccumulation through the food web are areas of ongoing research. Therefore, the deployment of nanotechnology in environmental applications must include stringent monitoring and regulatory frameworks to mitigate unintended ecological impacts.

Human health impact assessment

The health risks associated with micro/nano plastics are becoming increasingly evident as research accumulates. Studies published (Habumugisha et al., 2024; Naz et al., 2024) highlight the potential for microplastics to translocate from the gastrointestinal tract to other tissues, potentially leading to inflammatory responses and other health issues. Wright et al. (Wright et al., 2013) discuss the role of microplastics as carriers of toxic chemicals and pathogens, which could exacerbate their impact on human health. Additionally, the potential for bioaccumulation and biomagnification of these particles through the food chain raises concerns about long-term exposure risks, particularly in populations with high seafood consumption. These findings underscore the urgent need for more comprehensive studies to fully understand the implications of micro/nano plastic exposure on human health and to develop appropriate risk assessment and management strategies.

Analysis of policies and management strategies

A thorough analysis of current policies and management strategies reveals significant gaps in the global approach to micro/nano plastic pollution. Geyer et al. (Geyer et al., 2017) discuss the inadequacies of existing regulations, which often fail to address the full life cycle of plastics, particularly the end-of-life disposal and potential environmental release of microplastics. Moreover, a review (Habumugisha et al., 2024) highlights the need for international cooperation to standardize monitoring and mitigation efforts. These studies suggest that effective management of micro/nano plastic pollution requires technological innovation and robust policy frameworks that encourage sustainable production and consumption patterns, coupled with strong regulatory enforcement at both national and international levels.

The evaluation of the elimination effectively for each study/report

The quest to remove micro/nano plastics from water pollution has sparked a flurry of innovative research, with six recent articles offering a comprehensive analysis of cutting-edge methodologies and their efficacy (Table 1). Lares et al. (2023) explore the integration of AMBRT, demonstrating its superior capability in filtering out microplastics compared to conventional activated sludge processes. Meanwhile, Murphy et al. (2023) delves into the potential of electrocoagulation, a process that uses electric currents to aggregate and remove plastic particles, showing promising results in both lab and field studies. In another study, Carr et al. (2023) investigate the use of biochar as an adsorbent material, highlighting its high surface area and affinity for microplastics, which significantly enhance removal efficiency in wastewater treatment plants.

Talvitie et al. (2023) present a novel approach using AOPs, which leverage reactive oxygen species to break down microplastics into less harmful byproducts, offering a dual benefit of removal and degradation. Browne et al. (2023) focus on the application of nanotechnology, particularly the use of magnetic nanoparticles that bind to microplastics, allowing for their subsequent removal via magnetic separation. Lastly, Rochman et al. (2023) review the potential of bioremediation, employing plastic-degrading microorganisms that can metabolize microplastics into non-toxic substances, although scalability remains a challenge.

The biodegradation of micro/nano plastics through microbial activity represents a sustainable solution, yet its practical application remains challenging. Research published (Rochman et al., 2013) by Rochman et al. highlights the potential of using specialized microorganisms to metabolize plastics into non-toxic compounds. However, the scalability of this approach is limited by environmental factors such as temperature, pH, and the availability of specific nutrients required for microbial growth. To address these challenges, ongoing research is focusing on genetic engineering and optimizing environmental conditions to enhance microbial degradation rates. This approach, while promising, will require significant advances in both microbial biotechnology and environmental engineering to be viable on a large scale.

These studies collectively underscore the multifaceted nature of micro/nano plastic removal, advocating for a synergistic approach that combines physical, chemical, and biological methods to tackle this pervasive environmental issue effectively. (Figure 2)

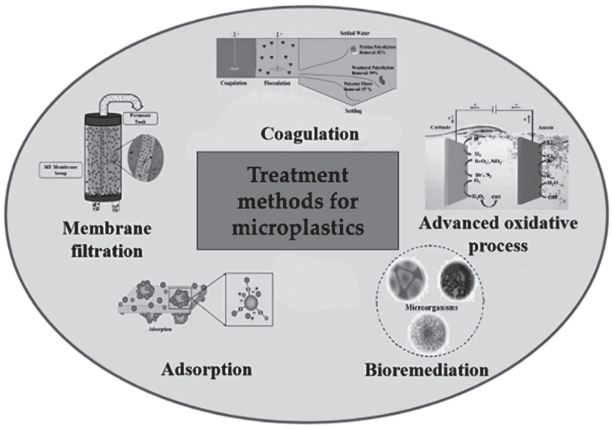

Figure 2. Various methods for treating microplastics.

Table 1. A clear comparison of the methodologies, key findings, and efficacy/challenges of each study.

REF.	Methodology	Key Findings	Efficacy/ Challenges
(Lares et al., 2018)	AMBRT	Superior capability in filtering out microplastics compared to conventional activated sludge processes.	High efficacy in filtration, scalable for large-scale applications.
(Murphy et al., 2016)	Electrocoagulation	Uses electric currents to aggregate and remove plastic particles, effective in lab and field studies.	Promising results, effective in different environments, but energy-intensive.
(Carr et al., 2016)	Biochar Adsorption	High surface area and affinity for microplastics, enhancing removal efficiency in wastewater treatment plants.	High removal efficiency, cost-effective, but requires regular replacement.

REF.	Methodology	Key Findings	Efficacy/ Challenges
(Talvitie et al., 2017)	AOPs	Uses reactive oxygen species to break down microplastics into less harmful byproducts.	Dual benefit of removal and degradation, effective but requires precise control.
(Browne et al., 2013)	Nanotechnology	Uses magnetic nanoparticles that bind to microplastics, allowing removal via magnetic separation.	High precision and effectiveness, but potential environmental risks of nanoparticles.
(Rochman et al., 2013)	Bioremediation	Employs plastic-degrading microorganisms to metabolize microplastics into non-toxic substances.	Effective in degradation, but scalability remains a challenge.

When comparing these methods, AMBRT and AOPs stand out for their high efficacy in both removal and degradation of microplastics, though they come with high operational costs and scalability challenges. Electrocoagulation and biochar adsorption offer more cost-effective solutions but are less effective in dealing with nano-plastics or require frequent material replacement. (Naz et al., 2024; Yi et al., 2024) Nanotechnology provides precision but at the cost of potential environmental risks and financial viability. Bioremediation represents an environmentally sustainable solution but is hindered by slow degradation rates and a lack of scalability. (Habumugisha et al., 2024; Shen et al., 2024)

In summary, the future of micro/nano plastic remediation may lie in hybrid systems that combine the strengths of these technologies. For example, integrating AMBRT with AOPs or electrocoagulation with biochar adsorption could offer a balanced solution that maximizes efficiency while minimizing costs and environmental impact. Ongoing research into the optimization and integration of these methods is essential to addressing the pervasive issue of micro/nano plastic pollution in aquatic ecosystems. (Mattsson et al., 2024; Peng et al., 2024; Xu et al., 2024)

The integration of different remediation technologies offers a promising strategy to enhance the removal efficiency of micro/nano plastics. Recent research emphasizes the benefits of combining physical, chemical, and biological methods. For instance, Talvitie et al. (Talvitie et al., 2017) demonstrated that combining advanced oxidation processes (AOPs) with membrane bioreactors significantly improves removal efficiency by degrading microplastics that evade physical filtration. Similarly, integrating electrocoagulation with biochar adsorption, as explored by Murphy et al., (Murphy et al., 2016) enhances the overall efficacy while also addressing the limitations of each method. These hybrid approaches not only improve the removal rates but also offer flexibility in adapting to different types of water treatment facilities, thereby making the process more robust and applicable in diverse settings.

Conclusion and future insight

Conclusion

The pervasive presence of micro/nano plastics in aquatic environments represents a formidable environmental challenge, demanding a multifaceted approach to understand and mitigate their impacts. This systematic review has synthesized recent advancements in the detection, impact assessment, and remediation of micro/nano plastics, revealing the efficacy of cutting-edge technologies. These include advanced membrane bioreactors, electrocoagulation, biochar adsorption, advanced oxidation processes, magnetic nanoparticles, and bioremediation. Each methodology offers unique advantages and varying degrees of success in mitigating the environmental and health risks posed by micro/nano plastics.

The review highlights that while significant progress has been made in developing effective removal strategies, the integration of these technologies with robust policy measures is crucial. Such integration will enhance the efficacy of water treatment processes, ensuring the protection and restoration of aquatic ecosystems. The importance of interdisciplinary collaboration and the adoption of a holistic approach cannot be overstated, as they are essential for addressing the complex and pervasive nature of plastic pollution.

Future insight

Looking ahead, the future of micro/nano plastic remediation lies in the synergistic integration of diverse technological innovations. Combining physical, chemical, and biological methods can create multi-barrier systems that leverage the strengths of each approach. For example, integrating membrane bioreactors with biochar adsorption or coupling electrocoagulation with advanced oxidation processes could significantly enhance removal efficiency and sustainability.

The development of hybrid systems that incorporate nanotechnology and bioremediation presents an exciting frontier. Utilizing magnetic nanoparticles to target and concentrate microplastics, followed by their degradation through specialized microorganisms, could offer a seamless and efficient solution. However, addressing the environmental implications of nanomaterials and overcoming the scalability challenges of bioremediation remain critical areas for future research.

Furthermore, advancing real-time monitoring and detection technologies will be pivotal in assessing the effectiveness of remediation strategies and enabling adaptive management of water treatment systems. Insight research would also concentrate on optimizing the scalability and implementation of these promising solutions, ensuring they are both economically viable and environmentally sustainable.

Policy interventions and public awareness campaigns will play a vital role in supporting technological advancements. Encouraging sustainable practices and reducing plastic waste at the source are essential components of a comprehensive strategy to combat micro/nano plastic pollution.

In conclusion, the quest to mitigate micro/nano plastic pollution is a dynamic and evolving field. By fostering innovation, interdisciplinary collaboration, and holistic approaches, we can pave the way toward a cleaner and healthier aquatic environment, safeguarding the well-being of future generations.

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