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Research Article

Detection to Remediation: Strategies for Managing Microplastic Pollution in Freshwater Systems

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Abstract:

Micro plastic pollution is currently a serious challenge to freshwater ecosystems and a strategy is required to ensure detection, control and alleviation. Micro plastics are defined as plastic pieces measuring less than 5mm in diameter and can be broken down in to primary sources of micro plastic, which include the synthetic fibres of fabrics used in clothing, and secondary sources, which include the worn out pieces of plastics. They are common in waste water, industrial effluents and agricultural run offs and they are long-lived in the rivers, lakes and reservoirs, serving as carriers of harmful contaminants and also upsetting the aquatic food chains. They are ingested by organisms at the zooplankton level to the fish, which causes them to bio accumulate, decrease biodiversity, and create a possible risk of health problems to humans via water consumption and seafood intake. These risks are further increased by Nano plastics, which are even smaller in size and dance through the lines of biological barriers. Detection Methods, such types include spectroscopy, microscopy, and imaging using machine learning, which are improved but have approximating protocols and issues in determining the Nano plastics. Technology options that treat pollution include membrane filtration, advanced oxidation processes, and biodegradation but are overly selective in their efficiency, subject to scalability, processing costs, and removal of neoplastic. Micro plastics are mostly eliminated through wastewater treatment facilities, but the sludge and fragmentation are still a question. The constructed wetlands are sustainable in terms of filtration although they are likely to turn into reservoirs of pollutants. The policy frameworks, including those of the U.S., the EU and the UNEP are divided and lack special indicators regarding secondary micro plastics and do not have international commitments. The paper is a review of state-of-the-art strategies that are summarized with an emphasis on technological, logistical, and regulatory barriers. In the future, the focus should be on standardized detection, scalable interventions, and complete impact assessment, and strong policies should minimize the introduction of micro plastics and facilitate the protection of freshwater systems both ecologically and in the area of human health.

1. Introduction

The micro plastic pollution has been a subject of concern to environmentalists and currently considered as one of the most urgent environmental problems in the aquatic ecosystems around the world. Micro plastics are plastic elements measuring less than 5 millimetres and are able to arise in many acting sources, such as the breakage of massive plastic litter, garment or textile products without exception wash water and personal cleansing items (Hale et al., 2020). Although micro plastics have already been observed in oceans, fresh water systems are being identified as important landscapes at which they accumulate and affect. Micro plastic contamination is especially of concern along freshwater ecosystems that are primary sources of drinking water, agricultural and industrial consumption (Fu and Wang, 2019).

The recent issue of micro plastic pollution in freshwater systems has been described in reference to their global concern in many studies. Zandaryaa, (2021) concluded a review of the growing awareness of micro plastic pollution of rivers, lakes, and reservoirs, the sources of clean water that millions of people around the globe use. Direct urban run-off, waste Water treatment plants (WWTPs) and industrial effluents make direct entry into these ecosystems and hence they constitute ubiquitous micro plastics (Habib et al., 2020; Landeros et al., 2022). Existence of the issue of the micro plastic pollution of the freshwater bodies under the pressure of the climate crisis and anthropogenic influence increases the risks to the water supply and its natural habitability, as well as to the human health.

The relevance of the subject matter of micro plastic contamination of the freshwater systems can hardly be overestimated. Micro plastics are also causing a tremendous harm to the aquatic life comprising of fishes, amphibians and invertebrates who risk by ingesting the micro plastics thus bio accumulating and becoming toxic (Al-Thawadi, 2020). In addition to the direct effect on marine life, there is this case of the endangerment of the human population that is exposed to these contaminants in administering the contaminated water supply and fish lifestyle. The rise of the awareness of the ecological and health-related risks of micro plastic is shown to increase the necessity of widespread approaches to the amelioration of their presence and impact.

Scope of the Paper

The purpose of the given paper is to conduct an extensive review of the current state-of-the-art approaches toward micro plastic pollution management in freshwaters. It will discuss the following major issues:

Sources and Fate of Micro plastics in Freshwater: It is also important to know how micro plastic formed and behaves in fresh water to better manage it. This part will discuss the different sources namely plastic waste, wastewater outflows, and agricultural runoff and the destination and conveyance of micro plastic in these ecosystems.

Detection and Quantification Techniques: Quantification and characterization of micro plastic in freshwater has been achieved using various analytical techniques including microscopy, spectroscopy, and chromatography as the identification and detection of micro plastic in environmental matrices become more advanced. This part will assess such techniques in terms of their accuracy, sensitivity and applicability.

Impacts on Ecosystems and Human Health: In this section, the effects of micro plastic pollution on ecology and health shall be discussed with focus on effects on aquatic life and how this would affect humans through water and by consuming contaminated fish.

Treatment and Removal Technologies: The following section will discuss the existing methods of treating micro plastic in freshwater, such as physical, chemical, and biological methods. It will further explain difficulties related to these technologies, e.g., efficiency and cost.

Policy and Regulatory Overview: Knowledge of the policy environments and legislatures of micro plastic pollution is also critical in informing future attempts to curb the problem. This section will examine the functions of EPA, EU and UNEP in the regulation of micro plastic pollution and the effectiveness of current policies.

Themes/Keywords

The main themes in this paper will include micro plastic pollution, freshwater systems, environmental concerns, and water contamination. These key words will be used to search the literature of relevance to the sources, fate, effects and mitigation of micro plastics in fresh waters. The review will also showcase emerging technologies and the policy measures implementing a reduction of micro plastic pollution to mitigate the impact on ecosystems and human health.

2. Sources and Fate of Micro plastics in Freshwater

Poisoning of micro plastic in freshwater systems has various sources but the major causes relate to wastewater, industrial effluents, agricultural runoffs, and broken pieces of plastic. These are plastic pollutants and consist of plastic particles less than 5 mm in size which access aquatic environments via primary and secondary routes. Primary micro plastics include microbeads used in personal care products, as well as synthetic textile fibres, and are produced in an intentional way, whereas secondary micro plastic is the degradation of larger plastics that are subjected to environmental stressors, including UV radiation and abrasion by mechanical forces (Xu et al., 2020; Acharya et al., 2021; Wang et al., 2020). A large source of microfibers is found in synthetic fabrics, mainly polyester, which shed thousands to millions of microfiber during domestic and industrial washing and laundering that washes every wash. This type of microfiber includes mostly polyester, acrylic and polyamide and it is estimated to contribute about 35 percent of micro-plastics in water bodies with many of the micro-fibres evading even waste water treatment plants (WWTPs) because they are so very small (100-800m). Personal care products, containing microbeads, and tire wear particles, which account for 5–10% of oceanic plastics, further exacerbate contamination through urban runoff. Agricultural practices, such as plastic mulching films, introduce micro plastics into soils, which can migrate to freshwater via runoff, while aqua cultural activities, including the use of plastic fishing gear, contribute through direct wastewater discharge.

WWTPs play a dual role as both a barrier and a pathway for micro plastic pollution. Despite removal efficiencies ranging from 35–99%, significant quantities of micro plastics persist in effluents due to high influent volumes. Studies report influent concentrations of 18–890 particles per litre, reduced to 6–26 particles per litre in effluents, with no preferential removal based on polymer type, shape, or size. Industrial WWTPs and direct discharges from chemical, textile, and electroplating industries release 6–23 particles per litre, while livestock farms and fish ponds contribute 8–40 and 13–27 particles per litre, respectively. Polyethylene (PE), polypropylene (PP), and polystyrene (PS) dominate across sources, comprising 83% of detected micro plastics, with fragments and films being the most common shapes. Particle-size is smaller (<500 1m) which is more dominating and dangerous, owing to its bioavailability (Wang et al., 2020).

The consequences of these sources are deep with regard to the environment. They contain microfibers because of their low density, which causes them to travel long distances and enhanced adsorption of pollutants; thus, aquatic biota can be threatened by ingestion and bioaccumulation. Their occurrence in freshwater systems even in areas that are inaccessible results in the importance of rivers in delivering terrestrial micro plastic to oceans, as 70 80% of marine micro plastics have their sources on land (Xu et al., 2020; Acharya et al., 2021).

The examined literature gives a good set of information about the sources of micro plastic but shows the methodological inconsistencies that impairs comparative analysis. The results are inconsistent due to the use of varying mesh sizes (e.g., 13 versus 250 m) and detection method (e.g., micro-Raman versus visual identification) even though these methods may result in underrepresentation of small particles such as microfibers (Wang et al., 2020). Occurrence of fibre-associated datasets that do not show fibres in some datasets may indicate a sieve restriction as opposed to habitat absence and hence, standardization of protocols (Acharya et al., 2021). WWTPs are referred to as the critical pathway but the studies do not dwell much upon the sludge management as the captured micro plastics may find their way back to land systems through the agricultural practice (Xu et al., 2020). In addition, synthetic micro plastics are being prioritized although natural-based fibres (e.g., cotton, rayon) might contain toxic substances and also need attention. The geographical restrictions of the study to China have a drawback to global generalization because the practices of the industrial waste management across the regions are different. Further studies should focus on uniformed methodology, complete tracking of sources, and the ecological repercussions of natural-based microfiber to develop specific mitigation measures.

Fate and Transport of Micro plastics in Freshwater

Freshwater ecological systems have very intricate behaviour and permanency of micro plastic pollution, as well as layering with pollutants that considerably alter their ecological destination and ecological presumptions. Micro plastics are particle sizes of less than 5 mm transported by the hydrodynamic process in the freshwater systems, i.e. rivers, lakes, and estuaries that include advection, dispersion, and sedimentation which are instigated by influences of water flow, wind, and turbulence. Physicochemical properties such as size, shape, density, and type of the polymer determine their distribution. Low density polymers such as polyethylene (PE) and polypropylene (PP) floated more whereas denser ones such as polyvinyl chloride (PVC) settled on benthic regions. The smaller particles, especially Nano plastics (<1 μm), have an enhanced mobility and bioavailability attributable to the larger surface area that enables transportation over longer distances and the contact with biota (Atugoda et al., 2022; Ma et al., 2016).

The micro plastics have persistence in freshwater, which is due to their lack of biodegradability. Photo-oxidation, mechanical abrasion, and microbial degradation result in slow degradation, usually breaking micro plastic to Nano plastics that are more potentially harmful to the environment through increased bioavailability. Bioaccumulation occurs throughout the trophic levels, whether they are lower level, such as primary producers of algae microbes or higher predators such as fish or birds. The non-selective filter feeders such as zooplankton e.g. Daphnia magna easily swallow micro plastic and become physically impaired, have low fecundity, and undergo trophic transfer. Research shows that the micro plastic can accumulate in the gastrointestinal tract of organisms, and smaller micro plastic goes into tissues, leading to oxidative stress and impaired metabolism (Ma et al., 2016; Atugoda et al., 2022).

The micro plastic functionality and sorption serve as a transporter vehicle of pollutants with hydrophobic organic properties (HOCs), such as: polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and heavy metals. The polymer crystallinity, particle size, and weathering affect sorption, and aged micro plastics have higher sorption capacity even though due to surface oxidation and biofilm development. An example of the existent relation is that weathered micro plastic sorbs more amounts of PAHs and metals and increases their toxicity upon ingestion. Micro plastic toxicity has been reported to be additive with phenanthrene, a model PAH, in D. magna and Nano plastics further stimulate bioaccumulation because they can also enter biological barriers. The desorption of pollutants in the gastrointestinal systems can enhance bioavailability which may result in bio magnification along food webs (MenEndez-Pedriza and Jaumot, 2020; Ma et al., 2016).

The studies reviewed give helpful information but discover flaws and omissions. The selected polymers include polystyrene and PE, which do not reflect the knowledge of other polymers such as PET and PVC, which are prevalent in some freshwater systems (Atugoda et al., 2022). Direct comparisons cannot be made due to methodological differences including the sizes of the particles as well as the levels at which they were exposed to. Indicatively, the D. tragna tests exhibit environmentally irrelevant doses, and hence it might be overestimating the toxicity (Ma et al., 2016). There exists no uniform guidelines regarding the collection and analysis of the data, especially in terms of Nano plastics that are poorly studied because of their difficulty to detect (Menendes-Pedriza and Jaumot, 2020). While sorption mechanisms are well-documented, the ecological significance of pollutant transfer through micro plastics remains debated, as some argue that dissolved organic matter outcompetes micro plastics in pollutant partitioning. The regional bias toward specific ecosystems, like Asian rivers, limits global applicability, and long-term field studies are scarce. Future research should prioritize standardized methodologies, environmentally relevant concentrations, and comprehensive polymer diversity to better elucidate micro plastic fate and ecological risks in freshwater systems.

3. Detection & Quantification Techniques

Overview of Detection Methods

The detection and quantification of micro plastics in environmental matrices, particularly freshwater systems, rely on advanced microscopy, spectroscopy, and chromatography techniques, each offering unique strengths and facing specific challenges. Morphological classification of micro plastics >500 μm can be achieved by optical microscopy with or without the assistance of staining with dyes such as Nile Red; however, the method becomes error-prone (20-70%) when applied to smaller particles, as they are easily confused with natural materials such as sand or chitin (Ebere & Ngozi, 2019). Scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) provides high-resolution imaging and elemental analysis, revealing surface degradation and inorganic additives in micro plastics, but is limited to solid samples and requires flat surfaces for accurate quantification (Ebere & Ngozi, 2019).

The most popular conversational (spectroscopic) techniques include Fourier-transform infrared (FTIR) and Raman spectroscopy due to their capacity to detect the composition of polymers. With a high specificity (based on molecular bonds like C-H and C=O) and effective at the particle size >20 μm, Micro-FTIR is operating on reflectance or transmittance mode, which is time-consuming when the sample size is large due to the single-detector issue (Bock et al., 2022; Ebere & Ngozi, 2019). Raman micro spectroscopy excels at identifying smaller particles (<1 μm) by measuring inelastic light scattering, offering subcellular precision in biological tissues. However, fluorescence from organic residues can obscure spectra, necessitating pre-purification (Ebere & Ngozi, 2019; Levermore et al., 2020). Optical photo thermal infrared (O-PTIR) spectroscopy, combined with simultaneous Raman, enhances resolution to submicron levels, improving identification through dual IR and Raman hit quality indices (2D-HQI), though it requires careful calibration to mitigate intensity variations (Böke et al., 2022). Raman spectral imaging, coupled with chemo metric analyses like Pearson's correlation and agglomerative hierarchical clustering, identifies micro plastics ≥2 μm in complex matrices like ambient particulate matter, but demands rigorous contamination controls (Levermore et al., 2020; Zhao et al., 2017).

Pyrolysis-gas chromatography/mass spectrometry (Pyr-GC/MS) quantifies polymer types by thermally decomposing samples into characteristic fragments, but its manual sample placement restricts analysis to larger particles (>500 μm) and limits high-throughput applications (Ebere & Ngozi, 2019). CHN analysers, using combustion to detect carbon, hydrogen, and nitrogen content, identify larger micro plastics but are less effective for heterogeneous or small samples (Ebere & Ngozi, 2019).

These studies highlight complementary strengths but reveal critical gaps. The lack of standardized protocols, including mesh sizes and purification methods, leads to inconsistent size detection limits and abundance estimates (Ebere & Ngozi, 2019; Zhao et al., 2017). Aggressive chemical digestion (e.g., HNO3, KOH) risks polymer degradation, affecting accuracy, while milder agents like 15% H2O2 minimize damage but may not fully remove organic matter (Zhao et al., 2017). The overlap of fluorescence in Raman and spectral overlap of additives such as pigments makes the identification difficult and may require advanced methods such as spectral subtraction or use of higher wavelength lasers (Bok and et al., 2022; Levermore et al., 2020). The preoccupation in marine and atmospheric samples does not provide a lot of information on freshwater issues unique to that system, like the presence of complex organic matrices. Researchers need to focus on using standardized non-destructive and automated systems in the future to facilitate throughput and comparable data across environmental matrices.

Recent Advances in Detection

The new development of micro-plastic detection is being done on new methods of detection, automation, and increased sensitivity and optimism to meet the challenges of performing micro-plastic detection in complex environmental samples such as freshwater systems. Another major breakthrough is the application of Nile red (NR) staining and fluorescence microscopy with automated image analysis which is a cost and time efficient method of detecting micro plastics as small as 50 µm. This approach explores the fluorescence emission spectrum of NR besides blue and green filters and provides the classification results through comparing popular machine learning (ML) models in order to quantify Red-Green-Blue (RGB) colours obtaining 95.8 and 88.1 detection percentages discrimination between plastics and non-plastics. Compared with three times longer analysis by traditional micro-FTIR, the automation allows the analysis of heavily loaded samples in about 80 min and offers greater throughput to monitor large-scale samples (Meyers et al., 2022).

ML-based approaches have further revolutionized detection by integrating hyperspectral imaging and deep learning. Support vector machines (SVMs) and random forests, applied to FTIR and Raman spectral data, improve classification of micro plastics (e.g., PE, PP, PS) in diverse matrices, with accuracies exceeding 90% even amidst organic interference. Convolutional neural networks (CNNs) automate image-based identification, analysing shape, size, and colour, reducing subjectivity inherent in manual microscopy. Hyperspectral imaging captures both spatial and chemical data, enabling non-destructive detection of particles as small as 10 µm, critical for addressing the underestimation of smaller micro plastics (Khanam et al., 2025; Zhang et al., 2023). Mobile-based detection using smartphone cameras and semi-automatic image processing, such as canny edge detection, offers scalable, field-applicable solutions, though image quality and connectivity remain constraints (Khanam et al., 2025).

More recent innovations such as laser direct infrared (LDIR) imaging with ML will minimise errors associated with classical spectroscopy and increase precision on complex samples. The optical photo thermal infrared (O-PTIR) spectroscopy, used alongside Raman, provides sensitivity enhancement of Nano plastics to sub microns to enhance their sensitivity. The lack of automation and high expenses of conducting the examination in terms of visual-based sorting and high costs of FTIR are some of the limitations of conventional methods encompassed by these empowerments, as they focused on automation and decreasing the pre-processing requirements (Zhang et al., 2023; Khanam et al., 2025).

All of these studies are helping the detection of micro plastic but undergo issues with standardization and applicability. Although the NR staining procedure is effective, it is also affected by fluorescent inconsistency caused by polymer additives and weathering, and this is likely to skew RGB-based classification (Meyers et al., 2022). Other methods Other methods, such as ML models, are very accurate, but they demand large and diverse datasets, which are not available when it comes to less common polymers or Nano plastics, hindering generalizability (Khanam et al., 2025). The hyperspectral and LDIR data scanning methods have potentials but are expensive in computational requirements and equipment, making them unattainable by resource-constrained environments (Zhang et al., 2023). The marine focus of such studies does not take into consideration the features of freshwater environments e.g. high organic content which may compromise spectral data. The issue of data comparability is enhanced by the absence of standardised methods of protocols. The uncommon methods, real-time in-situ detection and inclusive data sets could be prioritized by researchers in future to increase the global monitoring and mitigation measures.

4. Impacts on Ecosystems and Human Health

Ecological Impacts

Particles less than 5 mm in size known as micro plastics (MPs) have a substantial ecological effect on a freshwater ecosystem by ingestion, bioaccumulation, trophic transfer and disorder of seafood webs, ultimately endangering biodiversity. High frequencies of ingestion of MPs by aquatic organisms as small as zooplankton and fish occur because of their small size and the likelihood that they are confused with natural foods. Having a lower feeding efficiency, oxidative stress, and reduced reproduction rate, non-selective feeders such as Daphnia magna consume the particle size of 1 70 3m (Bellasi et al., 2020). Benthic feeding organisms (amphipods (Gammarus fossarum) and mussels (Dreissena polymorpha)) ingest MPs as well, with problems in MP assimilation efficiency, weight loss, and cell stress, and ingestion is size- and shape-dependent (Bellasi et al., 2020; Ziani et al., 2023). Sediments are dominated by fibres and fragmentation, especially relating to benthic communities, which play an increasing role in moving fish prey biomass up to 90 percent up the trophic ladder (Bellasi et al., 2020).

The bioaccumulation happens when the MPs accumulate in the tissues of the organisms, proliferating in the guts of the living organisms, and the wee MPs are carried by translocation in the significant organs of the body such as the liver and haemolymph. Research has documented the presence of MPs in 32-100 percent of freshwater invertebrates, and levels in the gills of the crab, Carcinus maenas, and the tissues of Anodonta anatina, which suggests their attachment and uptake in addition to ingestion (Bellasi et al., 2020; Okeke et al., 2023). One of the contributing factors is trophic transfer, whereby once the MPs are in primary consumers, they transfer to the predators such as fish, birds, and land creatures. As an example, the polycyclic aromatic hydrocarbons (PAHs) documented in larval MPs in freshwater fish (Rutilus rutilus) are associated with an increased tissue content of polychlorinated biphenyl (PCB), which is threatening to human consumers through seafood (Bellasi et al., 2020; Ziani et al., 2023). This transfers distorts the food web patterns, slowing the flow of energy and transformation in predator-prey relationships, which may cause a cascade effect to impact the stability of an ecosystem (Ali et al., 2024).

The effect of MPs on the occurrence of diversity is done by the alteration of habitats and community structure. Biofouling along with sedimentation of low density polymer with sediments (such as polyethylene, PE) results in an order of magnitude higher concentrations in sediments compared to those in water columns. Such agglomeration interferes with benthic bioturbation, nutrient processing, and microbial populations, decreasing the quality of habitats in which sediment organisms live (Bellasi et al., 2020; Okeke et al., 2023). The MPs also serve as carriers of the pollutants (persistent organic pollutants (POPs) and heavy metals) and increase the toxicity by the synergistic effects. As the example, PCBs are adsorbed by polyethylene pellets 100 times better than the natural particulate organic matter, which causes the increased risks of bioaccumulation (Bellasi et al., 2020; Ali et al., 2024). This compounding stress risks the diversity of the species, especially in some of the most affected urban lakes and rivers in which the levels of MP are linked to human activity (Ziani et al., 2023).

The research reviewed is thorough and has valuable information though showing much weakness. Experiments conducted in the lab normalize the concentrations of MPs to be high like in the case of Daphnia magna, experimental methods that are unable to standardize the concentrations of MPs to the environmental conditions and therefore can overestimate the effects of MPs ecologically (Bellasi et al., 2020; Okeke et al., 2023). The emphasis on widely occurring polymers (PE, PP, PS) ignores less widespread yet common plastics such as PVC and PET and impedes knowledge of peculiarities of polymers (Ali et al., 2024). There are methodological inconsistencies (classification of specific size, sampling procedures) between studies, which when combined with data comparison mainly affects sediment MP concentrations (Bellasi et al., 2020; Ziani et al., 2023). Higher bioavailability Nano plastics have not been well studied regarding their ecological role because of difficulty in detecting these pollutants (Okeke et al., 2023). More so, regional prejudice in the studies on European and Asian systems poses limits on international application. Studies pertaining to evaluations of impacts of MPs on freshwater biomes and food webs should focus on standardization of protocols, environmentally relevant levels, and field experiments.

Human Health Impacts

Micro plastics (MPs) are plastic particles less than 5 mm and introduce severe human health hazards given exposure avenues, including drinking water, consuming fishes, and breathing. MPs are prone to human health due to the fact that they could transfer toxic contaminants and additives. Seafood consumption, in general, is the major exposure route to the general population, and MPs have also been found in fish, shellfish, and even consumption water, such as tap and bottled water (Yuan et al., 2022). According to the researchers, human beings consume 10 and 100 MP particles in one litre of bottled water and even 39 000 particles per year due to seafood consumption, especially with mussels and oysters demonstrating significant levels of MP (Alekhya et al., 2024). Airwave exposure to MPs, including microfibers caused by clothing, also helps but the daily fall-out deposits 110 particles/m 2 in towns. Less is known about dermal infiltration which can occur during dermal exposure to MP-containing cosmetics (Yuan et al., 2022). The small size (<150 um) of the MPs permits the translocation across intestinal walls, lymph nodes, liver, and other organs, which may lead to cellular damages (Matavos-Aramyan, 2024).

Toxic contaminants such as persistent organic pollution (POPs) e.g. polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and heavy metals can adsorb to the surfaces of MPs as these are hydrophobic. Phthalates, bisphenol A (BPA), and flame retardants, included in the production of plastics, would leach to organisms that incorporate them in their ingestion affecting the endocrine system and carcinogenesis (Yuan et al., 2022). To give an example, polyurethane (PUR) and polyvinyl chloride (PVC) are reported to be highly toxic because of their monomeric composition and may also elicit acute toxicity, genotoxicity, and developmental toxicity (Yuan et al., 2022). The formation of Nano plastics (<l 1), the result of MP degradation, aggravates the problem due to their entry into biological barriers, such as the blood-brain barrier, causing chronic toxicities, i.e., cardiovascular, hepatotoxic, and neurotoxic effects (Matavos-Aramyan, 2024). MPs in seafood, particularly filter-feeding organisms, amplify contaminant transfer through the food chain, with studies reporting PCB concentrations 100 times higher on MP surfaces than in surrounding water (Alekhya et al., 2024).

Health impacts remain uncertain due to limited long-term data, but preliminary evidence suggests MPs may induce oxidative stress, inflammation, and immune responses. Chronic exposure could disrupt cellular processes, with Nano plastics potentially causing histopathological changes in tissues (Yuan et al., 2022). The presence of MPs in human blood, placenta, and breast milk raises concerns about systemic effects, though dose-response relationships are poorly defined (Matavos-Aramyan, 2024). Vulnerable populations, such as children, face heightened risks due to higher relative exposure and susceptibility to waterborne contaminants (Alekhya et al., 2024).

The reviewed studies provide a robust foundation but exhibit notable limitations. The reliance on high-exposure laboratory conditions, such as those used to assess MP toxicity, may overestimate risks compared to environmental levels, necessitating field-based studies with realistic concentrations (Yuan et al., 2022). The focus on marine-derived MPs overlooks freshwater-specific exposure pathways, such as groundwater contamination, which are critical for inland populations (Alekhya et al., 2024). Despite standardization in methodology, such as differences in the definition of MP size and detection limit, cross-study comparisons are difficult, especially because Nano plastics are extremely difficult to determine in biological matrices (Matavos-Aramyan, 2024). The focus of the studies on gastrointestinal exposure do not reflect the importance of exposure via inhalation and skin exposures, which can greatly contribute to the urban environment. Moreover, the toxicological research based on certain polymers (e.g., PUR, PVC) does not allow the consideration of the heterogeneity of MPs in nature and, thus, the applicability to other ones. Standardized procedures, longitudinal studies in humans, and extensive exposure investigations must be given priority in future research studies to determine the health risks of MP clarification and implementation of mitigation strategies.

5. Treatment & Removal Technologies

Physical, Chemical, and Biological Methods

There is a wide range of physical, chemical, and biological techniques used in the removal of micro plastic (MP) contaminants in freshwaters, with a unique mechanism and efficiency. Mechanical methods, which include filtration and sedimentation, are easy and common methods put into use since they can be utilized and are very practical. Membranes filtration (microfiltration (MF), ultrafiltration (UF)) have attained removal efficiency of >99% on MPs >1, uM where dynamic membranes and membrane bioreactors (MBRs) overcome the limitation of attaining removal efficiencies due to membrane fouling (Leone et al., 2023; Jani et al., 2024). Approximately 90-95 percent of MPs are removed in wastewater treatment plants (WWTPs) during primary and secondary treatment, but influent volumes still have critically high concentrations of MPs. Sorption techniques, using materials like activated carbon, effectively remove MPs but face challenges in sorbent regeneration (Miloloža et al., 2022).

Chemical methods, such as coagulation-flocculation, aggregate MPs for easier removal, achieving up to 90% efficiency in drinking water treatment. Advanced oxidation processes (AOPs), including photo catalysis with TiO_2 and ozonation, degrade MPs into smaller fragments or mineralize them into CO_2 and H_2O, though energy costs and potential toxic by-products limit scalability (Jani et al., 2024; Leone et al., 2023). Electrochemical oxidation, using reactive oxygen species, shows promise but requires further optimization for practical application (Miloloža et al., 2022).

Biological methods leverage microorganisms like bacteria (*Pseudomonas* spp.), fungi (*Aspergillus flavus*), and microalgae for MP Biodegradation. These organisms use oxidative enzymes (e.g., peroxidase, laccase) to break down polymers like polyethylene (PE) and polyethylene terephthalate (PET) into lower molecular weight compounds, metabolized via β-oxidation and the Krebs cycle. Bio augmentation and bio stimulation enhance degradation, with mixed microbial cultures outperforming single strains. However, biodegradation is slow, often taking months, and incomplete, producing intermediates that may persist (Miloloža et al., 2022; Jani et al., 2024). Combining biodegradation with physical or chemical methods, such as MBRs or sorption, improves efficiency, with hybrid systems achieving up to 99% MP removal in WWTPs (Leone et al., 2023).

The reviewed studies provide a comprehensive overview but reveal significant gaps. The emphasis on WWTP-based physical methods overlooks their limitations, such as sludge disposal, which can reintroduce MPs into terrestrial environments (Jani et al., 2024). Chemical methods like AOPs, while effective in controlled settings, lack field-scale validation, and their environmental impact, including by-product toxicity, is underexplored (Leone et al., 2023). Biological methods, though eco-friendly, are hindered by slow degradation rates and polymer-specificity, with limited data on neoplastic biodegradation (Miloloža et al., 2022). Methodological inconsistencies, such as varying MP size definitions and test conditions, impede cross-study comparisons. The studies' focus on high-income countries limits applicability to developing regions with resource constraints. Future research should prioritize standardized protocols, hybrid technology optimization, and environmental impact assessments to enhance the scalability and sustainability of MP removal strategies.

Challenges and Limitations

Micro plastic (MP) and neoplastic (NP) removal technologies face significant challenges in scalability, cost, and effectiveness, limiting their widespread adoption. Physical methods, such as membrane filtration (e.g., ultrafiltration, Nano filtration), achieve high removal efficiencies (>95%) for MPs but struggle with NPs due to their smaller size (<1 μm). Membrane fouling, driven by MP/NP adhesion, reduces efficiency and increases maintenance costs, particularly for high-pressure systems like reverse osmosis (Nene et al., 2025; Qi & He, 2025). Adsorption using materials like biochar or metal-organic frameworks (MOFs) offers 70–99% MP removal but faces scalability issues due to sorbent regeneration costs and potential secondary pollution from spent materials. Magnetic separation, leveraging functionalized nanoparticles, achieves 78–92% recovery for MPs but requires costly synthesis and optimization for diverse NP compositions (Mahmud et al., 2022).

Chemical methods, including advanced oxidation processes (AOPs) like photo catalysis and ozonation, degrade MPs into smaller fragments or mineralize them into CO2 and H2O. Photo catalysis, using TiO2 or ZnO, shows promise but is energy-intensive, with effectiveness varying by MP type (e.g., polyethylene vs. polystyrene). Ozonation achieves up to 90% MP degradation in 30 minutes but risks forming toxic by-products, complicating large-scale deployment (Qi & He, 2025; Nene et al., 2025). Coagulation-flocculation, while cost-effective for larger MPs (90% removal), is less efficient for NPs due to their low settling velocity, requiring additional treatment steps (Mahmud et al., 2022).

Biological methods, such as biodegradation by bacteria (*Ideonella sakaiensis*) or fungi, are sustainable but slow, often requiring months for partial MP degradation. Enzyme-based approaches (e.g., PETase) are effective for specific polymers like PET but lack versatility across MP types. Scalability is hindered by high enzyme production costs and limited field validation, with degradation efficiencies rarely exceeding 50% under environmental conditions (Nene et al., 2025; Mahmud et al., 2022). Biofilm-based systems in wastewater treatment plants (WWTPs) enhance MP removal (up to 98%) but are not designed for NPs, and sludge disposal poses recontamination risks (Qi & He, 2025).

The reviewed studies highlight a trade-off between effectiveness and practicality. Physical methods excel in MP removal but are cost-prohibitive and ineffective for NPs, a critical gap given NPs' higher toxicity (Nene et al., 2025). Chemical methods, while efficient, lack scalability due to energy demands and by-product concerns, particularly in resource-constrained regions (Qi & He, 2025). Biological methods align with sustainability goals but are impractical for immediate application due to slow kinetics and polymer specificity (Mahmud et al., 2022). The studies' focus on lab-scale experiments limits insights into real-world scalability, especially in developing countries where cost is a major barrier. Standardized detection and reporting protocols are absent, hindering comparative assessments. Future research should prioritize hybrid systems (e.g., AOPs with filtration), cost-effective sorbents, and NP-specific technologies, alongside robust life cycle assessments to ensure environmental sustainability.

6. WWTPs, Membranes, Constructed Wetlands, AOPs

WWTPs and Micro plastic Removal

Wastewater treatment plants (WWTPs) play a critical role in mitigating micro plastic (MP) pollution, capturing 90–99% of MPs from influent through primary, secondary, and tertiary treatment stages. Primary treatments, such as screening and sedimentation, remove larger MPs (>500 μm) via skimming and grit removal, achieving 40–90% efficiency, particularly for fibres. Secondary treatments, including activated sludge processes, further reduce MP concentrations by 42–98% through flocculation and biofilm formation, which trap smaller MPs (20–500 μm) in sludge. Tertiary treatments, like membrane bioreactors (MBRs), rapid sand filtration (RSF), and dissolved air flotation (DAF), exhibit high efficiencies (95–99.9%), with MBRs reducing MPs from 6.9 to 0.005 particles/L. Advanced methods, such as electrocoagulation (99.24% removal at pH 7.5), magnetic separation (78–92% for MPs 20 μm–1 mm), and photo catalysis (90.8% for LDPE), enhance removal but face scalability challenges (Jani et al., 2024; Depan, 2024; Mahmud et al., 2022).

Technological challenges persist, including MP fragmentation into Nano plastics (<1 μm) during mechanical processes like mixing and pumping, increasing effluent MP counts by up to 40 times. Sludge management is problematic, as MPs concentrated in sludge (0.2–14% of influent) can re-enter environments via land application. Membrane fouling in MBRs and ultrafiltration increases operational costs, while AOPs like ozonation risk producing toxic by-products. In developing regions like Bangladesh, inadequate WWTP infrastructure and high influent MP loads (0.14–3.14 × 10^4 particles/L) exacerbate challenges, compounded by limited recycling (9.2% of 545,300 tons plastic waste annually) and policy enforcement failures despite polythene bans (Jani et al., 2024; Depan, 2024; Mahmud et al., 2022).

The studies collectively underscore WWTPs' effectiveness but highlight inconsistent methodologies, such as varying sieve sizes (10–300 μm) and sampling techniques (grab vs. composite), which obscure cross-study comparisons. The focus on high-income countries limits insights into developing nations' unique challenges, like Bangladesh's reliance on open dumping. Nano plastic removal remains understudied due to detection limitations, and sludge disposal strategies are inadequately addressed, risking terrestrial contamination. While advanced technologies show promise, their high energy and cost requirements hinder scalability, particularly in resource-constrained settings. Future research should standardize protocols, prioritize NP detection, and develop cost-effective, region-specific solutions to enhance global MP management.

Membrane Filtration Systems

The Membrane filtration mechanism specifically microfiltration (MF), ultrafiltration (UF), is essential in reality in combating micro plastic (MP) pollution in freshwater systems providing quite effective removals of as small as 1 0m to as large as 5mm inferring pore sizes of approximately 0.1 10m in the membrane. Having smaller pore sizes (1 100 nm), UF performs best in the capture of smaller MPs, such as those <20 m (Poerio et al., 2019; Schuhen & Sturm, 2020; Sharma et al., 2023). The capacity of UF to selectively eliminate organic matter, pathogens, and MPs at the same time classifies it as an appropriate technology to use when producing drinking water but has difficulties with Nano plastics (NPs) and fibrous MPs, which may either block the pores or lead to fouling. Fe-based or Al-based salts coagulation improves the efficiency of UF by increasing the removal percentage of MPs up to 91% in case of polyethylene (PE) particles between 0 and 0.5 mm, but polyacrylamide (PAM) supplement use is a matter of concern as it can be carcinogenic (Poerio et al., 2019; Sharma et al., 2023). MBRs, combining MF/UF with biodegradation, achieve superior MP retention (99.4%), reducing effluent concentrations to 0.5 particles/L, but face challenges with membrane fouling and high energy costs (Schuhen & Sturm, 2020). Dynamic membranes (DMs), formed by cake layers on coarse meshes, offer a low-cost alternative, achieving >95% MP removal under gravity-driven conditions, though their efficacy for NPs remains untested (Poerio et al., 2019).

The studies highlight membrane filtration's potential but reveal critical limitations. The lack of standardized MP characterization protocols complicates efficiency comparisons, as size, shape, and polymer type (e.g., PE, PP, and PET) significantly influence removal (Sharma et al., 2023). UF outperforms MF for smaller MPs, but both struggle with NPs and fibres, necessitating tailored designs (Poerio et al., 2019). Fouling, exacerbated by small MPs forming cake layers, increases operational costs and reduces membrane lifespan, particularly in UF systems (Schuhen & Sturm, 2020). The studies' focus on lab-scale or WWTP settings limits insights into scalability and real-world applications, especially in developing regions. Future developments can focus on NP-specific membranes, standardized testing methods and hybrid systems in order to become more cost-effective and sustainable.

Constructed Wetlands and Natural Filtration

Natural filtration systems (NFs), as well as constructed wetlands (CWs), are becoming more popular in their ability to reduce micro plastic (MP) pollution of aquatic habitats in a way more compatible with the environment. These technologies utilize natural phenomena of plants, substrates, and microbe to clean a water source and provide a sustainable solution that is an alternative to traditional wastewater treatment facilities (WWTPs). CWs, with their substrates such as gravel or soil, with aquatic vegetation can perform sufficiently due to the physical entrapment of MPs through root roots and entrapment of their substrates, as well as the formation of the biofilm, with efficiencies of up to 68 to 100 percent elimination depending on the type of wetland, including horizontal subsurface flow (HSSF) or vertical streams (Dhilleswara Rao et al., 2024; Jensen et al., 2024). As natural filters, Riparian wetlands remove loads of nutrients and pollutants including MPs, through slowing water currents and aiding deposits, some studies report that the removal of MPs in surface water can reach 50 percent (Jensen et al., 2024). The positive aspects of such systems are that they need few amounts of energy, require little maintenance additionally and provide other ecological functions, such as creation of habits and biodiversity maintenance. Reeds, types of macrophytes, increase the retention of MP through the formation of microenvironments encouraging adsorption and biodegradation processes (Tavakoly Sany et al., 2014).

But difficulties still remain. An increase in MP concentration in sediments of wetlands may hamper nutrient dynamics, resulting in lower levels of nitrogen and phosphorus sequestration, owing to microbial community and plant-driven removal rates (Dhilleswara Rao et al., 2024). Permanent use can convert CWs to MP reservoirs, and is vulnerable to re-release during floods, seasonal changes, especially those CWs that lie in urban areas that influence large loads (Jensen et al., 2024). Regulation of the fate and toxicity of MP is hampered by the absence of standard monitoring procedures, and the process of MP reaction with other pollutants, such as heavy metals, has not been thoroughly discussed (Tavakoly Sany et al., 2014).

The literature underscores CWs' potential but highlights significant gaps. While removal efficiencies are promising, the studies lack consistency in MP size and type characterization, limiting comparability. The focus on physical retention mechanisms overlooks biodegradation potential, which could address NP challenges. Urban vs. rural differences in MP loads are understudied, and flood-induced resuspension risks are poorly quantified. Future research should standardize protocols, investigate MP-pollutant synergies, and optimize wetland designs for NP removal to ensure long-term sustainability.

Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) are increasingly vital for addressing micro plastic (MP) pollution in aqueous environments, leveraging reactive oxygen species (ROS) like hydroxyl (HO•) and superoxide (O2•−) radicals to degrade MPs and associated pollutants. Photo catalysis, primarily using TiO_2 and ZnO catalysts, achieves 30–100% degradation efficiencies for MPs like polyethylene (PE), polypropylene (PP), and polystyrene (PS), with modified catalysts (e.g., Ag-TiO_2, Pt-ZnO) enhancing performance by reducing electron-hole recombination (Sacco et al., 2023; Ricardo et al., 2021). Photo-Fenton processes, combining H_2O_2 and iron salts under UV light, generate HO• radicals but face challenges with sludge formation and limited efficacy for PS MPs (Sacco et al., 2023). Ozonation and electrochemical oxidation break down MPs into smaller fragments or mineralize them into CO_2 and H_2O, with efficiencies up to 90% in lab settings, though real-world applications are constrained by energy costs (Sutkar et al., 2023; Sacco et al., 2023). AOPs also degrade adsorbed pollutants, such as persistent organic pollutants (POPs) and heavy metals, reducing their bioaccumulation potential (Ricardo et al., 2021). Recent innovations include plasmonic photo catalysts (e.g., ZnO-Pt) and hybrid systems combining AOPs with filtration, achieving near-complete MP removal in wastewater (Sutkar et al., 2023).

The studies highlight AOPs' potential but reveal significant gaps. Lab-scale experiments dominate, often using idealized conditions (e.g., high MP concentrations, deionized water), limiting insights into real-world matrices with organic matter interference (Ricardo et al., 2021; Sacco et al., 2023). Variability in MP size, shape, and polymer type complicates degradation mechanisms, with smaller MPs degrading faster but posing detection challenges (Sutkar et al., 2023). The processes such as photo catalysis and ozonation, are energy-demanding and create scalability issues, especially in the environments with limited resources (Sacco et al., 2023). The by-products that are formed are toxic, including volatile organic compounds, which are not researched thoroughly, which is why they might hamper the gains on the environmental level (Ricardo et al., 2021). Experimental protocols have not been standardized, and this is a barrier to cross-study comparisons. The future work should be related to the field-scale tests, NP-specific AOPs, and toxicity of the degradation products to guarantee sustainable, scalable solutions.

7. Policy & Regulatory Overview

EPA Frameworks

The U.S. Environmental Protection Agency (EPA) has expressed few direct regulations to tackle pollution with micro plastic (MP) in freshwater and relies mainly on existing regulations, such as the Clean Water Act (CWA) to regulate the emerging contaminant. The CWA manages point source discharges as the National Pollutant Discharge Elimination System (NPDES) may regulate primary MPs such as hurdles released by industrial sites, but it is poorly enforced because of the challenge of identifying and assigning credit to MPs (Hopkins, 2023). The Microbeads-Free Waters Act of 2015 only prohibits primary MPs in rinse-off cosmetics, which also has a small application scope that omits other sources such as tire wear or textile fibres (Sorensen et al., 2023). Among the proposed measures in the 2023 Drafter National Strategic plan on preventing plastic pollution by the EPA, there is a strategy on reducing the volume of plastics produced and bettering waste management but no mandates on enforceable standards of MP-specific standards in regard to freshwater (Sorensen et al., 2023). Naturally, the regional efforts to address federal gaps are highly diverse, with state-level efforts like Michigan encouraging the use of CWA-based storm water permits to restrict MP releases (Schroeck, 2016). The impaired waters list published by the CWA may address MP-contaminated freshwater; however, the EPA has opposed establishing the water quality standard of MPs, which has been challenged many times (Hopkins, 2023).

In the literature, there is a clear fragmentation of the EPA approach, which is limited by the fact that the CWA addresses the issue of point sources and does not specify any criteria regarding MPs. The Microbead-Free Waters Act is a partial success, because it disregards secondary MPs and non-cosmetic sources (Sorensen et al., 2023). The lack of consistency in states-related enforcement increases the disparities since Michigan shows proactive work whereas federal oversight is weaker (Schroeck, 2016). The MPs have minimal regulation in the EPA because the latter refuses to categorize them as hazardous waste under the Resource Conservation and Recovery Act (Hopkins, 2023). To combat the problem of freshwater pollution in a very thorough manner, future policies will require standardized means of detecting MPs and water quality standards that are enforceable.

EU Regulations

European Union (EU) has already taken a proactive approach to addressing micro plastic (MP) contamination by introducing severe measures to control plastic waste and primary MPs, especially microbeads. The EU's Single-Use Plastics Directive (2019) bans specific plastic products and promotes a circular economy, reducing marine litter from land and sea sources (da Costa et al., 2020). The Marine Strategy Framework Directive (MSFD, 2008/56/EC) aims for Good Environmental Status (GES) by 2020, including MPs as a descriptor, though vague definitions allow member-state discrepancies (da Costa et al., 2020; Munhoz et al., 2022). The Water Framework Directive (2000/60/EC) regulates coastal waters, indirectly addressing MPs. The REACH regulation proposes restricting intentionally added MPs in products like cosmetics and agriculture, exempting biodegradable or soluble polymers, with a potential ban effective from 2022 (Mitrano & Wohlleben, 2020; da Costa et al., 2020). The Port Reception Facility Directive (2000/59/EC) enforces ship-generated waste disposal, though recent fixed-fee policies deviate from the "polluter pays" principle, potentially increasing waste volumes (da Costa et al., 2020). The EU's 2023 proposal targets MPs in textiles and tires, emphasizing source control (Munhoz et al., 2022).

The EU regulatory framework is worthy but it is hostile. The MSFD has an interpretive flexibility that compromises its implementation uniformity, and the large definition of MP used in REACH may create unnecessarily large control of use cases that do not pose threatening amounts of hazard to human health and the environment (Mitrano & Wohlleben, 2020; Munhoz et al., 2022). The research indicates the lack of enforcement and gaps in monitoring policies, especially in regard to secondary MPs (da Costa et al., 2020). The emphasis on the leading MPs, such as microbeads, overlooks the influential sources, such as tire wear, so specific policy is needed (Mitrano & Wohlleben, 2020). This will be more effective with the integration of the standardized methodologies, the importance of higher impact sources, and the strike of the innovation versus environmental security in the future rules.

UNEP Frameworks

The UN Environment Programme (UNEP) has played a leading role in ensuring that global efforts are made to tackle pollution caused by micro plastic (MP), and most of the measures aimed at addressing this issue have taken non-binding forms in the form of resolutions and through other collaborative processes, but a unified, legally binding structure is yet to be established. Since 2014 the United Nations

Environment Assembly (UNEA) has been adopted by UNEP, and these resolutions have prioritized reducing marine litter and MPs, encouraging sources, and enhancing waste management. UNEA-1 resolution (2014) required a study on the sources and effect of MPs, which was followed by UNEA-2 (2016) that promoted a lifecycle approach, and UNEA-3 (2017) that created an Ad Hoc Open-ended Expert Group that was to discuss governance options (Carlini & Kleine, 2018). Multi-stakeholder cooperation is facilitated by the Global Partnership on Marine Litter (GPML) initiated by UNEP, whereas regional seas conventions (RSCs) and action plans spanning 18 regions assists the mitigation of MP at a local level through the concerted effort of similar strategies (da Costa et al., 2020). Beyond that, the Honolulu Strategy and Global Programme of Action (GPA) developed by UNEP also propagates marine debris prevention and management, but these do not have any enforcement instruments. The necessity of binding targets to end discharges of MP with national action plans and capacity-building features in proposals of a global plastics convention addressing the amounts that appear in land-based sources, which constitute the majority by 80 percent of marine plastics (Simon & Schulte, 2017).

The initiatives by UNEP are leadership activities, but limited by voluntary nature and divided focus. The resolutions to the UNEA, though progressive, do not have enforceable commitments, and that is based on goodwill on the part of member states, which is controversial (Carlini & Kleine, 2018). Their attention on marine litter does not address the upstream availability of production and consumption, which are a major component of an overall control of MPs (Simon & Schulte, 2017). The differences in the implementation of RSC in various regions and incomplete coverage of Areas beyond National Jurisdiction (ABNJ) undermine the coordination globally (da Costa et al., 2020). The proposed convention would provide a promising solution and so far, it has been politically rejected, and it needs to have industry accountability characterized in a simpler way. Combined binding international standards, harmonized monitoring, and effective financing should be added in the future to increase the effectiveness of UNEP.

8. Challenges & Future Research Directions

Challenges in Micro plastic Management

It is technologically, logistically and regulatory difficult to treat micro plastic pollution in the freshwater systems effectively. These obstacles, rooted in the complexity of micro plastics (MPs) and Nano plastics (NPs), demand innovative solutions to protect ecosystems and human health.

Technological Challenges: Current technologies struggle to address the diverse sizes, shapes, and compositions of MPs and NPs. Physical methods like membrane filtration achieve high removal efficiencies (>95%) for MPs >1 µm but are less effective for NPs due to their smaller size (<1 µm), with membrane fouling increasing costs (Nene et al., 2025; Poerio et al., 2019). Chemical methods, such as advanced oxidation processes (AOPs) using photo catalysis, degrade MPs but are energy-intensive and risk producing toxic by-products, limiting scalability (Qi & He, 2025; Ricardo et al., 2021). Biological methods, including biodegradation by bacteria like *Pseudomonas* spp., are eco-friendly but slow, often requiring months for partial degradation, and lack versatility across polymer types (Miloloža et al., 2022). Detection technologies also face limitations, with inconsistent protocols and fluorescence interference complicating accurate quantification, particularly for NPs (Ebere & Ngozi, 2019; Böke et al., 2022). These gaps highlight the need for hybrid systems and standardized methodologies to enhance efficiency and applicability.

Large scale removal of the MPs is logistically challenging to implement. Recontamination potential exists in wastewater treatment plants (WWTPs) with 90-99 percent of MPs being eliminated, large influent volumes, and waste sludge creation, particularly in the developing world such as Bangladesh, which has underdeveloped infrastructure (Jani et al., 2024; Mahmud et al., 2022). Constructed wetlands have the advantage of providing sustainable filtration, and the disadvantage is that they might act like a reservoir of MP during flood events, so regular observations have to be taken over time (Dhilleswara Rao et al., 2024). Adsorption techniques have the additional cost of sorbent regeneration and biodegradation approaches have the extra expense of enzyme production, which can be difficult in resource-limited environments (Nene et al., 2025; Miloloža et al., 2022). Moreover, variable global sources of MPs (textiles, tire wear, agriculture) make standardised logistics problematic, and regional-based research (e.g., in China) does not allow generalizing (Wang et al., 2020; Xu et al., 2020).

Regulation structures are decentralized and do not have any MP-specific regulations. The Clean Water Act of the U.S. can control point-source emissions, but has difficulty controlling diffuse sources of MPs, such as urban runoff, and the EPA has been reluctant to make water quality guidelines (Hopkins, 2023; Sorensen et al., 2023). The EU Single-Use Plastic Directive and REACH only regulate the productions of primary MPs but not secondary sources of MPs such as tire wear whose monitoring varies by member state (da Costa et al., 2020; Mitrano & Wohlleben, 2020). The resolutions by the UNEP facilitate international collaboration, lack the obligations, and do not support the coordinated action (Carlini & Kleine, 2018). Segments of the lacking standardization of the detection and reporting procedures also compromise regulatory effectiveness (Munhoz et al., 2022).

To solve these issues, there should be some combined strategies: the creation of NP-specific technologies, the optimization of hybrid systems, the process of standardization, and the introduction of enforceable international laws to curb the pollution of micro plastics into the environment.

Research Gaps and Future Directions

The global concern of micro plastic (MP) pollution in freshwater systems is slowly becoming an urgent issue that must be better understood through research to fill breaks in any detection, treatment technology, and impact assessments. These are crucial spaces that have to be focused on to make sure that they come up with radical mitigation measures so that ecosystems can be secured as well as human health.

Traditional methods, including FTIR and Raman spectroscopy, have to contend with erratic protocols and identification of Nano plastics (<1 1m) because fluorescence and complex matrices interfere with their identification processes (Ebere and Ngozi, 2019; Boke et al., 2022). There are methodological differences, such as the sizes of different meshes and purification procedures used, which resulted in incomparable data, especially in small MPs and NPs (Zhao et al., 2017). Advances like Nile Red staining with machine learning achieve high accuracy (95.8%) but face challenges with polymer additives affecting fluorescence (Meyers et al., 2022). Hyperspectral imaging and AI-based methods show promise but require diverse datasets and standardized protocols to ensure generalizability across freshwater systems (Zhang et al., 2023; Khanam et al., 2025). Future research should prioritize non-destructive, automated detection systems, real-time in-situ monitoring, and standardized methodologies to enhance global comparability and NP detection.

MP removal technologies face scalability and efficiency limitations. Physical methods like membrane filtration achieve >95% MP removal but struggle with NPs and fouling, increasing costs (Poerio et al., 2019; Nene et al., 2025). Chemical methods, such as advanced oxidation processes (AOPs), degrade MPs but are energy-intensive and produce potential toxic by-products, lacking field-scale validation (Ricardo et al., 2021; Sacco et al., 2023). Biological methods, including biodegradation by bacteria and fungi, are sustainable but slow and polymer-specific, with limited NP data (Miloloža et al., 2022). WWTPs remove 90–99% of MPs, but sludge disposal and NP fragmentation remain unaddressed (Jani et al., 2024; Mahmud et al., 2022). Constructed wetlands are promising but risk MP re-release during floods (Dhilleswara Rao et al., 2024). Future research should focus on hybrid systems (e.g., AOPs with filtration), NP-specific treatments, cost-effective sorbents, and life cycle assessments to ensure scalability and sustainability, particularly in developing regions.

Ecological and human health impacts of MPs are underexplored, especially in freshwater systems. Laboratory studies often use unrealistic MP concentrations, overestimating effects on organisms like *Daphnia magna* (Bellasi et al., 2020; Okeke et al., 2023). The role of NPs, which penetrate biological barriers, remains understudied due to detection challenges (Matavos-Aramyan, 2024). Human health research does not provide long-term results of chronic exposure through water and seafood, and freshwater-specific exposures (such as groundwater) are not assessed (Yuan et al., 2022; Alekhya et al., 2024). The presence of regional biases to marine or urban system restricts universal usage (Ziani et al., 2023). The priority in future research is given to field based research carried out with environmental relevant concentrations, full spectrum of polymer diversity and longitudinal exposure studies of humans to elucidate ecological and health hazards.

The gaps should be addressed by designing uniform protocols, developing new technology, and conducting inclusive impact research to curtail micro plastic pollution.

9. Conclusion

Summary of Key Findings

Micro plastic (MP) pollution in the freshwater ecosystem is a high-urgency environmental issue, whose sources are varied and whose effects are compounded by difficulty of detection, treatment, and limited policies. They largely belong to the category of primary sources e.g., synthetic textiles, microbeads, waste effluents and are secondarily made through the process of plastic derivation (Xu et al., 2020; Acharya et al., 2021). Wastewater treatment plants (WWTPs), industries discharges, agricultural runoff, and polyethylene (PE) with polypropylene (PP) are the main sources of MPS in rivers and lakes and make up the majority of them (Wang et al., 2020; Atugoda et al., 2022). The vectors of the pollutants that adsorb such toxics as polycyclic aromatic hydrocarbons (PAHs) and present a higher ecological risk are the MPs and are explained by the bioaccumulation and trophic transfer processes (Ma et al., 2016; Menendez-Pedriza and Jaumot, 2020).At the ecological stage, the presence of MPs somehow interferes with freshwater ecosystem due to a decrease in the biodiversity and damage to the organisms (such as Daphnia magna), as well as the alteration in the sediment characteristics (Bellasi et al., 2020; Ziani et al., 2023). The causes around the human health related risks associated with the consumption of the MPs in consumed foods and drinking water are founded on the Nano plastics (NPs), which may cause the chronic toxicities, which in turn are linked to the breaking of the biological barriers (Yuan et al., 2022; Matavos-Aramyan, 2024). FTIR-based and Raman spectroscopy and Nile Red staining-based methods have improved due to the lack of standardized procedures and problems with detecting NPs (Ebere & Ngozi, 2019; Meyers et al., 2022). Machine learning and hyperspectral imaging offer promise but require standardization (Zhang et al., 2023; Khanam et al., 2025).Treatment technologies span physical, chemical, and biological methods. Membrane filtration achieves >95% MP removal but struggles with NPs and fouling (Poerio et al., 2019; Nene et al., 2025). Advanced oxidation processes (AOPs) degrade MPs but are energy-intensive and risk toxic by-products (Ricardo et al., 2021; Sacco et al., 2023). Biodegradation is sustainable but slow, limited by polymer specificity (Miloloža et al., 2022). WWTPs remove 90–99% of MPs, yet sludge disposal and NP fragmentation persist as challenges (Jani et al., 2024). Constructed wetlands provide eco-friendly filtration but risk MP re-release during floods (Dhilleswara Rao et al., 2024).Policy frameworks are fragmented. The U.S. Clean Water Act and Microbead-Free Waters Act address limited MP sources, lacking specific standards (Hopkins, 2023; Sorensen et al., 2023). The EU's REACH and Single-Use Plastics Directive target primary MPs but overlook secondary sources, with inconsistent enforcement (da Costa et al., 2020; Mitrano & Wohlleben, 2020). UNEP's resolutions promote global cooperation but lack binding mechanisms, necessitating a global plastics convention (Carlini & Kleine, 2018; Simon & Schulte, 2017).

Future Outlook

Continued efforts in research, technology development, and policy implementation are critical to mitigate MP pollution. Research must prioritize standardized detection protocols to ensure data comparability, particularly for NPs, which remain understudied due to methodological limitations (Böke et al., 2022; Nene et al., 2025). Developing scalable, cost-effective treatment technologies, such as hybrid systems combining filtration and AOPs, is essential to address both MPs and NPs, especially in resource-constrained regions (Jani et al., 2024; Qi & He, 2025). Comprehensive impact studies using environmentally relevant concentrations are needed to clarify ecological and human health risks, focusing on freshwater-specific pathways like groundwater (Okeke et al., 2023; Alekhya et al., 2024).The process of policy implementation should be changed by introducing enforceable international standards. That is why a binding international convention, suggested by UNEP, could become a trade-in, focusing on high-impact sources, such as textiles and tire wear (Simon & Schulte, 2017; Munhoz et al., 2022). Standardized monitoring and encouraging innovation instead of focusing strictly on environmental safety should be a part of the regional policies (Mitrano & Wohlleben, 2020).

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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References

[1] Acharya, S., Rumi, S.S., Hu, Y. and Abidi, N., 2021. Microfibers from synthetic textiles as a major source of micro plastics in the environment: A review. Textile Research Journal, 91(17-18), pp.2136-2156.

[2] Alekhya, V., Swathi, B., Kumar, A., Kumar, A., Jayronia, S. and Abood, A.S., 2024. Advanced Nanofiltration Techniques for Efficient Removal of Micro plastics from Water: A Review. In *E3S Web of Conferences* (Vol. 505, p. 01008). EDP Sciences.

[3] Ali, S.S., Elsamahy, T., Al-Tohamy, R. and Sun, J., 2024. A critical review of micro plastics in aquatic ecosystems: Degradation mechanisms and removing strategies. *Environmental Science and Ecotechnology*, p.100427.

[4] Al-Thawadi, S., 2020. Microplastics and nanoplastics in aquatic environments: challenges and threats to aquatic organisms. Arabian Journal for Science and Engineering, 45(6), pp.4419-4440.

[5] Atugoda, T., Piyumali, H., Liyanage, S., Mahatantila, K. and Vithanage, M., 2022. Fate and behaviour of micro plastics in freshwater systems. In *Handbook of Micro plastics in the Environment* (pp. 781-811). Cham: Springer International Publishing.

[6] Bellasi, A., Binda, G., Pozzi, A., Galafassi, S., Volta, P. and Bettinetti, R., 2020. Micro plastic contamination in freshwater environments: A review, focusing on interactions with sediments and benthic organisms. *Environments*, *7*(4), p.30.

[7] Böke, J.S., Popp, J. and Krafft, C., 2022. Optical photo thermal infrared spectroscopy with simultaneously acquired Raman spectroscopy for two-dimensional micro plastic identification. *Scientific Reports*, *12*(1), p.18785.

[8] Carlini, G. and Kleine, K., 2018. Advancing the international regulation of plastic pollution beyond the United Nations Environment Assembly resolution on marine litter and micro plastics. *Review of European, Comparative & International Environmental Law*, *27*(3), pp.234-244.

[9] Da Costa, J.P., Mouneyrac, C., Costa, M., Duarte, A.C. and Rocha-Santos, T., 2020. The role of legislation, regulatory initiatives and guidelines on the control of plastic pollution. *Frontiers in Environmental Science*, *8*, p.104.

[10] Da Costa, J.P., Mouneyrac, C., Costa, M., Duarte, A.C. and Rocha-Santos, T., 2020. The role of legislation, regulatory initiatives and guidelines on the control of plastic pollution. *Frontiers in Environmental Science*, *8*, p.104.

[11] Depan, P.M., 2024. MICROPLASTICS POLLUTION MITIGATION IN WASTEWATER TREATMENT: CURRENT PRACTICES, CHALLENGES, AND FUTURE PERSPECTIVES. *Malaysian Journal of Analytical Sciences*, *28*(1), pp.79-96.

[12] Dhilleswara Rao, H., Chintada, V. and Veeraiah, K., 2024. Effective strategies for mitigating toxicity in aquatic environments. *Sustainable Innovations in Life Sciences: Integrating Ecology, Nanotechnology, and Toxicology*, pp.42-68.

[13] Ebere, E.C. and Ngozi, V.E., 2019. Micro plastics, an emerging concern: a review of analytical techniques for detecting and quantifying microplatics. *Analytical methods in environmental chemistry journal*, *2*(2), pp.13-30.

[14] Fu, Z. and Wang, J., 2019. Current practices and future perspectives of microplastic pollution in freshwater ecosystems in China. Science of the Total Environment, 691, pp.697-712.

[15] Habib, R.Z., Thiemann, T. and Al Kendi, R., 2020. Microplastics and wastewater treatment plants—a review. Journal of Water Resource and Protection, 12(01), p.1.

[16] Hale, R.C., Seeley, M.E., La Guardia, M.J., Mai, L. and Zeng, E.Y., 2020. A global perspective on microplastics. Journal of Geophysical Research: Oceans, 125(1), p.e2018JC014719.

[17] Hopkins, T., 2023. The Clean Water Act's Nurdle-Shaped Gap: Using the CWA to Address Primary Micro plastic Pollution. *Mich. J. Env't & Admin. L.*, *13*, p.570.

[18] Jani, V., Wu, S. and Venkiteshwaran, K., 2024. Advancements and regulatory situation in micro plastics removal from wastewater and drinking water: a comprehensive review. *Micro plastics*, *3*(1), pp.98-123.

[19] Jensen, J.S., Kristensen, A.K.D., Jespersen, E.A., Arias, C.A. and Riis, T., 2024. USING RIPARIAN WETLANDS FOR SURFACE WATER PURIFICATION: EFFECT ON NUTRIENT CONCENTRATION AND BIOLOGICAL RESPONSE.

[20] Khanam, M.M., Uddin, M.K. and Kazi, J.U., 2025. Advances in machine learning for the detection and characterization of micro plastics in the environment. *Frontiers in Environmental Science*, *13*, p.1573579.

[21] Landeros, L., Williams, I., Shaw, P., Hudson, M. and Dominguez Cortinas, G., 2022. A review of the origins of microplastics arriving at wastewater treatment plants. Detritus, 20, pp.41-55.

[22] Leone, G., Moulaert, I., Devriese, L.I., Sandra, M., Pauwels, I., Goethals, P.L., Everaert, G. and Catarino, A.I., 2023. A comprehensive assessment of plastic remediation technologies. *Environment International*, *173*, p.107854.

[23] Levermore, J.M., Smith, T.E., Kelly, F.J. and Wright, S.L., 2020. Detection of micro plastics in ambient particulate matter using Raman spectral imaging and chemo metric analysis. *Analytical Chemistry*, *92*(13), pp.8732-8740.

[24] Ma, Y., Huang, A., Cao, S., Sun, F., Wang, L., Guo, H. and Ji, R., 2016. Effects of Nano plastics and micro plastics on toxicity, bioaccumulation, and environmental fate of phenanthrene in fresh water. *Environmental Pollution*, *219*, pp.166-173.

[25] Mahmud, A., Wasif, M.M., Roy, H., Mehnaz, F., Ahmed, T., Pervez, M.N., Naddeo, V. and Islam, M.S., 2022. Aquatic micro plastic pollution control strategies: sustainable degradation techniques, resource recovery, and recommendations for Bangladesh. *Water*, *14*(23), p.3968.

[26] Mahmud, A., Wasif, M.M., Roy, H., Mehnaz, F., Ahmed, T., Pervez, M.N., Naddeo, V. and Islam, M.S., 2022. Aquatic micro plastic pollution control strategies: sustainable degradation techniques, resource recovery, and recommendations for Bangladesh. *Water*, *14*(23), p.3968.

[27] Matavos-Aramyan, S., 2024. Addressing the micro plastic crisis: A multifaceted approach to removal and regulation. *Environmental Advances*, p.100579.

[28] Menéndez-Pedriza, A. and Jaumot, J., 2020. Interaction of environmental pollutants with micro plastics: a critical review of sorption factors, bioaccumulation and ecotoxicological effects. *Toxics*, *8*(2), p.40.

[29] Meyers, N., Catarino, A.I., Declercq, A.M., Brenan, A., Devriese, L., Vandegehuchte, M., De Witte, B., Janssen, C. and Everaert, G., 2022. Micro

plastic detection and identification by Nile red staining: Towards a semi-automated, cost-and time-effective technique. *Science of the Total Environment*, *823*, p.153441.

[30] Miloloža, M., Cvetnić, M., Kučić Grgić, D., Ocelić Bulatović, V., Ukić, Š., Rogošić, M., Dionysiou, D.D., Kušić, H. and Bolanča, T., 2022. Biotreatment strategies for the removal of micro plastics from freshwater systems. A review. *Environmental chemistry letters*, *20*(2), pp.1377-1402.

[31] Mitrano, D.M. and Wohlleben, W., 2020. Micro plastic regulation should be more precise to incentivize both innovation and environmental safety. *Nature communications*, *11*(1), p.5324.

[32] Munhoz, D.R., Harkes, P., Beriot, N., Larreta, J. and Basurko, O.C., 2022. Micro plastics: a review of policies and responses. *Micro plastics*, *2*(1), pp.1-26.

[33] Nene, A., Sadeghzade, S., Viaroli, S., Yang, W., Uchenna, U.P., Kandwal, A., Liu, X., Somani, P. and Galluzzi, M., 2025. Recent advances and future technologies in nano-microplastics detection. *Environmental Sciences Europe*, *37*(1), p.7.

[34] Okeke, E.S., Chukwudozie, K.I., Addey, C.I., Okoro, J.O., Ezeorba, T.P.C., Atakpa, E.O., Okoye, C.O. and Nwuche, C.O., 2023. Micro and Nano plastics ravaging our agroecosystem: A review of occurrence, fate, ecological impacts, detection, remediation, and prospects. *Heliyon*, *9*(2).

[35] Poerio, T., Piacentini, E. and Mazzei, R., 2019. Membrane processes for micro plastic removal. *Molecules*, *24*(22), p.4148.

[36] Qi, Y. and He, K., 2025. Science and Technology for Water Purification: Achievements and Strategies. *Water*, *17*(1), p.91.

[37] Ricardo, I.A., Alberto, E.A., Júnior, A.H.S., Macuvele, D.L.P., Padoin, N., Soares, C., Riella, H.G., Starling, M.C.V. and Trovo, A.G., 2021. A critical review on micro plastics, interaction with organic and inorganic pollutants, impacts and effectiveness of advanced oxidation processes applied for their removal from aqueous matrices. *Chemical Engineering Journal*, *424*, p.130282.

[38] Sacco, N.A., Zoppas, F.M., Devard, A., González Muñoz, M.D.P., García, G. and Marchesini, F.A., 2023. Recent advances in micro plastics removal from water with special attention given to photocatalytic degradation: review of scientific research. *Micro plastics*, *2*(3), pp.278-303.

[39] Schroeck, N.J., 2016. Micro plastic pollution in the Great lakes: State, federal, and common law solutions. *U. Det. Mercy L. Rev.*, *93*, p.273.

[40] Schuhen, K. and Sturm, M.T., 2020. Micro plastic pollution and reduction strategies. *Handbook of Micro plastics in the Environment*, pp.1-33.

[41] Sharma, A., Kumari, S., Chopade, R.L., Pandit, P.P., Rai, A.R., Nagar, V., Awasthi, G., Singh, A., Awasthi, K.K. and Sankhla, M.S., 2023. An assessment of the impact of structure and type of micro plastics on ultrafiltration technology for micro plastic remediation. *Science Progress*, *106*(2), p.00368504231176399.

[42] Simon, N. and Schulte, M.L., 2017. Stopping global plastic pollution: The case for an international convention. In *Stopping global plastic pollution: the case for an international convention: Simon, Nils| uSchulte, Maro Luisa*. Berlin: Heinrich-Böll-Stiftung.

[43] Sorensen, R.M., Kanwar, R.S. and Jovanovi, B., 2023. Past, present, and possible future policies on plastic use in the United States, particularly micro plastics and Nano plastics: A review. *Integrated environmental assessment and management*, *19*(2), pp.474-488.

[44] Sutkar, P.R., Gadewar, R.D. and Dhulap, V.P., 2023. Recent trends in degradation of micro plastics in the environment: A state-of-the-art review. *Journal of Hazardous Materials Advances*, *11*, p.100343.

[45] Tavakoly Sany, S.B., Hashim, R., Rezayi, M., Salleh, A. and Safari, O., 2014. A review of strategies to monitor water and sediment quality for a sustainability assessment of marine environment. *Environmental Science and Pollution Research*, *21*, pp.813-833.

[46] Wang, F., Wang, B., Duan, L., Zhang, Y., Zhou, Y., Sui, Q., Xu, D., Qu, H. and Yu, G., 2020. Occurrence and distribution of micro plastics in domestic, industrial, agricultural and aqua cultural wastewater sources: A case study in Changzhou, China. Water Research, 182, p.115956.

[47] Xu, C., Zhang, B., Gu, C., Shen, C., Yin, S., Aamir, M. and Li, F., 2020. Are we underestimating the sources of micro plastic pollution in terrestrial environment?. Journal of hazardous materials, 400, p.123228.

[48] Yuan, Z., Nag, R. and Cummins, E., 2022. Human health concerns regarding micro plastics in the aquatic environment-From marine to food systems. *Science of the Total Environment*, *823*, p.153730.

[49] Zandaryaa, S., 2021. Freshwater microplastic pollution: the state of knowledge and research. Plastics in the Aquatic Environment-Part I: Current Status and Challenges, pp.255-272.

[50] Zhang, Y., Zhang, D. and Zhang, Z., 2023. A critical review on artificial intelligence—based micro plastics imaging technology: recent advances, hot-spots and challenges. *International Journal of Environmental Research and Public Health*, *20*(2), p.1150.

[51] Zhao, S., Danley, M., Ward, J.E., Li, D. and Mincer, T.J., 2017. An approach for extraction, characterization and quantitation of micro plastic in natural marine snow using Raman microscopy. *Analytical methods*, *9*(9), pp.1470-1478.

[52] Ziani, K., Ioniță-Mîndrican, C.B., Mititelu, M., Neacşu, S.M., Negrei, C., Moroşan, E., Drăgănescu, D. and Preda, O.T., 2023. Micro plastics: a real global threat for environment and food safety: a state of the art review. *Nutrients*, *15*(3), p.617.