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Aquatic Macrophytes as Natural Filters for Microplastic Pollution in Freshwater Ecosystems

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Abstract- Microplastic pollution poses a growing threat to freshwater habitats, impacting aquatic life and ecological balance. Conventional removal methods are often tended to be expensive and ineffective, prompting interest in environment friendly and sustainable alternatives. This review highlights the potential of aquatic macrophytes as natural biofilters for microplastic remediation. It covered the sources and characteristics of microplastics influencing their interaction with plants, and the primary removal mechanisms, including physical entrapment, surface adsorption, and root-mediated retention. It emphasizes the role that rhizosphere and biofilm microbial communities play in aggregation and degradation processes. Aspects that impact removal efficiency are being examined, including plant morphology, microplastic properties, and water factors. The ecological implications and potential risks of microplastic–macrophyte interactions are also considered. Finally, significant research gaps are identified, highlighting the need for long-term, field-based, and integrative studies. Overall, macrophytes offer a promising, sustainable approach for mitigating microplastic contamination in freshwater environments.

Keywords: Microplastic • Sustainable • Remediation • Macrophytes • Microbial communities.

I. INTRODUCTION

The environmental problem of plastic pollution has expanded widely, since microplastics have been found in both freshwater and marine habitats (Courtene-Jones et al., 2020; Russell and Webster, 2021; Bertoldi et al., 2021). Recent estimates suggest that marine environments harbor 12.5–125 trillion MPs (Lindeque et al., 2020), while freshwater ecosystems act as critical channel for their transfer into oceans (Lebreton et al., 2017; Li et al., 2018). MPs obtained from a wide range of sources, including the fragmentation of terrestrial plastic debris, agricultural plastics, urban dust, treated wastewater, and landfill leachates (Galafassi et al., 2022). Wastewater treatment plants are particularly significant contributors, releasing millions of synthetic fibers and microbeads daily into aquatic systems (Alvim et al., 2020; Turan et al., 2021; Enfrin et al., 2022). Despite their widespread distribution, evidence of biomagnification of MPs along the food chain remains limited (Carbery et al.,2018; Miller et al.,2020).

Primary producers in transitional waters, such as seagrasses and macroalgae, are frequently neglect in studies of microplastic pollution, even though they can accumulate significant amounts of MPs (Sfriso et al.,2021; Huang et al.,2023). Macrophytes are important bioindicators and pollutant bioaccumulators (Polechońska & Klink,2023; Petrov et al.,2023), serving as temporary reservoirs that can extend MP duration and facilitate trophic transfer. Additionally, MPs are highly resilient in aquatic conditions, degrading slowly (Yuan et al.,2020; Debroy et al.,2022), and their breakdown can generate nanoplastics, which may pose further ecological risks (Koelmans et al.,2015; Jaiswal et al., 2025). Microplastics in water interact with different co-contaminants (antibiotics, PAHs, heavy metals, and pathogens) and microplastic–pollutant complexes via multiple physicochemical mechanisms. (Goutam et al.,2022; Singh et al.,2025). These complexes can be readily absorbed by plant roots, resulting in bioaccumulation and potential transfer through the food chain, as illustrated in Figure 1. Finally, these particles do not remain in the environment; they affect living organisms. Aquatic and terrestrial species, such as fish, mollusks, plankton, insects, and birds, consume them, allowing plastics to enter several trophic levels and link aquatic and terrestrial food webs (Srivastava et al., 2025).

Aquatic macrophytes including floating species (Eichhornia crassipes, Lemna minor, Pistia stratiotes) and emergent species (Typha latifolia, Phragmites australis) provide a sustainable method, low-cost, and eco-friendly strategy for in situ removal of MPs (Selvaraj & Velvizhi,2021; Sayanthan et al.,2024). Numerous research has reported MP adhesion on species such as Lemna minor, Sphagnum palustre, Fucus vesiculosus, and Spirodela polyrhiza (Kalčíková et al., 2020; Rozman et al.,2022; Sawangproh,2024) emphasizing their potential as natural biofilters. The adsorption, aggregation, and sedimentation of MPs are improved by the combination of large root systems, submerged surfaces, and biofilm formation; this significantly lowers MPs' mobility, bioavailability, and downstream transfer to marine habitats (Debroy et al.,2022; Qin et al.,2024). Furthermore, aquatic macrophytes can mitigate the negative effect of MPs on the environment by stabilizing sediments, promoting microbial colonization, and offering additional pathways for particle removal (Li et al,2024; Gao et al,2024).

This review aims to synthesize current knowledge on the role of aquatic macrophytes in microplastic remediation, focusing the mechanisms, species-specific efficiencies, and ecological effect of their phytoremediation potential. By highlighting knowledge gaps and recent developments, it provides a comprehensive framework for the using macrophytes as natural filters to reduce MP pollution in freshwater ecosystems.

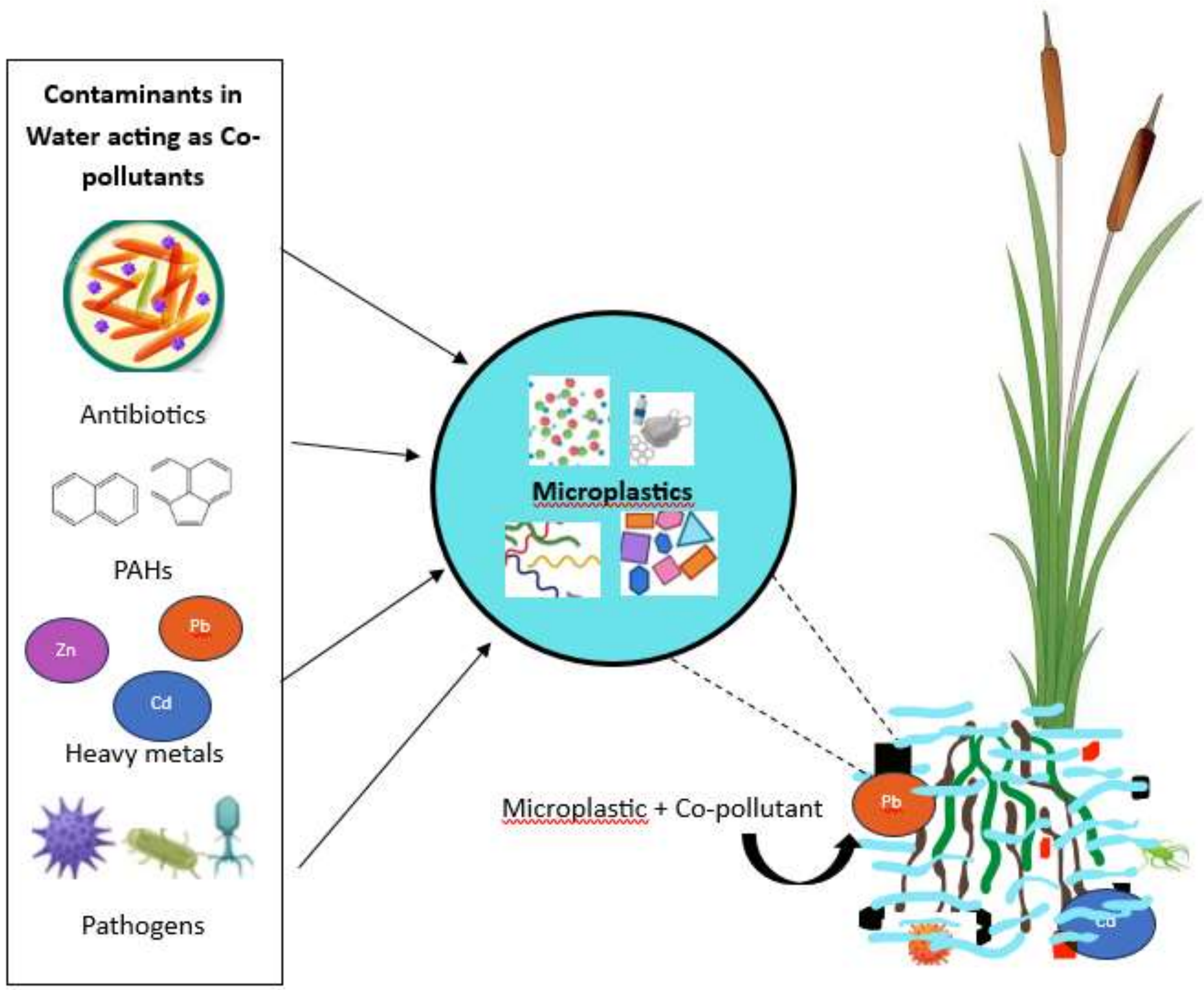

Fig.1 Interaction of microplastic with co-pollutants in water and their potential uptake by aquatic macrophytes through root absorption mechanisms

II. SOURCES OF MICROPLASTICS IN FRESHWATER ECOSYSTEMS

Plastics are commonly classified based on their size into macroplastics (>25 mm), mesoplastics (5–25 mm), microplastics (1 µm–5 mm), and nanoplastics (1–100 nm) (Sharma et al., 2023; Chaudhary et al.,2024). Additionally, some researchers subdivide microplastics into large microplastics (1–5 mm) and small microplastics (1 µm–1 mm) to better capture their environmental behavior and ecological impacts (Kim et al., 2020).

Some researchers also classify microplastics based on their origin like primary microplastics and secondary microplastics (Zhang and Liu, 2018; Sharma et al. 2023; Song et al. 2024). Primary microplastics are intentionally manufactured small plastic particles, such as microbeads in personal care products, synthetic fibers from textiles, and pre-production pellets used in industrial processes. These particles often enter aquatic environments directly through wastewater effluents, industrial discharges, or stormwater runoff (Alvim et al., 2020; Turan et al., 2021). In contrast, secondary microplastics are formed through the fragmentation and degradation of larger plastic items which includes packaging materials, plastic bottles, agricultural films, and fishing gear. Physical, chemical, and biological weathering processes break down these macroplastics into smaller particles, which are subsequently transported into freshwater ecosystems via surface runoff, rivers, or wastewater streams (Enfrin et al., 2020; Galafassi et al., 2022). Figure 2 illustrates the major sources of microplastics in aquatic environments, including wastewater effluents, industrial discharges, urban runoff, and degradation of larger plastic debris.

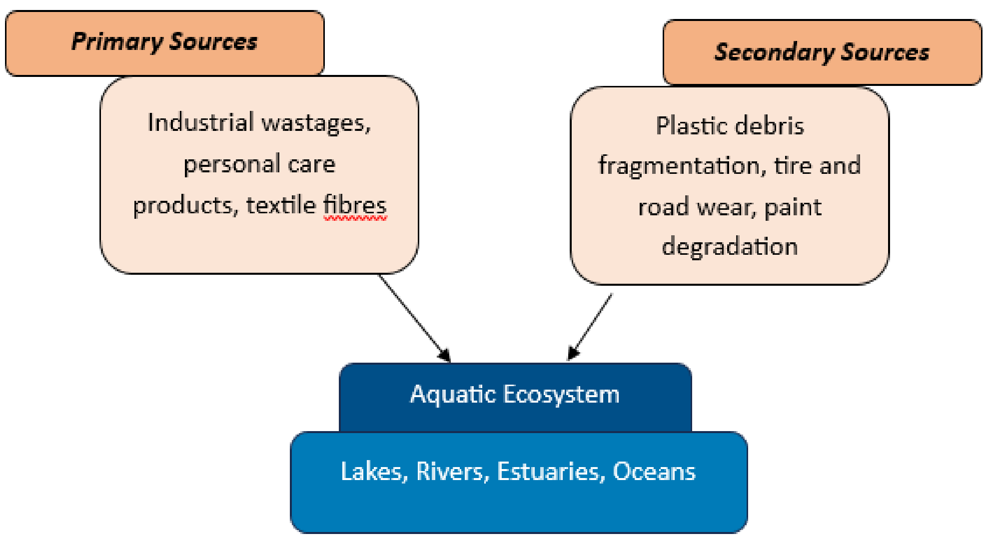

Fig.2 Sources of microplastics in aquatic environment

III. PHYSICAL AND CHEMICAL PROPERTIES INFLUENCING INTERACTION WITH PLANTS

The behavior of MPs in freshwater, including their adhesion to macrophytes, is largely determined by their size, shape, density, surface charge, and chemical composition:

Size and shape: MPs range from 1 µm to 5 mm and include fragments, fibers, films, and spheres. Fibers and films with large surface areas are more likely to entangle with plant roots and submerged surfaces (Kalˇcíkova G, 2020; McIlwraith et al.,2024).

Density: High-density MPs tend to sink, while low-density particles float, affecting their availability to different plant species in the water column (Kumar et al.,2021).

Surface chemistry: Hydrophobicity, functional groups, and surface roughness influence MP aggregation, biofilm formation, and adhesion to plant surfaces (Gao et al.,2025).

Additives and polymer type: Plasticizers, stabilizers, and different polymer compositions (e.g., polyethylene, polypropylene, polystyrene) might alter interactions with aquatic species and impact the potential of bioaccumulation (Li et al.,2024).

IV. ROLE OF AQUATIC MACROPHYTES AS NATURAL FILTERS

The increasing prevalence of MPs in freshwater and marine environments is growing interest in developing various effective strategies to limit their environmental release and accumulation (Ogunola et al.,2018; Tang et al.,2023). Out of all these, phytoremediation has emerged as a simple, cost-effective, and environmentally sustainable ways for the in-situ removal of MPs from aquatic systems. Several studies have demonstrated the adhesion potential of aquatic macrophytes toward MPs (Wentzell,2025); however, the interactions between MPs and macrophytes have not been systematically explored yet (Mao et al.,2023). Understanding these interactions is critical for evaluating the ecological role of macrophytes for the mitigation of microplastic pollution and for optimizing their application in water remediation strategies (Gao et al.,2024).

Aquatic macrophytes contribute significantly in the mitigation of MPs through a combination of physical entrapment and adsorption mechanisms (Mateos-Cárdenas et al.,2021; Rozman et al.,2022). The structural complexity and physiological traits of these plants allow them to act as natural filters which can effectively trap MPs from the water column. Dense arrangements of roots, stems, and leaves create physical barriers that reduce MP mobility, while surface properties such as surface roughness, hydrophobicity and the presence of biofilms enhance aggregation and adhesion of particles (Cheng et al.,2023; Moyal et al.,2023). All these mechanisms collectively promote the retention of MPs and confine their downstream transport in freshwater ecosystems.

The efficiency capturing the MPs varies on various factors like macrophyte species, root architecture, and surface area. Species having extensive root systems and larger leaf surface areas provide more sites for the attachment of MPs (Senavirathna et al.,2022). For example, Hydrilla verticillata and Mayaca fluviatilis have been reported to retain significant amounts of MPs in which leaf morphology and cellulose content playing important roles (Wang et al.,2024). Additionally, the type of macrophyte like submerged, emergent, or floating are strongly influences its filtration capacity. Submerged species, owing to their extensive root networks and full exposure to the water column, are often the most effective at entrapping suspended MPs (Kane & Clare,2019; Chen et al.,2024).

Overall, aquatic macrophytes offer a potential and sustainable biological approach to reduce the persistence and mobility of microplastics in freshwater environments. By understanding species-specific interactions and optimizing plant selection, phytoremediation can become a practical strategy for controlling MP contamination in situ.

V. BIOFILM AND RHIZOSPHERE INTERACTIONS

Aquatic macrophytes not only provide physical surfaces for microplastic (MP) entrapment but also host complex microbial communities on their roots and leaves, forming biofilms that play a pivotal role in MP dynamics.

Role of Microbial Communities in Particle Aggregation

Biofilms on macrophyte surfaces consist of bacteria, fungus, algae, and other microbes embedded in extracellular polymeric substances (EPS) (Liu et al.,2020; Chen et al.,2022). These microbial matrices improve surface stickiness, which promotes MP aggregation and adherence. Aggregated MPs are more likely to settle, reducing their mobility in the water column and facilitating their removal from the aquatic environment. Biofilm-mediated aggregation also affects the size, density, and surface properties of MPs, influencing their interactions with aquatic plants and other species (Jia et al.,2024).

Role in Degradation

Certain microbes in these biofilms have shown the ability to partially breakdown plastic polymers. Bacterial species capable of producing enzymes such as esterases, hydrolases, or laccases can break down polymers, inducing fragmentation or surface modification of MPs (Pathak,2017). While natural conditions limit MP mineralization, microbial activity can increase biofilm-mediated fragmentation, surface oxidation, and reduce MP persistence in aquatic systems. Certain bacteria (e.g., Pseudomonas, Bacillus) and fungi (e.g., Aspergillus, Penicillium) produce enzymes such as esterases, hydrolases, and laccases that can partially breakdown plastic polymers, change their surface properties, and increase biofilm-mediated aggregation (Yang et al.,2020; Kalčíková et al., 2023; Sun et al.,2023).

Rhizosphere Interactions

The rhizosphere, the zone around plant roots, is particularly active in MP dynamics. Root exudates provide nutrients that promote microbial growth and biofilm formation, which enhances MP adhesion and aggregation (Wang et al.,2024). These interactions form a synergistic system in which aquatic macrophytes and their associated microbial communities restrict MP mobility, improve sedimentation, and potentially contribute to polymer degradation (Dovidat et al., 2020; Wang et al.,2025).

Overall, biofilm and rhizosphere interactions highlight the biological component of phytoremediation, demonstrating that microbial communities associated with macrophytes are essential partners in the aggregation, retention, and partial degradation of microplastics in freshwater ecosystems. Table 1 summarizes the key microbial taxa in biofilms and the rhizosphere that are involved in microplastic aggregation and degradation. Bacteria such as Pseudomonas, Bacillus, and Rhodococcus, along with fungal species like Aspergillus and Penicillium, contribute to biofilm formation, particle aggregation, and enzymatic degradation of microplastics, thereby influencing their fate and transport in aquatic ecosystems.

Table 1. Key microbial taxa in biofilms and rhizosphere involved in microplastic aggregation and degradation

Microbial Group	Mechanism	Effect	References
Bacteria (e.g., Pseudomonas, Bacillus)	Enzyme-mediated degradation (esterases, hydrolases)	Partial polymer breakdown, surface modification	Othman et al.,2021; Procházková et al.,2025
Fungi (e.g., Aspergillus, Penicillium)	Surface oxidation, biofilm formation	Fragmentation and aggregation of MPs	Wu et al.,2023
Algae & Cyanobacteria	EPS production, biofilm matrix formation	Aggregation and sedimentation of MPs	Debroy et al.,2022; Rosati et al.,2024
Rhizosphere microbes	Root exudate-stimulated biofilm growth	Enhanced MP adhesion and localized degradation	Dovidat et al., 2020

VI. FACTORS AFFECTING REMOVAL EFFICIENCY

The efficiency of microplastic (MP) removal by aquatic macrophytes is influenced by a complex interplay of water quality parameters, microplastic characteristics, and plant-specific traits. Figure 3 illustrates the interaction of these various factors influencing microplastic removal by aquatic macrophytes.

Water Parameters

pH and temperature: These factors affect the surface charge of both microplastics and plant tissues, influencing adsorption and aggregation behavior (Senavirathna et al.,2022).

Turbidity and suspended solids: High turbidity can limit light penetration, reducing plant growth and surface contact with MPs.
Dissolved organic matter (DOM): DOM can either enhance or inhibit MP adsorption by altering the hydrophobicity of the surrounding medium (Fan et al.,2024).
Hydrodynamic conditions: Water flow rate and turbulence determine the contact time between MPs and plant surfaces.

Microplastic Properties
Size and shape: Smaller MPs (<100 μm) tend to be more easily trapped within biofilms and root mats, while fibers and fragments show different deposition patterns.
Polymer type and density: Low-density plastics (e.g., PE, PP) remain suspended and interact with floating plants, whereas high-density types (e.g., PVC) settle near submerged roots.
Surface roughness and aging: Weathered MPs have more functional groups and greater affinity for biofilm attachment.

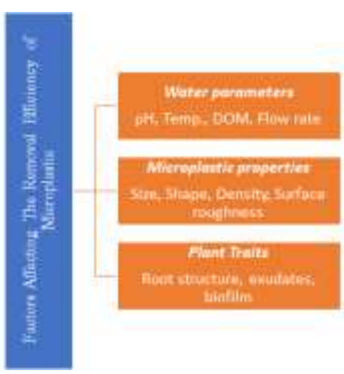

Fig.3 Factors influencing removal efficiency of Microplastic by Aquatic Macrophytes

Plant Traits
Root architecture and surface area: MPs have a higher trapping potential when their roots are densely fibrous or hairy.
Exudate secretion: Root exudates can modify local pH and enhance biofilm formation, indirectly affecting MP retention.
Growth form: The ability of floating, submerged, and emergent macrophytes to intercept MPs varies by ecological zone.
Biofilm association: Plants supporting dense microbial biofilms show higher MP entrapment due to enhanced aggregation and adhesion (Li et al.,2024).

VII. ECOLOGICAL AND ENVIRONMENTAL IMPLICATIONS

The interaction of microplastics with aquatic macrophytes has significant ecological and environmental implications, influencing both plant health and overall ecosystem functioning (Kumar et al.,2022; Li et al.,2024). The accumulation of microplastics in the rhizosphere can hinder root growth, limit nutrient uptake, may inhibit photosynthetic efficiency, ultimately impairing plant productivity (Ren et al., 2021; Azeem et al., 2021). Furthermore, co-contaminants including heavy metals, polycyclic aromatic hydrocarbons (PAHs), and antibiotics can be carried by microplastics, intensifying phytotoxic effects and changing plant metabolic processes (Li et al., 2020; Narwal et al., 2024). These interactions may also disturb the rhizospheric microbial community structure and nutrient cycling, which are essential for maintaining aquatic ecosystem stability (Schmidt et al.,2019; Gao et al., 2025). In addition, floating microplastics impair oxygen exchange and light penetration, which has a detrimental effect on submerged vegetation and primary productivity in aquatic systems (Prata et al., 2020).

Beyond direct impacts on macrophytes, microplastics pose indirect risks through trophic transfer. Aquatic plant-retained particles can enter the food web, where they are ingested by herbivores and subsequently transferred to higher trophic levels, resulting in potential bioaccumulation and biomagnification (Wright et al., 2013; Eerkes-Medrano et al., 2015). Furthermore, microplastics extracted or trapped by plants are not permanently sequestered they may be released back into the environment through plant decay, sediment resuspension, or hydrological fluctuations (Wang et al., 2024). Such remobilization and fragmentation contribute to the persistence and secondary pollution of microplastics in aquatic ecosystems. Addressing these challenges requires incorporated management approaches that combine phytoremediation with plastic waste reduction, improved wastewater treatment, and sustainable ecosystem restoration strategies (Sharma and Chatterjee, 2017).

VIII. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite an abundance of research showing the potential of aquatic macrophytes to eliminate contaminants like microplastic (Tang,2023; Gecheva et al.,2025), heavy metals (Eid et al.,2020; Singh et al.,2025) and organic pollutants (Dhir et al.,2009; Xiao et al.,2021) there are still significant challenges that prevent these systems from being fully utilized. We are unaware of their long-term efficacy and ecological effects in natural environments because majority of research are laboratory-based and short-term. Field-scale assessments are particularly lacking, which are crucial for the evaluation of seasonal fluctuations, plant health, pollutant dynamics, and resilience to shifting climate and water quality (Brix, 1997; Vymazal, 2011). Without such comprehensive, long-term studies, it is difficult to predict the sustainability and effectiveness of constructed wetlands and other nature-based solutions across different ecosystems and geographical regions (Thorslund et al.,2017).

Another critical research gap is the inadequate knowledge of co-pollutant interactions, particularly the combined effects of nutrients, heavy metals, organic contaminants, and emerging pollutants like microplastics (Liu et al.,2023; Shaji et al.,2025). The fate, bioavailability, and the potential synergistic or antagonistic impacts of these co-occurring contaminants remain largely unexplored, which limited our capability to optimize remediation strategies (Ye et al., 2017; Narwal et al., 2024). Furthermore, research combining current monitoring instruments, molecular-level analysis of rhizosphere microbial communities, and mechanistic understandings of pollution uptake and transformation is required. Addressing up these gaps will aid in the development of robust, ecologically integrated, multipurpose water treatment systems that enhance ecosystem services and biodiversity while contributing to water quality.

IX. CONCLUSION

In conclusion, aquatic macrophytes provide an efficient and sustainable way to reduce the microplastic pollution in freshwater environments. These plants can capture, aggregate, and possibly break down microplastic particles while also improving water quality and supporting biodiversity through mechanisms like root adsorption, surface entanglement, and interactions with rhizosphere microbial communities. Although there have been promising laboratory and small-scale field studies, there have been few long-term and large-scale evaluations, and little is known about the fate of microplastics in plant tissues and sediments. Addressing these gaps through field-based research, studies on co-pollutant interactions, and integrated remediation strategies will be crucial for optimizing macrophyte-based interventions. Overall, using aquatic plants as natural filters is a multifunctional, environmentally responsible approach that integrates ecosystem restoration and water purification, providing an effective way to microplastics in an environmentally sustainable manner.

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