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Bioremediation Potential of Water Hyacinth (*Eichhornia crassipes*) for Microplastic Pollution Control in Aquatic Ecosystem

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Keywords: Bioremediation, *Eichhornia crassipes*, Phytoremediation, Water Hyacinth, Microplastic Pollution.

Abstract:

Pollution is one of the most severe consequences of environmental degradation, resulting from the contamination of natural elements by harmful substances. With the rise of various industries, Microplastic Pollution (MP) has emerged as a crucial environmental issue for aquatic ecosystems. In recent decades, urbanization has drastically degraded the quality of water bodies. Microplastic pollution in aquatic ecosystems poses a significant threat to aquatic flora and fauna, degrading ecosystem health. Bioremediation is likely a natural process that reduces pollution levels using living organisms. An eco-friendly alternative such as *Eichhornia crassipes,* commonly known as Water Hyacinth, often called as "Terror of Bengal" a free-floating aquatic macrophyte can be used in a sustainable manner for reducing the microplastic pollution. This plant possesses an extensive fibrous and feathery root system with the high surface area that helps in Phytoremediation by absorbing the microplastic particles. Research has indicated that microplastic also has the tendency to accumulate in the root areas of plants by hydrophobic interaction. The complex root system of *Eichhornia crassipes* traps not only microplastic but also heavy metals like copper, aluminium, lead, mercury and pesticides too. Mainly the cap region of root is effective over absorbing and entrapping microplastic which helps to enhance the water quality and reduce pollution. Beyond its bioremediation potential, the harvested biomass of Water Hyacinth can be utilized for composting biofertilizer and biogas generations. However, the uncontrollable growth of this invasive species also creates an ecological imbalance and waterways obstruction. This study explores the bioremediation potential of Water Hyacinth for its unique characteristics in controlling microplastic pollution, waste water management with the restoration of aquatic ecosystem that can maximize its benefit and minimize the risk.

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Introduction

The most pressing environmental challenges of the 21st century include water pollution, which can adversely affect human health and aquatic life. Intensive agricultural practices, industrialization, and the use of a wide range of heavy metals, dyes, and microplastics lead to contamination of freshwater ecosystems. The traditional method of wastewater treatment is not cost-effective and is less accessible in developing countries, while there is an urgency to mitigate water pollution in a sustainable manner (Hu et al., 2019). Microplastic pollution (MP) has emerged as a widespread global concern and an issue for aquatic ecosystems in recent years. Traditional approaches of removing microplastics are much costlier as they include filtration and sedimentation, but bioremediation is a sustainable approach that removes pollutants in an eco-friendly way.

In the context of removing pollutants, Phytoremediation is a technique to remove pollutants from nature by using plants. Phytoremediation, through the absorption and accumulation of contaminants by plants, provides a sustainable method and promising solution for managing aquatic pollution and preserving the ecosystem (Laws, 2000). Among the aquatic macrophytes, *Eichhornia crassipes,* a free-floating aquatic plant often called "Terror of Bengal," has demonstrated the bioremediation potential by absorbing high levels of pollutants. Their dense fibrous root system provides a large surface area that tends to absorb particulate matter. The rhizosphere of water hyacinth can degrade organic and inorganic contaminants. This plant has a unique potential to remove polystyrene and nano plastics by its roots.

Though *Eichhornia* is an invasive species, but its sustainable use and cost-effective strategy help to reduce microplastic contamination. Physical trapping, sedimentation, and microbial-assisted degradation are essential methods for developing strategies of bioremediation. This study will explore the Bioremediation potential of *Eichhornia crassipes* for controlling microplastic pollution in aquatic ecosystems by highlighting its mechanisms, efficacy, and limitations. Water hyacinth plays a crucial role in a sustainable manner by applying phytoremediation techniques, integrating ecological knowledge.



Figure 1. Plastics are entrapped in water hyacinth. Water hyacinth (Eichhornia crassipes) colonizing a microplastic-contaminated freshwater body in Malda, West Bengal, India.

What is Microplastic?

Plastic pollution is a global environmental concern with its various forms and sizes that adversely create environmental obstacles (Pandey et al., 2023). Among them, microplastics are known as less than 5 millimeters. The term microplastics was introduced by Professor Richard Thompson in 2004 (Thompson, 2018).

These originate from several industrial sources. There are two main types of microplastics such as primary and secondary microplastics. Primary microplastics originate from cosmetics and industrial microbeads, and secondary microplastics originate from the degradation of larger plastic debris. Polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC) and polyethylene terephthalate (PET) are the most prevalent microplastics found in the freshwater ecosystem (Ivleva et al., 2017; Das et al., 2023).



Figure 2. Microplastics of different sizes can adhere strongly to skin surfaces.

Origin of Microplastic in Anthropocene

The large-scale manufacturing of plastics began in the mid-20th century, suggesting the onset of the Anthropocene. Microplastics during the Anthropocene mainly come from human actions, degradation of larger plastics, tire degradation, synthetic fabrics (washing), microbeads in consumer products, paints, and industrial granules. These minute particles, found everywhere in the air, water and soil, serve as a geological indicator of the "plastic age," infiltrating ecosystems via urban runoff, wastewater, and atmospheric deposition, ultimately becoming an enduring element of Earth's sedimentary history following significant industrialization post-1950s.

Primary Sources (Direct Produce)

#Synthetic Textiles: Washing synthetic clothes (polyester, nylon) releases fibres, which are carried via wastewater.

#Tire Wear: Scraping of car tires on road surface creates significant particulates matter, which dispersed by wind and water.

#Personal Care Products: Direct source microbeads in exfoliants and cosmetics, though banned increase.

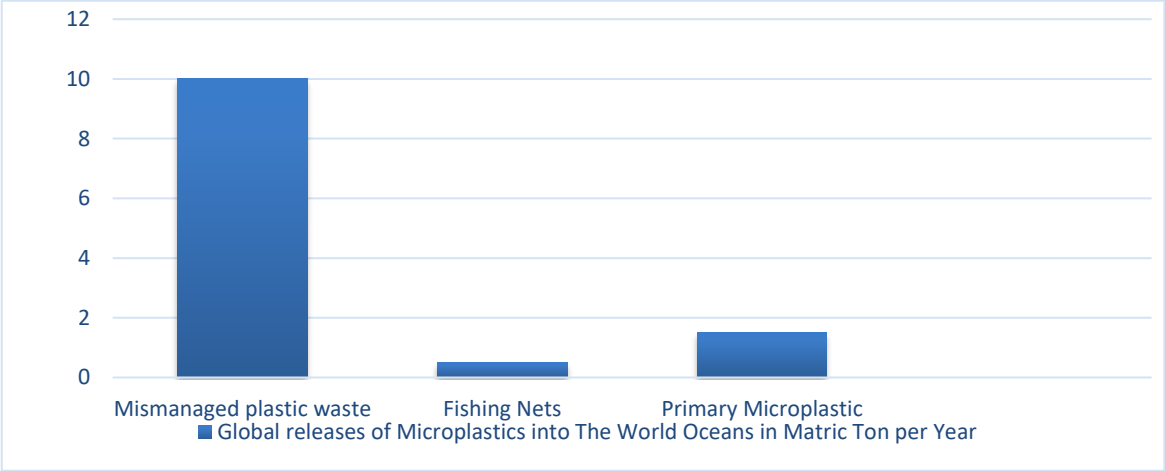
#Industrial Pellets: Plastic resin pellets which are used in manufacturing, are often spilled.

#Coatings: Wear and tear from marine paints, road markings, and building materials.

Secondary Sources (Breakdown of Larger Plastics)

#Macro plastic Breakdown: Larger plastic items like bags, bottles, and packaging break down into smaller pieces due to UV light, waves, and mechanical action.

#Landfills & Waste: Erosion from landfills and plastic debris, i.e., plastitones, releases particles into the environment.



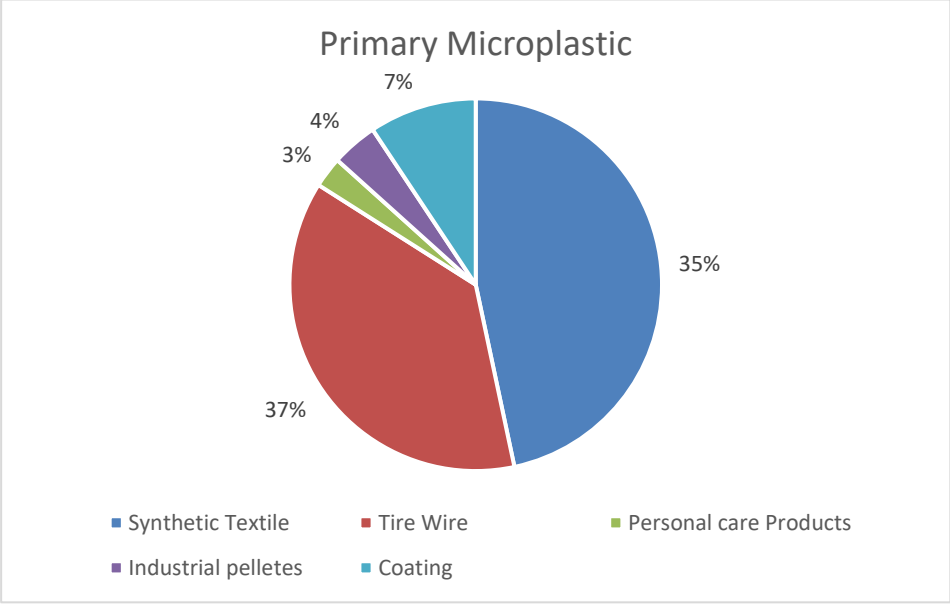


Figure 3 & 4. Global releases of microplastics into the world oceans and Primary Sources of Microplastic in Oceans data pie chart (An & Liu, 2020).

Essentiality of Microplastic in Anthropocene

Microplastics are not considered as essential in the Anthropocene in a beneficial or obligatory sense for the planet or human well-being; rather, they are a pervasive and harmful byproduct of human activities, acting as a key chronological marker of this new geological epoch (Chen, et al., 2022).

Obligatory (As an Indicator, not a Necessity)

#Geological Marker: Microplastics are persistent in the environment, becoming part of the geological record as "technofossils" that can be used to help date sediment layers and define the start of the Anthropocene epoch.

#Indicator of Human Impact: Their widespread presence is an unavoidable indicator of the extent to which human activities have altered the planet's systems, demonstrating the scale of the "throw-away society".

Optional (Their Presence is a Choice, not a Requirement):

#Preventable Pollution: Microplastic pollution is largely caused by human choices, such as inadequate waste management, the use of single-use plastics and the shedding of synthetic textiles.

#Harmful, Not Beneficial: Far from being essential, microplastics pose significant threats to ecosystems and human health. They:

*Harm marine and terrestrial life, impacting growth, reproduction, and organ function.

*Act as transport operators for harmful chemicals (like PCBs and heavy metals), which can then enter the food chain.

*Have been associated with increased health risks in humans.

Finding of Microplastic in Biota

Microplastics are found in all biota, from plankton to humans, causing harm through physical blockage, chemical leaching, leading to inflammation, oxidative stress, gut issues, reproductive problems, metabolic disruption, immune system changes, impact on organisms at all trophic levels, including humans via diet, air and direct contact, affecting fertility and potentially causing cell damage.

Findings in Biota (Animals & Humans)

Bioaccumulation: Accumulates in organisms, moving up the food chain, disrupting food webs.

Physical Effects: Causes gut blockages, tissue damage, reduced feeding, and growth retardation in fish.

Chemical Toxicity: Leaches chemicals (additives, heavy metals), leading to oxidative stress, liver changes and neurotoxicity.

Reproductive & Cellular Impacts: Linked to reduced sperm counts, reproductive issues, and inflammation in human cells; alters gene expression in fish (Kumar et al., 2025).

Effects on Humans

#Inflammation and oxidative stress: Microplastics can cause inflammation and oxidative stress in the lungs, gut, and other organs. This can lead to symptoms like coughing, shortness of breath, and fatigue.

#Cardiovascular risks: A 2024 study found that people with microplastics in their carotid artery plaque had a significantly higher risk of heart attack, stroke, or death compared to those without (Yarahmadi et al., 2024).

#Neurological effects: Nanoparticles can potentially cross the blood-brain barrier and accumulate in the brain, leading to inflammation and damage to brain cells, which may increase the risk of neurodegenerative diseases like Alzheimer's and dementia.

#Gastrointestinal issues: Microplastics can irritate the gut lining, alter the gut microbiome, and contribute to inflammatory bowel disease.

#Reproductive problems: Some microparticles can affect reproductive organs and may impact fertility.

#Chemical toxicity: Microplastics can carry and release harmful chemicals, such as BPA and phthalates, that disrupt hormones and have been linked to various health issues.

#Increased cancer risk: Some research has shown microplastics are more frequently found in cancerous lung tissue than in healthy tissue (Blackburn and Green, 2022). Their presence is also associated with an increased risk of other forms of cancer.

The removal of microplastics from the environment has become a global priority due to their persistent nature, ecological toxicity and also potential risks to human health. The implementation of a sustainable and cost-effective remediation process is essential to inhibit the spread of MPs in aquatic ecosystems. Within this framework, we choose a promising agent which is commonly known as “Terror of Bengal” or major aquatic macrophytes of Bengal i.e., *Eichhornia crassipes*. Despite its reputation as an invasive species, this dominant aquatic macrophyte of Bengal possesses extensive fibrous root systems, high biomass productivity, and exceptional pollutant-adsorption capabilities. These attributes confer significant potential for the phytoremediation and bio-adsorptive removal of microplastics from contaminated water bodies. Employing *E. crassipes* as a remediation tool not only aligns with the principles of environmental sustainability but also offers an innovative approach for effective pollution management.

Potentiality of *Eichhornia crassipes*

Eichhornia crassipes, also commonly known as water hyacinth, is a free-floating aquatic macrophyte that belongs to the family Pontederiaceae. This is a native plant of the Amazon basin of South America, and now spreads all over the tropical and subtropical regions of the world. Initially this plant was introduced as an ornamental species as it has beautiful purple colour but later it has become the most invasive aquatic weed.

Morphology

The feathery root system of *Eichhornia crassipes* is submerged and highly efficient in absorbing nutrients from water, and also acts to grab microplastics. The stem, also called a rhizome, produces a branch stolon with nodes. The new roots, leaves, flowers, and stalks emerge from the stolon, and this also facilitates vegetative propagation. Leaves are rosettes, and they are attached to the stem by spongy petioles.



Figure 5. Different morphological parts of *Eichhornia crassipes*, including flower, leaf, bulb and rhizome.

These bulbous petioles are air-filled and made up of aerenchyma cells that provide buoyancy to the plant. Leaf blades are also thicker and smoother with a glossy, green, oval-shaped appearance with fine and semi-parallel veins (Penfound and Earle, 1948). This plant has a spike inflorescence and each spike bears 8 to 15 flowers. These flowers are lavender to purple-blue in colour and have a noticeable yellow diamond-shaped spot on the upper petal. Flowers bearing six stamens with two different lengths. The fruits are capsules and contain minute ovoid seeds that remain viable up to 20 years. E. crassipes reproduces both sexually and asexually with stolon and produces daughter plants, i.e., ramets.

Physiology

Water hyacinth physiology centers on its successful adaptation as a free-floating aquatic plant, featuring buoyant, air-filled petioles (stems) for floating, aerenchyma tissue for gas exchange, and extensive root systems for nutrient absorption and anchorage, alongside rapid growth driven by high nutrient uptake (especially N & P) and versatile reproduction (asexual

budding, sexual seeds), making it an excellent bioaccumulator of pollutants but also highly invasive.

Swollen, bulbous petioles filled with parenchyma tissue containing large air cavities (aerenchyma) provide buoyancy, keeping the plant afloat. The aerenchyma tissue facilitates oxygen transport to submerged parts and carbon dioxide to photosynthetic tissues, crucial for its aquatic life. Long, fibrous, feathery roots efficiently absorb nutrients (like nitrates, phosphates) and metals directly from the water, with roots sometimes comprising 50% of biomass. Leaves are broad, glossy, and adapted for efficient light capture above water, though sensitive to extreme CO_2 /pollutant levels. Thrives in nutrient-rich waters (high N & P), doubling its population quickly through high rates of vegetative propagation (budding) and viable seeds.

The role in Bioremediation

Entrapment of microplastic

Eichhornia crassipes, or Water hyacinth, acts not only as an aquatic invasive species but also as a phytoremediator for its capacity to remove heavy pollutants from water. This is a highly effective aquatic plant that can remove pollutants from water by its unique physiological feature. The structural features such as fibrous roots, can trap suspended particulate matter and can act as natural physical barrier for suspended particulate matter (Saha et al., 2022). Their dense root system acts as a natural filter in water that can trap microplastics and solid suspension in water. This plant can also accumulate heavy metals such as cadmium and lead, excess nutrients such as nitrogen and phosphorus, dyes, and wastewater (Rasool et al., 2023). The roots can provide shelter to the microbial community that can help with the degradation of pollutants by enhancing the process. Root exudates released by water hyacinth can help to adhere the microplastic to stick with the surface. Their complex root structure can slow water flow, allowing microplastics to settle. This nature-based approach helps to mitigate water pollution through physical entrapment and microbial interaction within the rhizosphere.

Interaction with microbial community

The fibrous root of *Eichhornia crassipes* provides habitat for diverse microorganisms, including bacteria and fungi. These microbial communities form biofilms on the root surface, which starts the process of biodegradation. Those microbes help metabolise organic pollutants and break them down into less harmful substances (Konopka, 2009). The combination of physical entrapment with their complex root system enhances the overall removal efficiency of microplastics. That biological degradation helps reduce the pollutant load, which can restore water quality and help maintain water health.



Figure 4. *Eichhornia crassipes* in a polluted water body at Malda, showing its potential for microplastic bioremediation.

Root chelating agent found in Eichhornia

Eichhornia is found as one of the most noxious weeds that has been investigated for use in aquatic ecosystems to reduce microplastic pollution. Absorption of heavy metals like Copper (Cu) and Zinc (Zn) primarily occurs through the roots that contain a natural chelating agent. Mainly, phytochelatins (PCs) are cysteine-rich peptides with multiple thiol groups(-SH) that are enzymatically synthesized from glutathione (GSH), with the enzyme Phytochelatin synthase. Heavy metals like Cu^{2+}, Zn^{2+}, and Cd^{2+} enter the root cell, triggering glutathione to form phytochelatin, which activates the enzyme, increasing the capacity to handle toxicity (Nor, 1990). Metallothioneins, some organic acids such as citric acid, malic acid, oxalic acid, and succinic acid also act as binding ions in the rhizosphere areas of Water Hyacinth that enhance metal intake. Functional groups such as amines(-NH_2), hydroxyl(-OH), pectin and hemicellulose have a carboxyl group (-COO-), which absorbs metals via ionic interaction in the roots.

Microbes that degrade microplastic in *Eichhornia*

Metagenomic studies of the microbiome showed that the bacterial community in the rhizosphere of Eichhornia crassipes helps it survive in a polluted ecosystem. Proteobacteria are the most abundant in the root of *Eichhornia crassipes* (79%), followed by Fungi and cyanobacteria (8%) (Singh et al., 2024). Bacteria such as Pseudomonas aeruginosa can degrade Polyethylene (PE) and Polypropylene (PP) microplastics by polyestarase enzymatic mechanism. *Ideonella sakaiensis*, a gram-negative bacterium, is capable of degrading PET plastic by breaking it down into two key enzymes, such as PETase and MHETase. Bacillus subtilis can degrade polystyrene (PS), and *B. cereus* can degrade by the lipase-mediated depolymerization by

targeting PE and PP (Gamage and Asaeda, 2005). Fungi such as *Aspergillus* and *Fusarium* help to degrade PE by the enzyme laccase and Oxidative degradation. *Cyanobacteria* such as *Chlorella vulgaris* enhance the bacterial and fungal colonization on the microplastics.

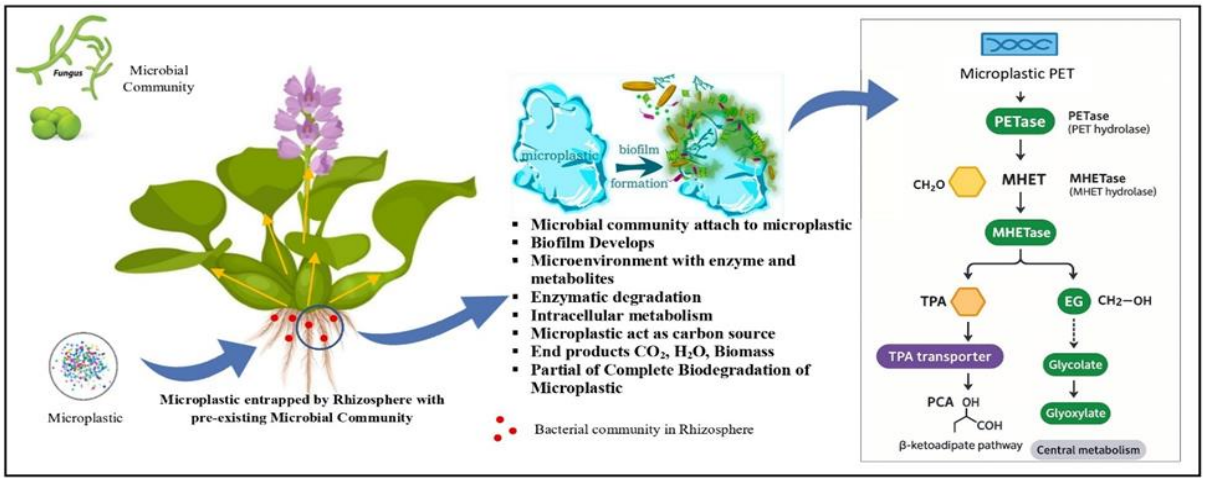
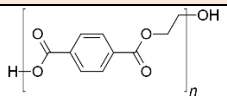
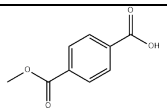
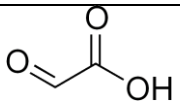
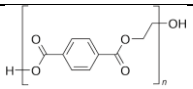


Figure 5. Proposed mechanism of microplastic removal and biodegradation by *Eichhornia crassipes* (Mandal et al., 2024).

Table 1. Molecules and their chemical structure.

Molecule/ Enzyme	Chemical Structure	Description
PET		Polymer made from terephthalic acid+ ethylene glycol
MHET		PET degradation intermediate containing one ester and one carboxyl group
TPA	$HOOC\text{-}C_6H_4\text{-}COOH$	Aromatic dicarboxylic acid produced from MHET cleavage
EG	$HO\text{-}CH_2\text{-}CH_2\text{-}OH$	Small diol also released from PET degradation
Glycolate	$HO\text{-}CH_2\text{-}COO^-$	Intermediate in EG metabolism, oxidized from ethylene glycol
Glyoxylate		Key metabolic intermediate entering the glyoxylate cycle
PETase		Enzyme that breaks PET to MHET
MHETase	MHET hydrolase enzyme	Large Protein ag/beta-hydrolase

Significance

Eichhornia crassipes plays a significant role in restoring aquatic ecosystems by reducing pollutant loads, including microplastics. Water hyacinth absorbs nutrients from water and helps to control eutrophication, which prevents algal bloom and oxygen depletion. Their dense and complex root system provides habitat for microbes that enhance the natural biodegradation process of water bodies. *Eichhornia* also acts as a natural biofilter that stabilizes the ecosystem and balances the ecosystem. Removing contaminants from water supports the revival of aquatic flora and fauna and promotes biodiversity.

Sustainable Development Goal (SDG)

The sustainable development goal provides a global framework for addressing critical environmental and social and challenges (Chatterjee et al., 2023; Mukherjee et al., 2022). The goals related to clean water, climate resilience, and ecosystem restoration emphasize the urgent need for sustainable strategies to protect nature from pollution. Water pollution in response to the growing concern of microplastic pollution poses a significant threat to aquatic ecosystem health and overall well-being (Hák et al., 2016).

In this context, bioremediation emerged as a nature-based solution by using living organisms to detoxify the environment. Water Hyacinth, as an invasive species, has attracted attention globally with its ability to absorb and accumulate pollutants as well as heavy metals. Their dense, complex root systems help collect toxic chemicals from contaminated water bodies. Exploring the bioremediation potential of *Eichhornia crassipes* supports multiple Sustainable Development Goals (SDGs) particularly SDG 6 which is clean water and sanitation, SDG 14 life below water and SDG 12 responsible consumption. Promoting this sustainable pollution control strategy and integrating bioremediation by Water Hyacinth that aligns with global sustainability to restore the aquatic ecosystem.

SDG 6- Clean Water and Sanitation

Clean water and sanitation (SDG 6) aim to ensure sustainable water availability by 2030 through improved water quality, reduced pollution, effective wastewater treatment, recycling and protection of freshwater ecosystems. Strengthening sanitation systems, practising integrated water resource management, and promoting awareness of sustainable water use are essential for supporting agriculture, industry, and public well-being. Water hyacinth–based bioremediation directly contributes to SDG 6 by naturally removing microplastics and other pollutants from contaminated water bodies (Abba & Sabarinath, 2025). This eco-friendly, low-cost method enhances water quality through natural filtration, offering a sustainable alternative to chemical treatment methods.

SDG 12- Responsible Consumption and Production

Responsible consumption and production (SDG 12) focus on sustainable resource use and effective waste management, promoting reduced pollution through eco-friendly processes, green technologies, and recycling (Moitra et al., 2023). This goal highlights that long-term development cannot depend on the overexploitation of natural resources. In the context of microplastic pollution, SDG 12 stresses the need for sustainable waste-removal alternatives. *Eichhornia crassipes* serves as a nature-based solution, helping to remove pollutants from aquatic ecosystems (Nahar & Sunny, 2024). Water hyacinth reduces microplastic loads and supports circular economic practices such as biomass composting, biofuel production, and sustainable wastewater management.

SDG 14- Life below water

Sustainable Development Goal 14 focuses on conserving aquatic resources, which are vital for biodiversity, climate regulation, and livelihoods (Moitra et al., 2023). However, rapid industrialization and urbanization have degraded freshwater systems through microplastics, heavy metals, and organic pollutants. Reducing these contaminants is essential for protecting aquatic biodiversity and improving water quality. Nature-based solutions such as bioremediation support SDG 14 by removing harmful substances from freshwater ecosystems. Aquatic macrophytes, including *Eichhornia crassipes*, can enhance ecosystem resilience by absorbing pollutants (Küfeoğlu, 2022). Although invasive when uncontrolled, water hyacinth holds significant potential as a bioremediation tool aligned with SDG 14.

Challenges

While this aquatic weed Water Hyacinth or *Eichhornia crassipes* is widely accepted for its bioremediation potential due to its rapid growth and pollutant intake capability, but there are some limitations in the application. As this is an invasive species and harmful for the aquatic habitat so without proper management this can lead to loss of Biodiversity. Understanding this problem is essential to initiate control measurement and optimized its use.

Ecosystem disruption & biodiversity loss

Water hyacinth is one of the most aggressive invasive aquatic plants. Its rapid growth forms dense surface mats that block the sunlight, reduce oxygen levels, change nutrient cycles, and obstructer for water flow. These mats can trap sediments and microplastics, degrading water quality that affecting aquatic life. The plant can grow up to 201% within seven days, and its seeds can remain dormant for up to 15 years (Irewale et al., 2024). It is very difficult to control. When biomass decays, it releases organic matter that can trigger algal blooms, which further disrupt the ecosystem balance.

Limited efficiency in large-scale use

Water hyacinth can absorb only a limited amount of microplastics; once saturated, its efficiency declines. After uptake, the harvested biomass itself becomes a pollutant if not properly treated, as it may release trapped contaminants (Mishra & Maiti, 2017). This challenge underscores the need to combine water hyacinth with complementary methods—such as mechanical filtration or microbial bioremediation—to achieve effective large-scale microplastic removal.

Future prospects and Research dimensions

The future prospects of *Eichhornia crassipes* in microplastic pollution control are promising and diverse. Water hyacinth can be incorporated into the engineered phytoremediation systems, including constructed wetlands and biofiltration units, to enhance pollutant removal control. Biotechnological inoculation may further improve its microplastic degradation potential by modification of rhizosphere microorganisms or genetic engineering to enhance root-based trapping and breakdown mechanism. Due to its high accumulation capacity, water hyacinth can also serve as a bioindicator of microplastic levels in polluted waters. Future research aims to use harvested biomass for biogas, biofertilizer, and biochar production (Sharma et al., 2022), and to better understand the behavior and transport of nanoplastics compared with larger microplastics.

Conclusion

Water pollution with the emergence of microplastic pollution poses a serious threat to aquatic ecosystem, biodiversity and human health. Conventional methods for waste water treatment is not only costly but also energy intensive. In this context, the bioremediation potential of *Eichhornia crassipes* emerges as one of the sustainable or eco-friendly solution. The rapid growth of this weed with its dense fibrous root enable to accumulate and absorb a wide variety of contaminants including heavy metals. The fibrous dense root system act as natural filter that can physically trap microplastic particles by providing a habitat for microbial biofilm for enhancing bio degradation of organic pollutants. Reducing the load of pollutants and mitigating the accumulation of microplastic in water bodies Water Hyacinth contributes to the revival of aquatic flora and fauna. Overall, this weed acts a nature-based solution but there are also some hindrances that may not trigger to perform large scale application in water bodies. The application of *Eichhornia crassipes* helps in constructing wetlands and contaminated waterbodies demonstrates how a problematic aquatic weeds could be transformed into valuable resources for sustainable management of the ecosystem. This paper has highlighted the bioremediation potential of Water Hyacinth as well as how it is aligned with sustainable development goal.

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