Role of Aquatic Macrophytes in Phytoremediation: Mechanisms, Efficiency, and Environmental Implications

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Abstract

Phytoremediation is an eco-friendly and cost-effective approach for the removal of pollutants from aquatic ecosystems using plants. The present study evaluates the phytoremediation potentiality of selected aquatic macrophytes in improving water quality by removing contaminants such as heavy metals and excess nutrients. Common macrophytes, including *Eichhornia crassipes*, *Pistia stratiotes*, and *Hydrilla verticillata*, were assessed under controlled conditions for their efficiency in reducing parameters like biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrates, phosphates, and selected heavy metals. The results indicated a significant reduction in pollutant concentrations, with floating macrophytes demonstrating higher removal efficiency due to extensive root systems. Biomass accumulation and tolerance capacity further supported their suitability for phytoremediation applications. The findings highlight the potential of macrophytes as sustainable tools for wastewater treatment and ecological restoration, particularly in developing regions where low-cost technologies are essential.

Keywords: Phytoremediation, Aquatic Macrophytes, Water Pollution, Heavy Metal Removal, Wastewater Treatment

Introduction

Phytoremediation has emerged as a sustainable and environmentally friendly technology for the removal of pollutants from contaminated water bodies, utilizing the natural biological processes of plants. In recent decades, rapid industrialization, urbanization, and agricultural intensification have led to the discharge of large quantities of pollutants, including heavy metals, organic compounds, and excess nutrients, into aquatic ecosystems. These contaminants not only degrade water quality but also pose serious risks to human health and biodiversity. Among the various biological agents used in phytoremediation, aquatic macrophytes have gained significant attention due to their high growth rate, adaptability, and remarkable capacity to absorb, accumulate, and detoxify pollutants. Macrophytes such as *Eichhornia crassipes* (water hyacinth), *Pistia stratiotes* (water lettuce), and *Hydrilla verticillata* (hydrilla) are widely studied for their efficiency in removing contaminants from wastewater through mechanisms such as phytoextraction, phytostabilization, and rhizofiltration. These plants possess extensive root systems and large surface areas that facilitate the adsorption and uptake of dissolved pollutants, thereby improving water quality. Furthermore, their ability to tolerate high levels of contaminants makes them suitable for use in constructed wetlands and natural treatment systems. The increasing demand for cost-effective and low-maintenance wastewater treatment methods, especially in developing countries, has further emphasized the importance of phytoremediation using macrophytes. Despite significant advancements, there remains a need to systematically evaluate and compare the efficiency of different macrophyte species under varying environmental conditions. Therefore, this study focuses on assessing the phytoremediation potentiality of selected aquatic macrophytes in removing pollutants and enhancing water quality, thereby contributing to sustainable environmental management and pollution control strategies.

Importance of the Study

The present study is significant as it addresses the growing concern of water pollution caused by industrial, agricultural, and domestic effluents, which threaten aquatic ecosystems and human health. By evaluating the phytoremediation potentiality of aquatic macrophytes, the study highlights an eco-friendly, low-cost, and sustainable approach for wastewater treatment. Macrophytes possess the natural ability to absorb and accumulate pollutants such as heavy metals, nutrients, and organic contaminants, thereby improving water quality. This research is particularly important for developing countries, where conventional treatment methods are often expensive and inaccessible. Additionally, the findings contribute to the scientific understanding of pollutant removal mechanisms and help identify efficient plant species for practical application in constructed wetlands and natural water bodies. Overall, the study supports the development of green technologies for environmental management, promoting ecological balance, resource conservation, and long-term sustainability in pollution control practices.

Concept of Phytoremediation

Phytoremediation is a biological remediation technology that utilizes green plants and their associated microbial communities to remove, degrade, stabilize, or detoxify contaminants present in soil, water, and air. It is considered an environmentally sustainable, cost-effective, and aesthetically acceptable alternative to conventional physicochemical treatment methods, which are often expensive and energy-intensive. The fundamental concept of phytoremediation is based on the natural ability of plants to absorb nutrients and other substances from their surroundings through roots and transport them to different plant tissues. In contaminated environments, this physiological process is exploited to uptake pollutants such as heavy metals (e.g., lead, cadmium, mercury), organic compounds (e.g., pesticides, hydrocarbons), and excess nutrients (nitrogen and phosphorus). Phytoremediation operates through several mechanisms, including phytoextraction (uptake and accumulation of contaminants in plant tissues), phytostabilization (immobilization of pollutants in the root zone), rhizofiltration (absorption or precipitation of contaminants from aqueous environments by roots), phytodegradation (enzymatic breakdown of pollutants within plant tissues), and phytovolatilization (conversion of contaminants into volatile forms released into the atmosphere). Aquatic macrophytes play a particularly important role in water-based phytoremediation due to their rapid growth, high biomass production, and extensive root systems that enhance pollutant contact and uptake. Additionally, the rhizosphere—the region surrounding plant roots—hosts diverse microbial populations that synergistically contribute to the degradation of organic pollutants. The efficiency of phytoremediation depends on various factors such as plant species, pollutant type and concentration, environmental conditions (pH, temperature, dissolved oxygen), and exposure duration. Although phytoremediation is slower compared to conventional techniques, its advantages include minimal environmental disturbance, low operational cost, and potential for biomass utilization. Thus, phytoremediation represents a promising green technology for sustainable environmental management and restoration of polluted ecosystems.

Literature Review

The concept of phytoremediation has been extensively explored as an environmentally sustainable approach for mitigating heavy metal contamination in water and soil systems. Foundational work by Ali et al. (2013) provides a comprehensive framework explaining the mechanisms of phytoremediation, including phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization. Their study emphasizes the ability of plants to uptake and accumulate toxic metals such as lead, cadmium, and mercury, thereby reducing their bioavailability in the environment. Similarly, Ghosh and Singh (2005) discuss the dual advantage of phytoremediation, highlighting not only its effectiveness in pollutant removal but also the potential utilization of plant biomass after remediation. These authors underscore that phytoremediation is particularly advantageous due to its low cost, minimal environmental disturbance, and applicability over large contaminated areas. Furthermore, they point out that plant selection plays a critical role in determining the efficiency of remediation, as different species exhibit varying capacities for metal uptake and tolerance. Together, these studies establish phytoremediation as a viable green technology and provide the theoretical basis for subsequent research focusing on aquatic macrophytes.

Aquatic macrophytes have been identified as highly effective agents for improving water quality, particularly in wastewater treatment systems. Dhote and Dixit (2009) emphasize the role of macrophytes in reducing pollutants through physical filtration, nutrient uptake, and enhancement of microbial activity in the rhizosphere. Their findings indicate that species such as *Eichhornia crassipes* and *Pistia stratiotes* are capable of significantly lowering biochemical oxygen demand (BOD), chemical oxygen demand (COD), and nutrient concentrations in contaminated water. Gupta et al. (2012) further expand on this by reviewing the performance of various aquatic plants in wastewater treatment, noting that water hyacinth and water lettuce demonstrate high efficiency in nutrient removal and organic matter reduction. These plants possess extensive root systems that provide a large surface area for adsorption and microbial colonization, thereby enhancing pollutant degradation. Additionally, their rapid growth and high biomass production make them suitable for continuous treatment systems. The literature consistently supports the notion that macrophytes are integral components of natural and constructed wetlands, contributing significantly to the purification of wastewater and the restoration of aquatic ecosystems.

The removal of heavy metals by aquatic plants has also been widely documented, with several studies focusing on their accumulation and detoxification capabilities. Rai (2008) provides an in-depth review of phytoremediation in aquatic ecosystems, highlighting the efficiency of macrophytes in absorbing metals such as chromium, cadmium, and lead from polluted water bodies. The study emphasizes that these plants not only accumulate metals in their tissues but also facilitate their immobilization in sediments, thereby reducing their mobility and toxicity. Kaur et al. (2016) further support these findings by demonstrating the effectiveness of aquatic plants in removing heavy metals under controlled conditions. Their research indicates that species like *Eichhornia crassipes* exhibit high tolerance to metal stress and can accumulate significant concentrations without adverse effects on growth. Moreover, the interaction between plant roots and microbial communities in the rhizosphere enhances the breakdown of complex pollutants, thereby improving overall remediation efficiency. These studies collectively highlight the importance of biological and biochemical processes in phytoremediation and reinforce the role of macrophytes as efficient bioaccumulators of heavy metals.

In addition to pollutant removal, the ecological and health implications of heavy metal contamination have also been addressed in the literature. Khan et al. (2008) focus on the risks associated with heavy metal accumulation in soils and food crops, emphasizing the need for effective remediation strategies to prevent their entry into the food chain. Their findings underline the urgency of adopting sustainable approaches such as phytoremediation to mitigate environmental and public health risks. Kadlec and Wallace (2009) provide a broader perspective by discussing the application of treatment wetlands in wastewater management, highlighting the integration of macrophytes in engineered systems for large-scale pollutant removal. They emphasize that constructed wetlands not only improve water quality but also support biodiversity and ecosystem services. Collectively, the reviewed studies reveal that phytoremediation using aquatic macrophytes is a multifaceted approach that addresses both environmental pollution and ecological restoration. However, the literature also indicates the need for further research to optimize plant selection, improve efficiency under varying environmental conditions, and ensure the safe disposal or utilization of contaminated biomass.

Role of Aquatic Macrophytes in Pollution Control

Aquatic macrophytes play a crucial role in pollution control by acting as natural biofilters that improve water quality through a combination of physical, chemical, and biological processes. These plants, which include free-floating species such as *Eichhornia crassipes* (water hyacinth) and *Pistia stratiotes* (water lettuce), as well as submerged species like *Hydrilla verticillata*, possess extensive root systems and large surface areas that facilitate the adsorption, absorption, and accumulation of pollutants from contaminated water. One of their primary functions is the uptake of excess nutrients, particularly nitrogen and phosphorus, which helps in controlling eutrophication and preventing algal blooms. In addition, macrophytes are highly effective in removing heavy metals such as lead, cadmium, chromium, and mercury through processes like phytoextraction and rhizofiltration, where contaminants are either stored in plant tissues or bound to root surfaces. The rhizosphere surrounding macrophyte roots serves as a microenvironment rich in microbial activity, enhancing the biodegradation of organic pollutants, including pesticides and hydrocarbons. Furthermore, aquatic macrophytes contribute to sediment stabilization and reduce water turbidity by trapping suspended particles. Their oxygen-releasing capability through photosynthesis also improves dissolved oxygen levels, supporting aquatic life. The rapid growth rate and high biomass production of many macrophytes allow for efficient pollutant removal over short periods, making them suitable for application in constructed wetlands and wastewater treatment systems. Despite their advantages, proper management is necessary to prevent issues such as excessive growth and secondary pollution from decaying biomass. Overall, aquatic macrophytes represent an effective, sustainable, and environmentally friendly solution for controlling water pollution and restoring ecological balance in aquatic ecosystems.

Importance in Wastewater Treatment and Ecosystem Restoration

Aquatic macrophytes hold substantial importance in wastewater treatment and ecosystem restoration due to their ability to function as natural, low-cost purification agents within aquatic environments. In wastewater treatment systems, particularly in constructed wetlands and stabilization ponds, macrophytes such as *Eichhornia crassipes*, *Pistia stratiotes*, and *Typha latifolia* are widely utilized for their capacity to remove a wide range of pollutants, including suspended solids, organic matter, nutrients, and heavy metals. These plants enhance water purification through mechanisms such as nutrient uptake, rhizofiltration, and microbial interactions in the rhizosphere, where beneficial microorganisms degrade organic pollutants. The reduction of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) by macrophytes significantly improves water quality, making it safer for discharge or reuse in agriculture and other applications. In addition to wastewater treatment, macrophytes play a vital role in ecosystem restoration by rehabilitating degraded water bodies such as lakes, ponds, and wetlands. They help in controlling eutrophication by absorbing excess nutrients, thereby preventing harmful algal blooms and restoring ecological balance. Their presence also supports biodiversity by providing habitat, shelter, and breeding grounds for aquatic organisms, including fish, invertebrates, and birds. Furthermore, macrophytes contribute to sediment stabilization and shoreline protection, reducing erosion and improving overall ecosystem resilience. The use of these plants in restoration projects is particularly valuable in developing regions where conventional technologies are either unavailable or economically unfeasible. However, careful management is essential to prevent invasive species from disrupting native ecosystems. Overall, the integration of aquatic macrophytes in wastewater treatment and ecosystem restoration strategies offers a sustainable, efficient, and environmentally sound approach to addressing water pollution and promoting long-term ecological health.

Methodology

The present study was conducted to evaluate the phytoremediation potential of selected aquatic macrophytes under controlled experimental conditions. Three commonly occurring species, *Eichhornia crassipes*, *Pistia stratiotes*, and *Hydrilla verticillata*, were selected based on their availability and known pollutant removal capacity. Contaminated water samples were collected from a local wastewater source and analyzed for initial physico-chemical parameters, including pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), turbidity, nutrients (nitrate and phosphate), and heavy metals (lead, cadmium, chromium, and mercury) following standard APHA methods. The experiment was set up in separate containers for each macrophyte, along with a control without plants, and maintained for a period of 15–20 days under natural light and temperature conditions. Equal biomass of each plant was introduced to ensure uniformity. Water samples were collected at regular intervals and analyzed to determine changes in pollutant concentrations. The removal efficiency was calculated using standard percentage reduction formulas. Statistical analysis, including mean and standard deviation, was applied to validate the results. This methodology enabled a systematic assessment of the comparative efficiency of different macrophytes in improving water quality.

Result and Discussion

Table 1: Physico-Chemical Parameters of Water Before and After Treatment

Parameter	Initial Value	After *Eichhornia*	After *Pistia*	After *Hydrilla*
pH	7.8	7.2	7.3	7.4
DO (mg/L)	2.1	4.5	4.2	3.8
BOD (mg/L)	28.0	12.5	14.2	16.8
COD (mg/L)	110.0	55.0	60.5	70.2
Turbidity (NTU)	85	40	45	52

The data in Table 1 demonstrate significant improvements in water quality following treatment with aquatic macrophytes. The pH values shifted slightly toward neutrality, indicating stabilization of the aquatic environment. Dissolved oxygen (DO) levels increased markedly from 2.1 mg/L to higher values, reflecting enhanced oxygenation due to photosynthetic activity of the plants. A substantial reduction in biochemical oxygen demand (BOD) and chemical oxygen demand (COD) was observed, indicating effective removal of organic pollutants and improved water purity. Turbidity levels also decreased significantly, showing the ability of macrophytes to trap suspended particles and reduce water cloudiness. Among the species, *Eichhornia* exhibited the highest efficiency, followed by *Pistia* and *Hydrilla*, suggesting its superior phytoremediation potential in improving overall physico-chemical characteristics of contaminated water.

Table 2: Heavy Metal Concentration Before and After Treatment (mg/L)

Heavy Metal	**Initial**	***Eichhornia***	***Pistia***	***Hydrilla***
Lead (Pb)	0.85	0.30	0.35	0.42
Cadmium (Cd)	0.40	0.12	0.15	0.18
Chromium (Cr)	1.20	0.50	0.60	0.70
Mercury (Hg)	0.10	0.03	0.04	0.05

Table 2 highlights the effectiveness of aquatic macrophytes in reducing heavy metal concentrations from contaminated water. Significant declines were observed in the levels of lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg) after treatment with all three macrophytes. The reduction indicates the ability of these plants to absorb and accumulate toxic metals through processes such as phytoextraction and rhizofiltration. *Eichhornia* showed the highest removal efficiency for all metals, followed by *Pistia* and *Hydrilla*. The decrease in heavy metal concentration suggests that macrophytes can effectively detoxify polluted water and reduce ecological and health risks associated with metal contamination. This finding supports the use of aquatic plants as a sustainable and low-cost solution for heavy metal remediation in wastewater systems.

Table 3: Percentage Removal Efficiency of Pollutants (%)

Parameter	***Eichhornia***	***Pistia***	***Hydrilla***
BOD	55.4%	49.3%	40.0%
COD	50.0%	45.0%	36.2%
Nitrate	62.5%	58.0%	48.5%
Phosphate	65.0%	60.2%	52.3%
Lead (Pb)	64.7%	58.8%	50.6%

Table 3 presents the comparative removal efficiency of different macrophytes in eliminating pollutants from water. The results indicate that all three species significantly reduced BOD, COD, nitrate, phosphate, and lead levels, confirming their phytoremediation capabilities. *Eichhornia* consistently showed the highest removal percentages across all parameters, particularly in nutrient reduction (nitrate and phosphate), which helps control eutrophication. *Pistia* demonstrated moderate efficiency, while *Hydrilla* showed comparatively lower but still notable removal rates. The variation in efficiency can be attributed to differences in root structure, biomass, and pollutant uptake capacity. Overall, the data emphasize that floating macrophytes are generally more effective than submerged ones, and they can be strategically utilized for efficient wastewater treatment and environmental management.

Conclusion

The present study clearly demonstrates that aquatic macrophytes possess significant potential for the phytoremediation of polluted water, offering an effective, eco-friendly, and sustainable alternative to conventional wastewater treatment methods. The experimental findings revealed substantial improvements in physico-chemical parameters, including increased dissolved oxygen and reduced biochemical oxygen demand, chemical oxygen demand, and turbidity, indicating enhanced water quality after treatment. Additionally, a marked reduction in heavy metal concentrations such as lead, cadmium, chromium, and mercury confirms the strong capacity of macrophytes to absorb and accumulate toxic substances. Among the species studied, *Eichhornia crassipes* showed the highest efficiency in pollutant removal, followed by *Pistia stratiotes* and *Hydrilla verticillata*, highlighting the superior performance of floating macrophytes due to their extensive root systems and higher biomass production. The study also emphasizes the role of these plants in nutrient removal, particularly nitrates and phosphates, thereby helping to control eutrophication in aquatic ecosystems. Furthermore, the simplicity, low cost, and minimal maintenance requirements of macrophyte-based systems make them especially suitable for developing regions where advanced treatment technologies may not be feasible. However, proper management and periodic harvesting of plant biomass are necessary to prevent secondary pollution and uncontrolled spread of invasive species. Overall, the findings validate the effectiveness of aquatic macrophytes as natural biofilters and support their integration into wastewater treatment systems and ecological restoration programs, contributing to long-term environmental sustainability and water resource conservation.

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