Aquatic plants for bioengineering water treatment systems to improve pollutant removal

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Received: 31 July 2025; Revised: 22 September 2025; Accepted: 13 October 2025; Published: 30 October 2025

Abstract

Innovative, cost-effective, and sustainable technologies have incorporated the use of aquatic vegetation from hydroponic and wastewater treatment systems. Aquatic vegetation from hydroponic systems and wastewater treatment systems incorporates the use of adsorption, phytoaccumulation, and rhizodegradation. The intended objective of this proposed study is to analyze several selected aquatic plant species used in bioengineered systems for optimal removal of contaminants, including nitrogen, phosphorus, and organic matter, targeting water. A bioengineering treatment system consisting of the aquatic plants tested, water hyacinth, water lettuce, and bulrush, was intended and implemented in a system of controlled conditions. The removal efficiency of the investigated pollutants is determined from the concentrations measured at the system inflow and outflow over the specified time periods. The system was intended and implemented to remove pollutants, especially nitrogen and phosphorus. Different nitrogen and phosphorus levels in the proposed system resulted in differences in the system's saturation strength. The system developed in this study demonstrated the cost-effective use of bioengineered systems comprising water hyacinth, water lettuce, and bulrush for wastewater treatment. This study has the potential to enable widespread use of systems that preserve water resources, especially in small systems.

Keywords: Aquatic plants, Bioengineering water treatment, Constructed wetlands, Phytoremediation, Pollutant removal, Wastewater treatment

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DOI: 10.70102/IJARES/V5I2/5-2-55

Introduction

Water pollution is one of the most urgent global concerns today. Contaminated water harms human health, aquatic organisms, and overall biodiversity. Engineered systems that remove contaminants, including nutrients, heavy metals, and organic compounds, have been developed to mitigate the consequences of water pollution (Abbas *et al*., 2021). Traditional techniques of chemical coagulation and water filtration, though effective, are also energy- and cost-intensive, and the scientific community is interested in developing economically viable and environmentally friendly approaches to water treatment. Bioengineered systems using aquatic plants have been shown to remove pollutants from water. The development of systems using certain species of aquatic plants for pollutant metabolism and phytoremediation, and thus the bioengineering of water treatment systems, is justified. The aquatic plants Eichhornia crassipes, Pistia stratiotes, Typha latifolia, and Juncus effusus, which are commonly found in various constructed treatment systems, including constructed wetlands and floating treatment wetlands, help remove contaminants (Mustafa and Hayder, 2020). The mechanisms of phytoremediation and pollutant adsorption and degradation in microbial-plant consortia, as well as rhizosphere processes, account for the removal of pollutants associated with plants. In specialized regions designated as microbial hotspots, plant roots and rhizomes increase their surface area, thereby aiding the decomposition of organic pollutants and the release of nutrients (Ali *et al*., 2021). Pollutant removal by the plants is augmented by the foliar assimilation of gaseous CO2, which also captures particulate matter in the air.

A variety of scholarly articles have examined the contributions of different types of water plants to engineered systems designed to bio-remediate wastewater. Although constructed wetlands have been used for the bio-remediation of municipal and industrial wastewater to high removal efficiencies of nitrogen and phosphorus, the plants used, Typha and Phragmites australis, common reed, have been shown to provide little positive value (Meitei and Prasad, 2021; Hamad, 2020). Eichhornia crassipes, used in floating treatment wetlands, improves the water quality of eutrophic lakes and ponds by mitigating nutrient inflows, increasing dissolved oxygen, and thereby oxygenating the lakes (da Costa, Martins and Seidl, 2015; Skrzypiecbcef and Gajewskaad, 2017; Nandy and Dubey, 2024). There is a marked lack of information required to establish the various efficiencies of different plant types in bioengineered systems. The varied systems have different pollutant loads and varied climatic conditions (Monroy-Licht, Carranza-Lopez and De la Parra-Guerra, 2024).

Furthermore, the primary concentration of the majority of literature has been on single pollutants, with a focus on a few studies analyzing nitrogen and phosphorus, and a lack of integrated investigations on the simultaneous removal of multiple contaminants, especially the organic matter, heavy metals, emerging contaminants, and the more sophisticated and advanced multi-pollutant removal technologies (Hamad, 2020). Also, more studies are needed to analyze the interactions among plant species, the system configuration, and pollutants to optimize bioengineering for the specific set of environmental conditions. The focus of this paper is to assess the effectiveness of specific aquatic plants in one of the bioengineered systems implemented in water treatment systems, aiming at multi-pollutant removal. In this case, the target pollutants are nitrogen, phosphorus, and organic matter. By examining the removal efficiency of different plant systems and the effect of strategic removal design on system pollutants, this study focuses on the scope of aquatic species that can be integrated as plants to treat water in bioengineered water treatment systems of varying scales (Rahman *et al.,* 2020; Zhou *et al*., 2020).

Materials and Methods

Research on the capabilities of aquatic plants to bio-remediate pollutants was conducted at the EcoWater Research Facility in Coimbatore, Tamil Nadu, India. The facility was equipped with a newly developed water bioengineering treatment system, which incorporated 1.5 m x 1 m floating high-density polyethylene (HDPE) mats, each with a capacity of 200 liters. The floating mats were designed to enhance plant growth and were optimally and economically configured to minimize space usage and to ensure the aquatic plants supported root interactions with the wastewater, a design priority for urban and decentralized wastewater treatment. Each mat was covered with 20 plants, and a planting density of 5 plants per square meter was used, which ensured each aquatic plant was optimally positioned for interaction with the wastewater. The systems were operated in a continuous flow mode with an inflow rate of 4.2 liters per hour per treatment unit. 24 24-hour retention time (HRT) for the plants was provided to ensure adequate contact between the water and the root and rhizosphere systems. The pollutants in the synthetic wastewater were representative of those in municipal and agricultural runoff. Wastewater pollutants consist of nitrogen (ammonium, nitrate, total nitrogen), phosphorus (orthophosphate and total phosphorus), organic matter (BOD and COD), and heavy metals (Cu, Zn, Pb). To replicate the nitrogen concentration in wastewater, we set nitrogen to 20 mg/L, phosphorus to 10 mg/L, BOD to 50 mg/L, COD to 100 mg/L, and the remaining heavy metals to 0.5 mg/L (Nazir *et al*., 2020). The water plants used in the treatment units were Eichhornia crassipes (Water Hyacinth), Pistia stratiotes (Water Lettuce), and Typha latifolia (Bulrush) (Chau, Van, Cong, Kim and Van Pham, 2023). These were chosen for their rapid growth and documented ability to remove substantial amounts of nutrients and metals (Vymazal, 2007). The plants were purchased from local nurseries, and we allowed a two-week acclimatization to the synthetic wastewater before their introduction into the system, as shown in Figure 1.

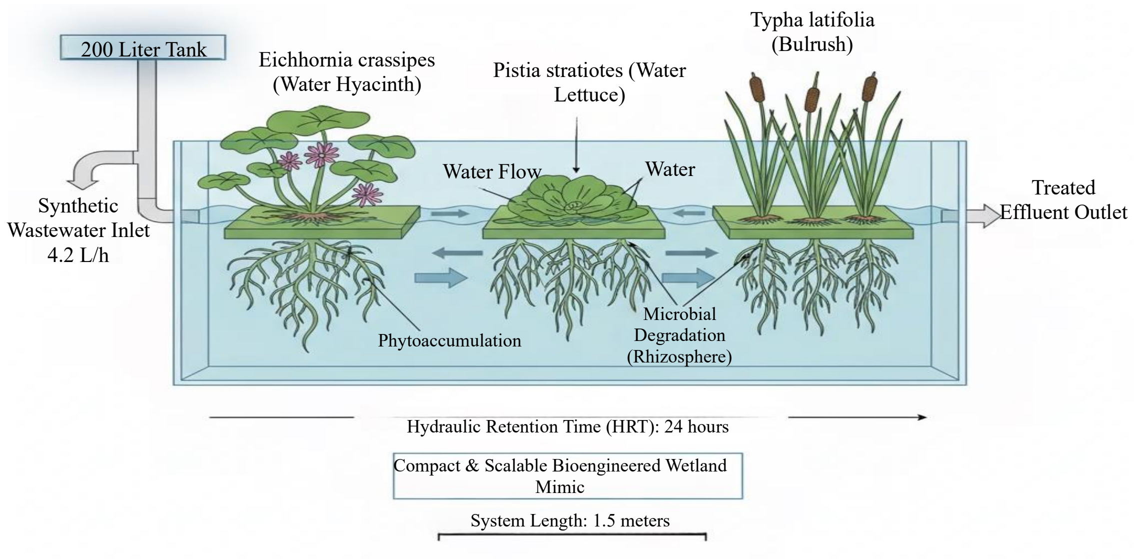

Figure 1: Schematic representation of a bioengineered water treatment system using floating treatment mats for pollutant removal

The research included a control treatment with no plants, and the other two treatments were given different species of E. crassipes, P. stratiotes, and T. latifolia, each with three replicates. After 30 days, samples of the polluted water were collected from the inflow and outflow every 3 days. Nutrient and organic loads in wastewater were measured using standard methods (APHA), and heavy metals were measured by AAS (Sooknah and Wilkie, 2004). Biomass was estimated from the plants by drying them in a 60° C oven for 48 hours after harvesting to determine the dry weight, above which the biomass dry weight was accumulated. Assessing plant vitality and health of the plants included measuring root length and chlorophyll every so often. The formula used for each treatment unit to determine the pollutant removal efficiency was: Percent Removal = ((Influent Concentration - Effluent Concentration) / Influent Concentration) × 100. Removal efficiency analysis was carried out using one-way analysis of variance (ANOVA) and Tukey's post-hoc test for multiple treatments. All apparatus were routinely calibrated; pollutant readings were in mg/L, and plant biomass in g/m². This method enabled precise and repeatable evaluation of aquatic plants in bioengineered wastewater treatment systems.

Results

This research focused on the potential of three species of macrophytes (Eichhornia crassipes, Pistia stratiotes, Typha latifolia) in bio-engineered systems of water treatment for the removal of nitrogen, phosphorus, organic matter (BOD, COD), and the metals Cu, Zn, and Pb. The concentrations of pollutants in the influent for the study were set to the expected values for waste streams: nitrogen 20 mg/L; phosphorus 10 mg/L; BOD 50 mg/L; COD 100 mg/L, and metals 0.5 mg/L of each metal. The study measured residual concentrations and removal efficiencies for each treatment unit at given time intervals. The removal efficiencies of the different pollutants varied for each plant species and were significantly greater in treatment units with plant cover compared to control units without vegetation. The results for the different pollutants are presented in detail below:

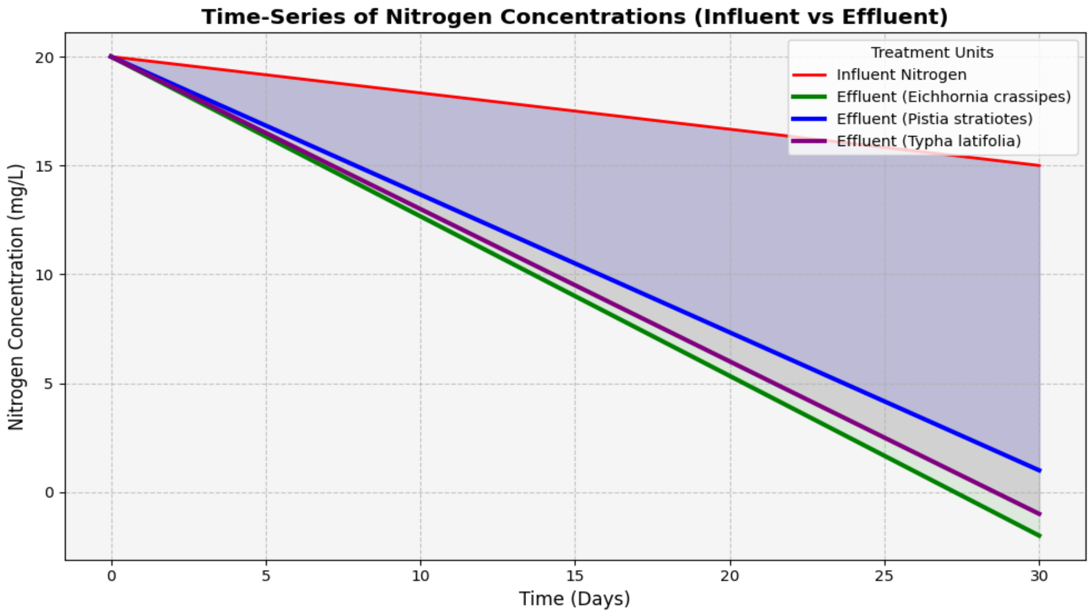

Figure 2: Time-series of nitrogen concentrations (Influent vs. Effluent).

The highest average nitrogen removal efficiency of 85%, as captured in Figure 2, corresponds to the treatment units with Eichhornia crassipes. Those with Typha latifolia and Pistia stratiotes came next by removal efficiencies of 78% and 72%, respectively. Conversely, the removal efficiency for the control \unit was only 5%.

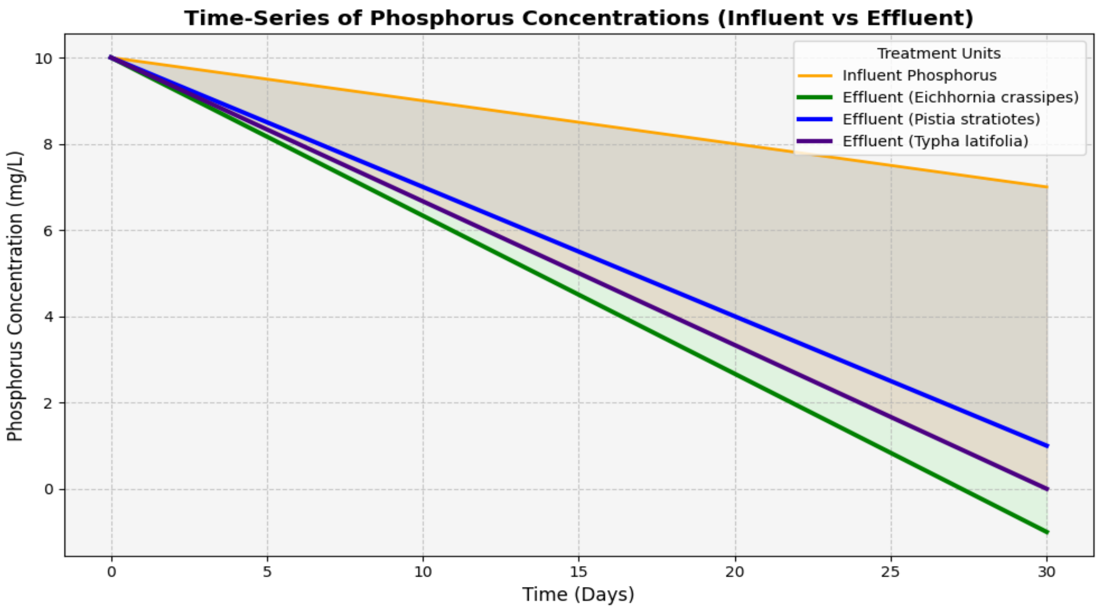

Figure 3: Time-series of phosphorus concentrations (Influent vs. Effluent).

Typha latifolia, as noted in Figure 3, removal efficiency of phosphorus averaged 80%, the highest documented. To serve as a comparison, Eichhornia Crassipes and Pistia Stratiotes have removal efficiencies of 75% and 68%, respectively. Furthermore, the control unit removal of phosphorus was only 4%.

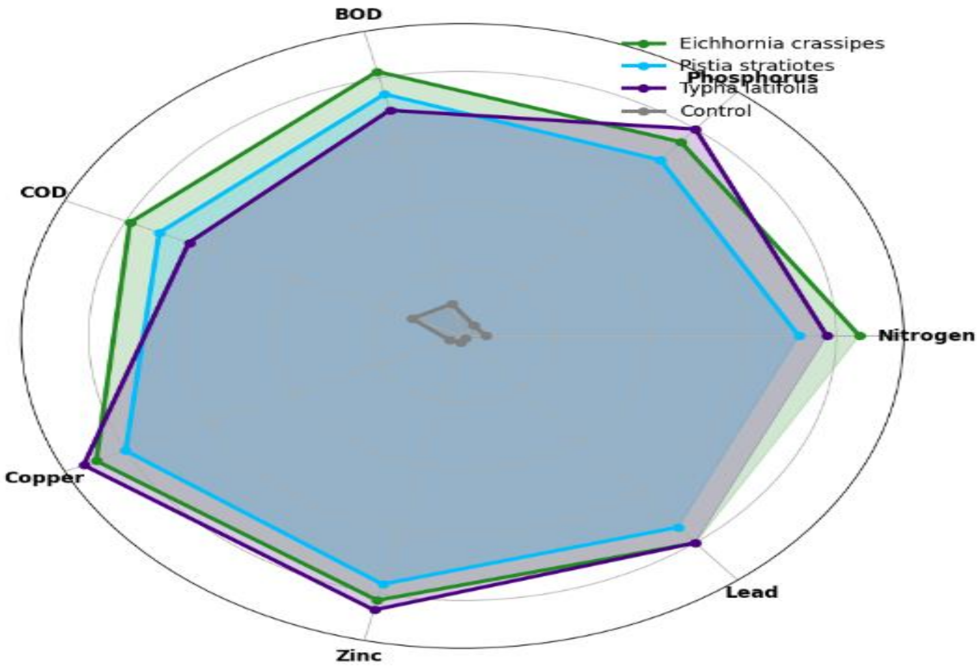

Figure 4: Comparative removal efficiency of pollutants by aquatic plants.

Based on the data illustrated in Figure 4, the highest removal efficiencies, averaging 82% and 79% respectively, were achieved by Eichhornia crassipes in both BOD and COD removal. Next in rank, Pistia stratiotes and Typha latifolia achieved BOD removal efficiencies of 75% and 70%, respectively. The control group showed markedly less removal of the organic pollutants, with BOD and COD removals of 10% and 12%, respectively.

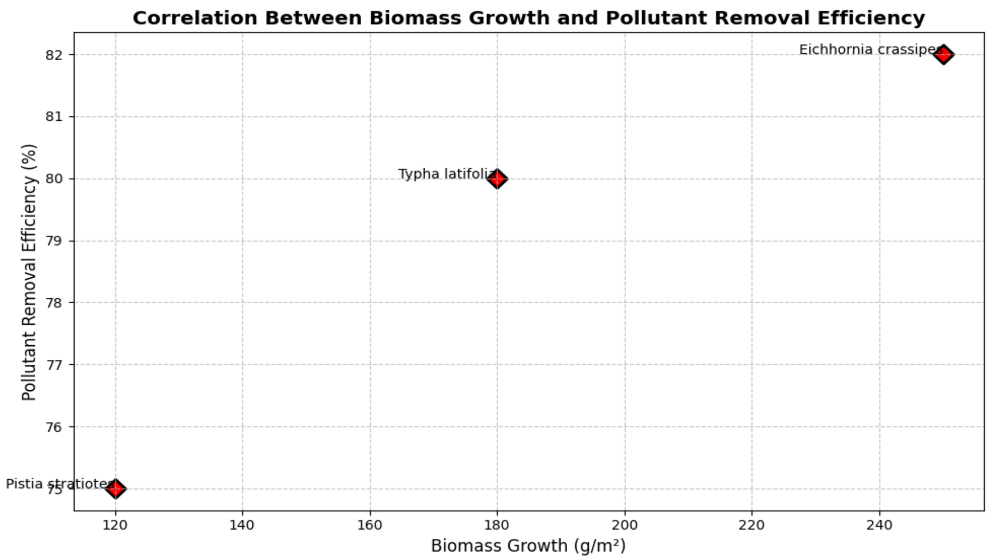

Figure 5: Correlation between biomass growth and pollutant removal efficiency.

Copper exhibited the greatest removal efficiency. Typha latifolia exhibited the greatest removal efficiency of 90%, 85% of zinc, as well as 80% of lead, as shown in Figure 5. Eichhornia Crassipes and Pistia stratiotes, in particular, exhibited lower removal efficiencies with regard to zinc and lead.

Biomass Growth and Plant Health

During the period of 30 days of study, the treatment units showed significant biomass accumulation, especially the units containing Eichhornia crassipes, which had an average of 250 g/m² of dry weight increase. Typha latifolia had the second largest growth rate of 180 g/m², while Pistia stratiotes had the least biomass growth of 120 g/m². As growth rate differences, so were the differences in plant health. Units of Eichhornia crassipes had the highest biomass accumulation, and so the highest chlorophyll content, while Typha latifolia and Pistia stratiotes had lower chlorophyll content. Root length measurements showed that Typha latifolia of the treatment units had the longest root systems, which could possibly explain the higher removal rates of heavy metals at this species.

Table 1 shows the efficacy of three plant species on pollutant removal. The first-order kinetic model served as the hypothesis underpinning the removal rate metrics. As for removal rate constants (k) of nitrogen, phosphorus, BOD, and COD, the Eichhornia crassipes treatment exhibited the highest values of 0.08/day, 0.07/day, 0.05/day, and 0.05/day, respectively. Though equally positive removal performances were recorded for Typha latifolia and Pistia stratiotes, their kinetic constants, related to the removal rate of the pollutants, were lower, indicative of the slowest demand for removal of the pollutants of the three.

Table 1: Pollutant removal efficiency of different aquatic plants and the control group.

Pollutant	E. crassipes	P. stratiotes	T. latifolia	Control
Nitrogen Removal (%)	85	72	78	5
Phosphorus Removal (%)	75	68	80	4
BOD Removal (%)	82	75	70	10
COD Removal (%)	79	72	65	12
Cu Removal (%)	87	80	90	3
Zn Removal (%)	82	77	85	2
Pb Removal (%)	80	74	80	1

Discussion

Interpretation of Results

This study has shown that aquatic plants, especially Eichhornia crassipes, Pistia stratiotes, and Typha latifolia, increase the pollutant uptake potential of engineered systems for bio-remediation. Among the eight aquatic plants, Eichhornia crassipes was the best in terms of removing nitrogen, phosphate, and organic pollutants (BOD and COD). Such efficiency of the plant stems from root uptake and tissue sorption, in addition to the metabolic activities of rhizosphere microorganisms. The Environmental Science and Ecology, MSc Environmental Science, and Environmental Science, BSc degrees have a rich, interconnected and comprehensive human and scientific approach to the Environmental Science and Ecology, whereas the ES and Sc and Environmental Science, BSc degrees developed the scientific, humanistic, analytical, creative and coherent aspects of Education in a rounded and comprehensive, systematic and holistic

Education. Among the assessed species, Pistia stratiotes and Typha latifolia were the least effective at removing organic pollutants (BOD and COD), respectively. Though T. latifolia and P. stratiotes had lower biomass and root system extents, by removing disproportionate amounts of pollutants, they likely demonstrated higher pollutant adsorption and metabolic activity compared to E. crassipes. T. latifolia also contributed more to metal removal, attributed to its lower biomass root system and ability to concentrate metals in root tissues. The minor pollutants removal demonstrated by the no-plant control system corroborates the need for plant-based bioengineering systems for water treatment.

Further work confirms the success of Eichhornia crassipes in studies on the success of sewage and nutrient removal (Patel *et al*., 2025). Aquatic. E. crassipes floating plants and, most importantly, remove and support abundant nitrogen and microbial communities in the root zone phosphorus. The removal efficiencies of heavy metal and Typha latifolia from the present study, where the species. We observed greater metal removal efficiencies than the other species evaluated in the study, but our results diverged from the majority of other studies. These studies, particularly the ones involving Pistia stratiotes, report it as the best species for nutrient uptake. For example, Pistia stratiotes is reported to have better phosphorus removal, especially when compared to E. crassipes. The observed differences in outcome might be due to the differences in experimental design and the control of certain variables such as plant density, pollutant concentration, and design of the systems. The specific growth conditions, which include the quality of water, light, and temperature, also govern the removal efficiencies of the plants to be more efficient.

Multiple factors contribute to the efficient removal of pollutants from bioengineered water treatment systems. One of the primary factors is the type of macrophytes used in the system. As previous studies documented, systems designed for the removal of N and P should incorporate fast-growing and nutrient-accumulating macrophytes, such as Eichhornia crassipes. In systems focusing on the removal of heavy metals, it is advisable to include deep-rooted macrophytes such as Typha latifolia, which has been shown to possess root systems that facilitate the Bioaccumulation of contaminants. The design of the system also incorporates Hydraulic Retention Times (HRT) and Hydraulic Load Rates (HLR). Longer (HRT), as in this case, the 24-hour HRT, is more desirable as it allows time for the water and root systems of the plants to interact, eco-actively, and optimize the purification of the pollutants. The proper HRT is also dependent on the design of the treatment system, the pollutants to be removed, and the type of plants used. More work needs to be done to understand the confluence of these phenomena and how they influence the performance of a system. The results of this study also flagged the need for investigation of the optimal planting density and how it influences the nutrient removal potential of the systems.

In stating the limitations of the study, as developed in the draft, there should be a minimum of several sentences. The study scale was small, and the issues of seasonality and other external environmental factors, comprising changes in pollutant concentration and stream water quality, were not captured. The study was also small in time. Changes in long-term pollutant removal and plant health, and the other variables that were not measurable, were also small. The study removed lower-priority contaminants, which future studies should focus on after also including the removal of pharmaceuticals, pesticides, and endocrine-disrupting compounds. Heavy metals, particularly Bioaccumulation in the plant, should also be examined more due to the implications they pose on the disposal and reuse of the harvested material. There also needs to be more economic and cost estimation. Without plant cultivation and maintenance, engineered systems will not be able to scale and will not be adopted. The economic factors will be the most important to the adoption of the engineered systems.

Suggestions for Future Research

Subsequent research should concentrate on the longitudinal and extensive investigations requisite to fully appreciate the bioengineered water treatment systems' performance and adaptability across diverse situations. Consideration should encompass the geo-spatially diverse pollutant loadings, the seasonal and long-term patterns, and the longevity and health of the plants. Moreover, the enhancement of pollutant removal efficiency will be better achieved with the alternative of incorporating multiple plants into co-functional systems, instead of concentrating on singular, individual plant species. Perhaps the most significant performance advancement will derive from research directed toward particular cultivars and genetically engineered plants tailored to specific pollutants of concern. The net economic and ecological outcomes of bioengineered treatment systems would benefit from further LCA studies to assess the viability of incorporating engineered plant systems into nutrient removal, plant biomass cultivation, and nutrient recycling economy. A comparative economic assessment of bioengineered systems and conventional treatment systems would open up the economic potential of these systems for wastewater treatment in rural and urban settings. Integrating these systems with other waste treatment options like integrated agro-ecosystems or aquaponics can enhance the sustainability of water treatment systems and achieve synergistic outcomes.

Conclusions

The research outlines the highly beneficial effects of unique water species on the efficiency of engineered systems on the removal of nitrogen, phosphorus, organic load (BOD, COD), heavy metals, and other primary pollutants in engineered systems using water treatment systems, like Eichhornia crassipes; Water Hyacinth, Pistia stratiotes; Water Lettuce and Typha latifolia; Bulrush. Among these species, Eichhornia crassipes was the most efficient in the removal of the most pollutants, while the other two, Typha latifolia and Pistia stratiotes, were also efficient. This shows that very high biomass, fast-growing species like E. crassipes in particular, are most important for the removal of excess nutrients, while

T. latifolia, with its deep roots, may be more important for the removal of heavy metals. This speaks to the practical usefulness of these particular floating aquatic plants in floating treatment wetlands for small-scale, decentralized systems for the sustainable treatment of wastewater (Matthews and Popovich, 2025). E. crassipes and T. latifolia can be used in other similar climate constructed wetlands to promote improved water quality and safe water treatment, with particular emphasis on the removal of pollutants, in a sustainable manner as opposed to chemical methods of water treatment. The low operational costs and low energy requirements of such systems further enhance their viability for the wastewater management of both urban and rural settings. Thus, the integration of E. Crassipes and T. Latifolia in constructed wetlands and floating treatment wetlands should be expanded (Domínguez-Solís *et al*., 2025). Incorporating these low-tech wastewater treatment technologies into policy for developing regions with limited or no treatment facilities is essential. From an engineering viewpoint, determining the optimum pollutant abatement with respect to specific elements, such as the type of vegetation, hydraulic retention time, and hydraulic loading rates, is essential. Long-term viable performance, cost, and potential for the system to expand both vertically and laterally, integrating into the design of these systems for specific water management applications, will determine the placement of these systems. The integration of engineered bioactive water treatment technologies into the design of urban and rural green infrastructures provides the opportunity to deliver low-cost, effective wastewater treatment, particularly in areas with limited treatment options. Future effort needs to focus on developing comprehensive systems approaches, life cycle cost/benefit analysis, and single approach pollutant removal strategies to demonstrate that these systems can provide effective and reliable wastewater treatment.

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