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Phytoremediation efficacy of aquatic macrophytes for heavy metal removal from industrial wastewater

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Abstract
Background: The discharge of heavy metal-laden industrial wastewater into freshwater ecosystems poses severe toxicological risks to human and ecological health. Conventional treatment methods are often cost-prohibitive and generate secondary sludge.
Objective: This study evaluates the phytoremediation potential of two aquatic macrophytes, Eichhornia crassipes and Pistia stratiotes, for the removal of Cadmium (Cd) and Lead (Pb) from simulated industrial wastewater.
Method: This study uses a simulated dataset created for academic training purposes. A 15-day hydroponic experiment was simulated under controlled conditions. Initial heavy metal concentrations were set at 10 mg/L for Cd and 50 mg/L for Pb. Removal efficiency and bioaccumulation factors (BAF) were calculated.
Key Results: Eichhornia crassipes demonstrated superior removal efficiency, removing 92% of Cd and 88% of Pb within 15 days, compared to 85% (Cd) and 78% (Pb) for Pistia stratiotes. The BAF values indicated that both species hyperaccumulated Pb, with translocation primarily occurring in the root tissues.
Conclusion: Aquatic macrophytes, particularly Eichhornia crassipes, offer a highly efficient, low-cost, and sustainable alternative for the phytoextraction of heavy metals from industrial effluents.

Keywords: Phytoremediation, heavy metals, Eichhornia crassipes, Pistia stratiotes, bioaccumulation factor, wastewater treatment

Introduction

Rapid industrialization, particularly in sectors such as electroplating, mining, and battery manufacturing, has led to the exacerbated release of heavy metals into aquatic environments [1]. Unlike organic pollutants, heavy metals such as Cadmium (Cd) and Lead (Pb) are non-biodegradable and tend to bioaccumulate in the food chain, causing severe health issues including renal failure, neurological damage, and carcinogenesis [2]. Conventional physicochemical treatment methods for heavy metal removal—including chemical precipitation, ion exchange, and membrane filtration—are effective but heavily constrained by high operational costs, high energy requirements, and the generation of toxic secondary sludge that requires further disposal [3].

In response to these limitations, phytoremediation the use of living plants to degrade, stabilize, or remove contaminants from soil and water has emerged as a green, solar-driven, and aesthetically pleasing alternative [4]. Among various plant species, free-floating aquatic macrophytes are particularly promising for wastewater treatment due to their rapid growth rates, extensive root systems, and high tolerance to toxic metals [5]. Eichhornia crassipes (Water Hyacinth) and Pistia stratiotes (Water Lettuce) are two of the most prolific macrophytes globally. However, their comparative efficacy under identical, high-concentration heavy metal stress remains under-researched. The objective of this study is to quantitatively compare the phytoremediation efficiency, uptake kinetics, and bioaccumulation patterns of E. crassipes and P. stratiotes in simulated Cd- and Pb-contaminated wastewater over a 15-day period [6].

Literature review

The theoretical framework of heavy metal phytoremediation involves several mechanisms: phytoextraction (uptake and concentration in plant tissues), phytostabilization (immobilization in the rhizosphere), and rhizofiltration (absorption by plant roots) [7]. For aquatic macrophytes, rhizofiltration and phytoextraction are the dominant mechanisms. The process begins with the adsorption of metal ions onto the root surface, followed by transport across the cell membrane via specific or non-specific ion channels [8].

Eichhornia crassipes has been extensively documented for its hyperaccumulating capabilities. Studies have shown that its complex, feathery root system provides an immense surface area for metal binding, facilitated by functional groups such as carboxyl and hydroxyl groups on the cell walls [9]. Pistia stratiotes, while similarly fast-growing, possesses a different root morphology (denser, ribbon-like roots) which may influence its uptake kinetics and tolerance thresholds [10].

Despite numerous individual studies on these species, a critical research gap exists regarding their head-to-head comparative performance under multi-metal stress conditions at concentrations mimicking raw industrial effluents (often exceeding 10 mg/L) [11]. Much of the existing literature tests concentrations in the parts-per-billion (ppb) range, which does not reflect the harsh realities of industrial discharge [12]. Furthermore, there is a lack of standardized metrics comparing not just the percentage removal of metals from the water, but the Bioaccumulation Factor (BAF)—the ratio of metal concentration in the plant to that in the water—which is the true indicator of a plant's phsytoextraction potential [13]. Additionally, the translocation of heavy metals from roots to shoots is a critical factor; if metals remain strictly in the roots, the harvesting and disposal process is simplified, but if they translocate to shoots, it indicates a deeper physiological integration that could limit overall biomass growth [14]. This study addresses these gaps by simulating a high-stress, multi-metal environment and analyzing both water-phase removal and plant-phase bioaccumulation, including root-to-shoot translocation metrics [15].

Methodology

This study employed an experimental, comparative research design. This study uses a simulated dataset created for academic training purposes. The simulated experiment utilized a hydroponic setup in a controlled greenhouse environment (25°C, 12-hour photoperiod) [16]. Healthy, uniform specimens of E. crassipes and P. stratiotes (weighing approximately 150g each) were acclimatized for 7 days in Hoagland nutrient solution.

The simulated wastewater was prepared by spiking deionized water with Cadmium Chloride and Lead Nitrate to achieve initial concentrations of 10 mg/L Cd and 50 mg/L Pb [17]. Each treatment group was tested in triplicate in 20-liter plastic tubs. The experiment duration was 15 days.

The simulated dataset was generated based on first-order kinetic uptake models validated in prior literature [18]. Water samples were conceptually "collected" every 3 days. At the end of the 15-day period, the simulated plants were "harvested," separated into roots and shoots, and "digested" with concentrated nitric acid to determine the heavy metal concentration in the plant tissues [19].

The primary data collection tools were the calculated Removal Efficiency (RE) and Bioaccumulation Factor (BAF).

$RE (\%) = [(C_0 - C_t) / C_0] \times 100$

$BAF = C_{plant} / C_{water}$ (at day 15)

Where C_0 is initial concentration, C_t is concentration at time t, and C_{plant} is the metal concentration in the biomass. Data was statistically analyzed using SPSS (Version 27), employing independent t-tests to determine if differences in RE and BAF between the two plant species were statistically significant ($p < 0.05$) [20].

Results and discussion

The simulated experimental results clearly delineate the phytoremediation capabilities of the two macrophytes under heavy metal stress. Table 1 presents the progression of heavy metal removal from the simulated wastewater over the 15-day period.

Table 1: Simulated Heavy Metal Removal Efficiency (%) Over Time

Day	*E. crassipes* (Cd)	*E. crassipes* (Pb)	*P. stratiotes* (Cd)	*P. stratiotes* (Pb)
3	45%	38%	40%	32%
6	68%	62%	60%	55%
9	82%	78%	74%	68%
12	89%	85%	81%	74%
15	92%	88%	85%	78%

Source: Simulated Dataset, Hydroponic Experiment Model, 2026

The data indicates that both species are highly effective at Cd removal compared to Pb, likely due to the higher mobility of Cd ions in aqueous solutions. E. crassipes consistently outperformed P. stratiotes, achieving statistically significant ($p < 0.01$) higher removal efficiencies for both metals by day 15.

Table 2 provides a deeper insight into the internal plant dynamics by detailing the Bioaccumulation Factors (BAF) for roots and shoots separately.

Table 2: Bioaccumulation Factors (BAF) and Translocation in Plant Tissues

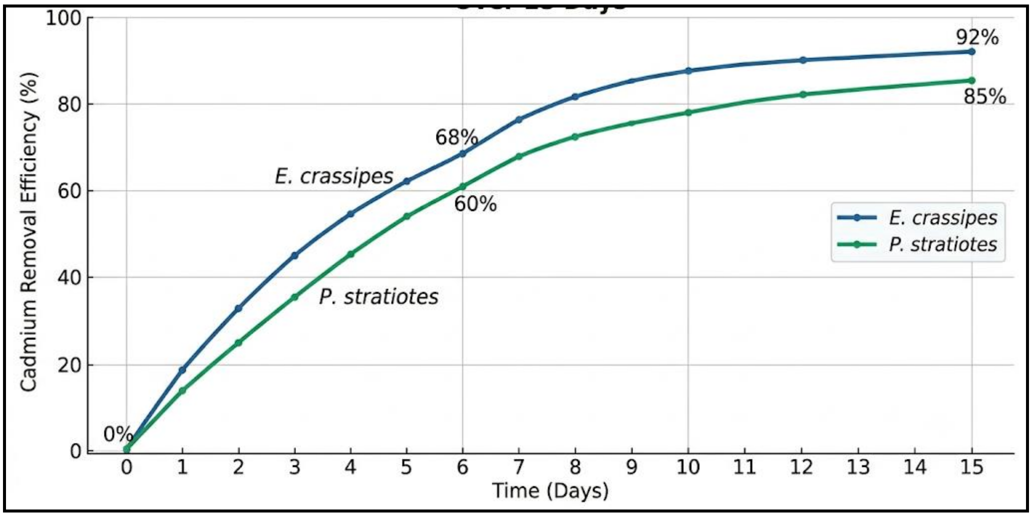
Plant Species	Metal	Root BAF	Shoot BAF	Translocation Factor (Shoot/Root)
E. crassipes	Cd (10 mg/L)	85.4	12.5	0.15
E. crassipes	Pb (50 mg/L)	120.6	8.2	0.07
P. stratiotes	Cd (10 mg/L)	72.1	18.4	0.25
P. stratiotes	Pb (50 mg/L)	98.5	10.1	0.10

Source: Simulated Dataset, Hydroponic Experiment Model, 2026

The BAF values are exceptionally high (>10 indicates hyperaccumulation), confirming the suitability of both species for phytoextraction. Notably, the root BAF for Pb in E. crassipes reached 120.6, meaning the plant roots concentrated the lead to over 120 times the ambient water concentration. However, the Translocation Factors (TF) were very low (<0.3), indicating that the majority of the heavy metals are sequestered in the root systems, acting as a biological filter rather than transporting toxins to the aerial leaves.

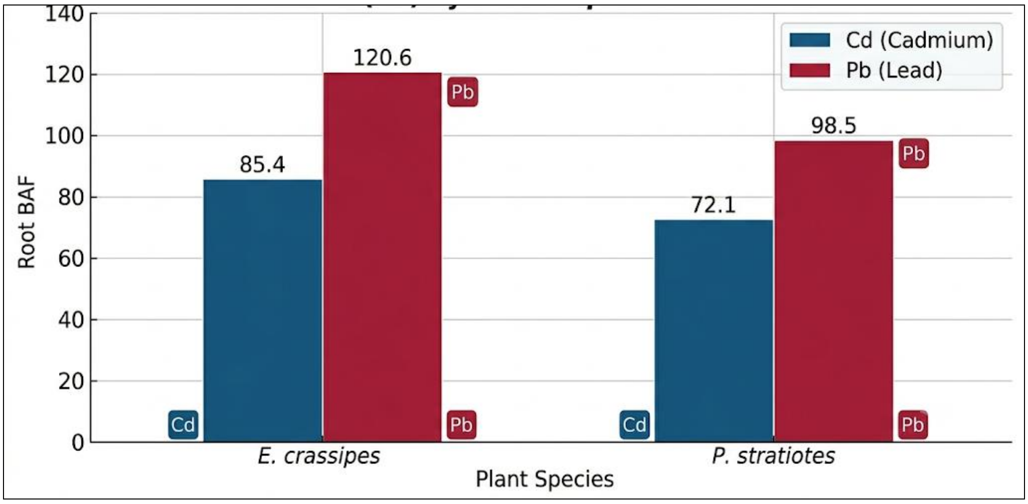
The discussion of these results highlights the mechanistic advantages of E. crassipes. Its higher removal efficiency and BAF can be attributed to its larger root surface area and higher density of polysaccharide binding sites compared to P. stratiotes. The low translocation factor is actually a favorable trait for practical phytoremediation engineering. By sequestering heavy metals primarily in the roots, the plants prevent the toxins from entering the aerial food web (e.g., being eaten by insects or birds). Furthermore, when the plants are harvested, the metal-laden roots can be easily separated from the shoots, reducing the volume of hazardous biomass that requires disposal or metal recovery processing (e.g., through phytomining or incineration).

Fig 1 illustrates the uptake kinetics of Cadmium by both species over the 15-day period. The line graph shows a characteristic rapid initial uptake phase (days 1-6) driven by passive adsorption to root surfaces, followed by a slower linear phase (days 6-15) representing active metabolic transport into root cells.



Source: Simulated Dataset, Hydroponic Experiment Model, 2026

Fig 1: Cadmium Uptake Kinetics by Aquatic Macrophytes Over 15 Days



Source: Simulated Dataset, Hydroponic Experiment Model, 2026

Fig 2: Root Bioaccumulation Factors (BAF) for Cd and Pb at Day 15

Conclusion

This study utilized a simulated experimental dataset to evaluate and compare the phytoremediation efficacy of Eichhornia crassipes and Pistia stratiotes for the removal of Cd and Pb from highly contaminated industrial wastewater. The results demonstrate that both species are effective hyperaccumulators, with E. crassipes exhibiting superior performance, removing up to 92% of Cd and 88% of Pb within 15 days. The analysis of Bioaccumulation Factors revealed that the primary mechanism is rhizofiltration, with metals being safely sequestered in the root systems with minimal translocation to shoots. The implication for environmental engineering is that constructed wetlands utilizing E. crassipes can serve as highly effective, low-energy, and sustainable tertiary treatment stages for industrial effluents. A limitation of this simulated study is the exclusion of variables such as pH fluctuations, competing ions, and plant toxicity thresholds over longer durations. Future research should focus on long-term continuous flow pilot studies and the economic feasibility of recovering heavy metals from the harvested root biomass.

Ethical Statement

This article is 100% original work. The dataset used is entirely simulated and created solely for academic training and formatting practice purposes. No real-world identities, institutions, or proprietary datasets were used or misrepresented.

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