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Advanced Mechanisms and Comparative Efficiency of Aquatic Macrophytes in Heavy Metal Remediation: A 2025 Systematic Review

Deepak Kumar barik , Acharya Narendra Dev college Department of Botany, University of Delhi,New Delhi,India
Email: deepakbarik702@gmail.com , Deepak.ae-011@andc.du.ac.in

Abstract

Heavy metal (HM) contamination in aquatic ecosystems remains a significant environmental threat due to the non-biodegradable nature and bioaccumulation potential of metals like Cd, Pb, and Cr. This review synthesizes cutting-edge research from 2024-2025, focusing on the genomic and transcriptomic pathways of aquatic hyperaccumulators. Specifically, we analyze the recently published 1.11 Gbp genome of Eichhornia crassipes and its whole-genome duplication (WGD) events that facilitate metal sequestration. Comparative data between Pistia stratiotes and Lemna minor reveal significant removal efficiencies (up to 99.7% for Pb at low concentrations). The study concludes by identifying the regulatory role of ABC transporters and ZIP family genes as primary targets for bioengineering the next generation of phytoremediation systems.

Keywords: Phytoremediation, Heavy Metals, Eichhornia crassipes, Transcriptomics, Wastewater Treatment, Bioaccumulation Factor (BCF).

I. INTRODUCTION

Heavy metal pollution in aquatic environments has surged due to rapid industrialization, mining, and urban runoff. Unlike organic pollutants, heavy metals such as Lead (Pb), Cadmium (Cd), and Nickel (Ni) persist indefinitely, posing carcinogenic risks to human health through trophic transfer in the food chain [1],.[2] Traditional physicochemical treatments often involve high operational costs and secondary sludge production.[3] Phytoremediation, specifically rhizofiltration and phytoextraction using aquatic macrophytes, offers a cost-effective, "green" alternative. Recent advancements in 2025 focus on enhancing these biological systems through genomic insights and microbial augmentation to move beyond baseline descriptive studies [4],.[5]

II. MOLECULAR MECHANISMS AND GENOMIC INSIGHTS

A. Genomic Basis of Invasiveness and Sequestration

A landmark study in late 2024 reported the full genome sequencing of Eichhornia crassipes (Water Hyacinth), revealing a genome size of 1.11 Gbp with 63,299 coding genes.[6] The research identified a recent whole-genome duplication (WGD) event that resulted in significant expansion in gene families associated with abiotic stress tolerance and heavy metal sequestration [6],.[7] This duplication provides the evolutionary framework that allows E. crassipes to withstand toxic concentrations that would be lethal to other species.

B. Transcriptomic Regulation of Transporters

Transcriptomic profiling has identified specific gene families responsible for metal flux. Under Cd stress, the ZIP family (Zinc-Iron Permease), Nramp (Natural Resistance-Associated Macrophage Proteins), and P1B-type ATPases are differentially regulated [4],.[8] In 2024 studies, ABC transporters (specifically GmABCB48 and GmABCB52) were shown to localize at the plasma membrane, reducing metal accumulation in root cell walls to promote tolerance.[9] In model organisms like Synechococcus elongatus, RNA sequencing revealed that nitrate ABC transporter permease is significantly upregulated (over fivefold) during heavy metal exposure, suggesting a critical role in cellular detoxification.[10]

III. COMPARATIVE REMEDIATION EFFICIENCY: 2025 DATA

Recent experimental data from 2025 has provided precise metrics for comparing the efficiency of common aquatic plants (Table I).

Table I: Comparative Metal Removal Efficiency (2025 Data Summary)

Plant species	Metal	Concentration	Removal Efficiency/Accumulati on
Pistia stratiotes	Pb	15 mg/L	365.10 mg/kg (High accumulation) [11,12]
E. crassipes	Cd	15 mg/L	78.95 mg/kg (Bioaccumulation) [13]
Lemna minor	Pb	0.5 ppm	99.7% Removal [14]
Lemna minor	Ni	1 ppm	99.75% Removal [14]
Lemna minor	Cd	0.5 ppm	92.0% Removal [14]

A. Density-Dependent Removal Rates

Studies published in 2025 highlight that plant density is a statistically significant factor ($P < 0.05$). High-density treatments (75% coverage) of Lemna minor (duckweed) demonstrated the greatest removal efficiency for Pb (82.4%) and Cd (78.6%) over a 21-day period compared to low-density setups.[15] This suggests that for engineering applications, maintaining high biomass density is critical for maximizing binding sites in contaminated water bodies.

IV. TECHNOLOGICAL ENHANCEMENTS

A. Microbial-Augmented Floating Wetlands (FTWs)

Engineered Floating Treatment Wetlands (FTWs) represent a scalable engineering solution. Inoculating Phragmites australis with specialized bacterial consortia has shown removal efficiencies of up to 81.0% for Iron (Fe) and 76.7% for Lead (Pb) in complex textile wastewater
[16],.[17] The majority of this degradation occurs within the root-associated biofilm, where microbial metabolic activity reduces Biochemical Oxygen Demand (BOD) by approximately 85.1%.[17]

B. Nano-Phytoremediation

The application of green-synthesized nanoparticles (e.g., ZnO-NPs derived from algae) has been shown to increase the removal of Chromium (Cr) and Lead (Pb) from leather industry effluents.[18] These nanoparticles act as stimulants for plant antioxidant systems, reducing oxidative stress and allowing for higher internal metal loads without inducing chlorosis [18],.[19]

V. CONCLUSION

The shift in 2024-2025 research from descriptive to mechanistic science marks a new era for phytoremediation. The integration of genomic data, such as the E. crassipes WGD event, provides a roadmap for CRISPR-based gene editing to enhance sequestration. Furthermore, the high removal efficiencies observed in Lemna minor and microbial-augmented FTWs demonstrate that aquatic plants are not only biological filters but active engineering tools for sustainable wastewater management. Future work should focus on the circular economy of post-remediation biomass through pyrolysis to stabilize recovered metals in biochar.

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