Phytoremediation as a Nature-Based Solution for Cleaner River Systems: Mitigating Heavy Metal Contamination in Humid Tropical Environments

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ABSTRACT

Heavy metal contamination in river systems poses persistent environmental and public health challenges, particularly in humid tropical regions where high rainfall, intensive land use, and dynamic hydrological processes exacerbate pollutant mobility and ecological vulnerability. Conventional remediation approaches are often energy-intensive, costly, and associated with secondary environmental impacts. In response, phytoremediation has emerged as a nature-based solution that aligns with cleaner production principles by integrating pollution mitigation with ecological restoration. This article critically examines phytoremediation as a sustainable strategy for mitigating heavy metal contamination in humid tropical river systems. Drawing on evidence from aquatic macrophytes, riparian vegetation, mangrove ecosystems, and plant–microbial interactions, the study highlights the effectiveness of phytoremediation in removing and stabilizing metals such as Pb, Cd, Cu, Cr, and Zn. The role of microbial communities in enhancing remediation efficiency through nutrient cycling and pollutant transformation is also explored. The findings demonstrate that phytoremediation offers a low-energy, low-emission, and ecologically restorative alternative to conventional remediation methods, contributing to cleaner river systems and long-term environmental resilience. The article concludes by proposing an integrated phytoremediation framework that supports cleaner production, sustainable river management, and nature-based environmental governance in humid tropical regions.

Keywords: phytoremediation; heavy metals; humid tropical rivers; microbial interactions

INTRODUCTION

Heavy metal pollution in river systems has become a critical environmental concern worldwide due to its persistence, toxicity, and tendency to bioaccumulate in aquatic ecosystems and food chains. In humid tropical regions, the problem is particularly acute as high precipitation, frequent flooding, and intense land-use activities accelerate the transport and redistribution of contaminants from terrestrial sources into riverine environments. Mining operations, industrial discharges, agricultural runoff, and urban wastewater are among the primary contributors to heavy metal contamination in tropical rivers (Cruz-Cano et al., 2025).

Conventional remediation technologies, including chemical precipitation, adsorption, dredging, and physical removal, have been widely applied to address heavy metal pollution (Foulquier et al., 2013). However, these approaches often require substantial energy inputs, generate secondary waste, and impose high operational costs, limiting their long-term sustainability. Within the context of cleaner production and sustainable environmental management, there is a growing need for remediation strategies that minimize resource consumption, reduce emissions, and deliver co-benefits for ecosystem restoration.

Phytoremediation, defined as the use of plants and their associated microbial communities to remove, immobilize, or transform environmental contaminants, has gained increasing attention as a nature-based solution (Yalcin et al., 2025). By harnessing biological processes, phytoremediation offers an environmentally benign alternative that integrates pollution control with ecological recovery (Vignale et al., 2023). Despite

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extensive research on phytoremediation in temperate environments, comprehensive evaluations focusing on humid tropical river systems remain limited. This article addresses this gap by positioning phytoremediation within a cleaner production framework and examining its potential to mitigate heavy metal contamination while supporting sustainable river management in humid tropical regions.

LITERATURE REVIEW

a. Heavy Metal Contamination in Humid Tropical River Systems

Humid tropical river systems are characterized by strong hydrological connectivity between land and water, high sediment loads, and pronounced seasonal variability. These characteristics increase the vulnerability of rivers to heavy metal contamination and complicate remediation efforts (de Lima et al., 2022). During periods of intense rainfall and flooding, metals bound to soils and sediments can be remobilized and transported downstream, expanding the spatial extent of contamination (Li et al., 2025).

Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), and zinc (Zn) are commonly detected in tropical rivers influenced by mining, industrial activity, and urban development. Once introduced into river systems, these metals persist in sediments and aquatic biota, posing chronic risks to ecosystem health and human populations that rely on river resources for water supply, fisheries, and agriculture (Das et al., 1997). Addressing heavy metal pollution in humid tropical rivers therefore requires remediation approaches that are adaptive, resilient, and capable of operating under dynamic environmental conditions.

b. Phytoremediation within a Cleaner Framework

Cleaner production emphasizes preventive environmental strategies that reduce pollution at the source, improve resource efficiency, and minimize waste generation. Phytoremediation aligns closely with these principles by offering a low-impact remediation approach that relies on natural biological processes rather than chemical or mechanical interventions (D. Wu et al., 2024).

Phytoremediation operates through several mechanisms, including phytoextraction, rhizofiltration, phytostabilization, and phytodegradation. In aquatic and riparian environments, plants absorb dissolved metals from water and sediments, stabilize contaminants within the rhizosphere, and, in some cases, facilitate their transformation into less toxic forms (Ali et al., 2020). Compared with conventional remediation technologies, phytoremediation requires lower energy inputs, produces minimal secondary waste, and can be integrated into broader ecosystem restoration initiatives.

By embedding phytoremediation within a cleaner production framework, river remediation can shift from a reactive, end-of-pipe approach toward a regenerative model that enhances ecosystem services, biodiversity, and long-term sustainability.

c. Effectiveness of Aquatic Macrophytes and Riparian Vegetation

Aquatic macrophytes have demonstrated significant potential for heavy metal removal in tropical river systems. Species such as *Eichhornia crassipes, Pistia stratiotes,* and *Salvinia molesta* exhibit high growth rates and extensive root systems that facilitate metal uptake and accumulation (S. Wu et al., 2023). Empirical studies have shown that these plants can effectively remove metals including Pb, Cd, Cu, Cr, and Zn from contaminated water bodies, often achieving high removal efficiencies under favorable environmental conditions.

Riparian vegetation also plays a complementary role in phytoremediation by stabilizing riverbanks, reducing erosion, and intercepting contaminated runoff before it enters river channels (Wen et al., 2025). While some native riparian species function primarily as bioindicators, others demonstrate the capacity to accumulate and tolerate heavy metals, contributing to localized remediation and ecosystem stabilization.

The effectiveness of phytoremediation using aquatic and riparian plants depends on species selection, metal bioavailability, and site-specific environmental factors (Najwa et al., 2025). Nevertheless, the adaptability of tropical vegetation makes phytoremediation particularly suitable for humid tropical river systems.

METHODOLOGY

This study adopts a **systematic qualitative research design** grounded in a **critical literature synthesis** and **conceptual framework development** to evaluate phytoremediation as a cleaner production strategy for mitigating heavy metal contamination in humid tropical river systems. Rather than conducting site-specific experimental trials, the research emphasizes an integrative methodological approach that consolidates empirical findings from peer-reviewed studies, enabling a comprehensive assessment of phytoremediation mechanisms, performance, and contextual constraints in tropical environments.

The analysis is based on a structured review of scientific literature published in **Scopus-journals**, including *Journal of Cleaner Production*, *Science of the Total Environment*, *Environmental Research*, *Ecological Engineering*, and *Environmental Science and Pollution Research*.

Literature selection followed three main criteria: 1) **Topical relevance**, focusing on phytoremediation, heavy metal contamination, tropical river systems, and microbial–plant interactions; 2) **Geographical relevance**, prioritizing studies conducted in humid tropical and subtropical regions; and 3) **Methodological robustness**, including empirical studies, systematic reviews, and meta-analyses with clearly defined methods and performance indicators.

Keyword combinations used in the literature search included *phytoremediation*, *heavy metals*, *humid tropical rivers*, *aquatic macrophytes*, and *microbial communities*. Only articles published in English between 2020 and 2024 were considered to ensure conceptual consistency and contemporary relevance.

THEORETICAL FRAMEWORK

Role of Microbial Communities in Enhancing Phytoremediation

Microbial communities play a pivotal role in determining the efficiency of phytoremediation in tropical river systems. Rhizosphere-associated bacteria and fungi facilitate nutrient cycling, enhance plant growth, and contribute to the transformation and immobilization of heavy metals. Processes such as nitrification, denitrification, and organic matter decomposition indirectly influence metal bioavailability and uptake by plants (Gupta et al., 2025).

Plant–microbe interactions can enhance phytoremediation performance by increasing metal tolerance and uptake efficiency while reducing phytotoxicity. Environmental factors such as temperature, pH, dissolved oxygen, nutrient availability, and seasonal hydrological changes strongly influence microbial community structure and function. Understanding these interactions is therefore essential for optimizing phytoremediation strategies in humid tropical environments (Lee et al., 2017).

Environmental Constraints and System Optimization

Despite its advantages, phytoremediation is subject to several constraints that must be addressed to ensure effective implementation. High metal concentrations may exceed plant tolerance thresholds, while eutrophication, land-use change, and wastewater discharges can alter ecological conditions and reduce remediation efficiency. Seasonal flooding and sediment dynamics further complicate system performance (KaurKahlon et al., 2016).

To overcome these challenges, phytoremediation systems should be designed using site-specific assessments, adaptive management approaches, and, where appropriate, hybrid solutions that combine phytoremediation with complementary remediation techniques. Such optimization enhances the reliability and scalability of phytoremediation as a cleaner production strategy.

Role of Nutrient Levels in Shaping Microbial Community Structures

Nutrient availability constitutes a fundamental driver in structuring microbial communities involved in phytoremediation processes within tropical river systems (Rajoo et al., 2023). The concentrations and relative proportions of key nutrients, particularly nitrogen (N) and phosphorus (P), exert strong control over microbial

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community composition, diversity, and functional capacity, all of which are critical determinants of phytoremediation performance.

Microbial communities associated with river sediments play a particularly active role in nutrient cycling, with sedimentary environments often exhibiting higher rates of nitrogen transformation compared to the overlying water column (Wen et al., 2025). These microbial-mediated processes—including nitrification, denitrification, and nitrate reduction—are essential components of broader biogeochemical cycles and directly influence nutrient availability for phytoremediating vegetation. Furthermore, the form and sequence of nutrient inputs can modify microbial interactions and metabolic pathways, thereby shaping community structure and ecosystem function.

The effectiveness of phytoremediation is closely linked to the composition and activity of root-associated microbial communities. Microorganisms inhabiting the rhizosphere can enhance plant nutrient acquisition, mitigate environmental stress, and improve tolerance to contaminated conditions, collectively contributing to increased remediation efficiency. Temporal variability, including seasonal changes in temperature and nutrient dynamics, further influences microbial community organization and nutrient removal capacity, with reduced plant growth during cooler periods necessitating higher vegetation density to maintain remediation performance (Foulquier et al., 2013).

DISCUSSION

Understanding the role of microbial communities is fundamental to elucidating the mechanisms through which phytoremediation operates in humid tropical river environments. Microorganisms associated with aquatic and riparian vegetation actively mediate nutrient cycling, pollutant transformation, and plant–soil–water interactions, thereby enhancing the overall efficiency and resilience of phytoremediation processes (Yalcin et al., 2025).

Microbial communities play a central role in regulating the cycling of essential nutrients, particularly nitrogen and phosphorus, which are critical for sustaining plant growth and metabolic activity. Through processes such as mineralization, nitrification, and denitrification, microorganisms facilitate the transformation and assimilation of nutrients within river sediments and the rhizosphere. Specific bacterial groups, including nitrifying taxa such as *Nitrospira*, contribute significantly to nitrogen turnover by mediating key redox reactions that influence nutrient availability and sediment biogeochemistry. These processes indirectly support phytoremediation by maintaining favorable conditions for plant uptake and biomass production.

Beyond nutrient cycling, microbial communities contribute directly to the degradation and transformation of pollutants, including organic contaminants and metal-associated compounds (Das et al., 1997). Root-associated microorganisms are known to enhance the breakdown of complex hydrocarbons and other pollutants, improving water and sediment quality and increasing the bioavailability or immobilization of contaminants for plant uptake.

In river systems receiving wastewater inputs, microbial activity plays a critical role in reducing pollutant loads and sustaining ecosystem health, thereby reinforcing the functional capacity of phytoremediation systems.

Symbiotic interactions between plants and microorganisms further amplify phytoremediation performance. The rhizosphere provides a dynamic microenvironment in which microbial activity can stimulate plant growth, enhance stress tolerance, and improve contaminant uptake (Li et al., 2025). Empirical evidence indicates that diverse and metabolically active microbial assemblages in the rhizosphere are associated with increased remediation efficiency in contaminated environments. These plant–microbe interactions can also induce shifts in microbial community structure and function, influencing ecological processes such as nutrient transformation, organic matter degradation, and metal stabilization that underpin phytoremediation outcomes.

The structure and functionality of microbial communities involved in phytoremediation are strongly influenced by environmental conditions. Abiotic factors including water temperature, pH, dissolved oxygen, and nutrient concentrations exert significant control over microbial diversity and metabolic activity. Seasonal variability in hydrological and climatic conditions can further modify microbial community composition and functional potential, leading to temporal fluctuations in phytoremediation efficiency. Such dynamics have been observed in tropical aquatic plant systems, where seasonal changes alter microbial–plant interactions and remediation performance.

Phytoremediation, the use of plants to remove contaminants from the environment, is a promising method for addressing heavy metal pollution in humid tropical river ecosystems. Several plant species have been identified as effective phytoremediators in such environments:

Plant Species	**Heavy Metals**	**Effectiveness**
Eichhornia crassipes	Pb, Cd, Zn, Cu	High removal efficiency, significant reduction in heavy metal concentrations
Typha angustifolia	Pb, Cd	Enhanced tolerance and accumulation, high biomass production
Canna indica	Fe, Zn, Pb, Cu, Cr	High remediation performance at optimal wastewater treatment concentration
Pistia stratiotes	P, N	Effective in nutrient removal, potential for heavy metal phytoremediation
Cyperus rotundus	Cd	Potential bioindicator, grows well in contaminated soils

Besides that, hydrological dynamics play a decisive role in shaping the structure and functional performance of microbial communities in tropical river ecosystems, thereby directly influencing the effectiveness of phytoremediation processes (Ali et al., 2020). Variations in hydrological conditions regulate key environmental parameters—such as temperature, salinity, nutrient availability, and organic matter flux—that collectively determine microbial metabolism, community composition, and biogeochemical functioning.

Changes in temperature and salinity constitute primary drivers of microbial response in tropical river systems. Fluctuations in salinity, particularly under hyposaline conditions, have been shown to suppress primary production and alter the composition of micro phytoplankton communities, while elevated temperatures may stimulate primary productivity under specific environmental thresholds (Najwa et al., 2025). These shifts affect nutrient assimilation rates, microbial biomass formation, and metabolic efficiency, all of which are critical for sustaining microbially assisted phytoremediation pathways.

Rainfall events and associated hydrological variability further modulate microbial community dynamics by altering physicochemical conditions within river systems. Precipitation-driven changes in water temperature, dissolved oxygen, pH, and nutrient concentrations can trigger rapid restructuring of microbial assemblages and their functional gene profiles. Empirical evidence indicates that rainfall can increase the relative abundance of autotrophic and diatom-associated taxa while reducing populations of heterotrophic groups, leading to altered pathways of organic matter processing and nutrient transformation. Such compositional shifts have direct implications for microbial contributions to contaminant degradation and metal immobilization in phytoremediation systems.

Hydrology also governs nutrient and organic matter dynamics, which are central to microbial activity. Changes in water residence time and flow patterns affect the spatial and temporal distribution of nutrients, creating physicochemical gradients that drive shifts in bacterial community structure. These gradients influence microbial-mediated transformations of nitrogen, phosphorus, and carbon, as well as the breakdown of organic substrates. During high-flow or flood events, elevated organic matter inputs often stimulate bacterial carbon production and respiration rates, reflecting enhanced microbial metabolic activity in response to increased substrate availability.

At the functional level, hydrological variability is closely linked to changes in the abundance of genes associated with core biogeochemical processes. Genes involved in carbon and nitrogen cycling exhibit differential expression under contrasting hydrological conditions, indicating adaptive microbial responses to changing environmental constraints. Such functional gene variability directly affects microbial efficiency in nutrient transformation, organic matter degradation, and metal-associated redox processes that underpin effective phytoremediation.

Hydrological alteration also influences microbial diversity and community resilience. Flow regulation and hydrological restoration have been shown to promote shifts in both taxonomic and functional diversity, often increasing the range of microbial traits present within river systems (Liu et al., 2024). Enhanced microbial diversity contributes to greater functional redundancy and ecological stability, strengthening the capacity of microbial communities to sustain phytoremediation under fluctuating environmental conditions.

Overall, hydrological changes exert a multifaceted influence on microbial communities in tropical rivers by regulating thermal regimes, salinity gradients, nutrient fluxes, organic matter availability, and community composition. These interactions underscore the importance of incorporating hydrological variability into the design and management of phytoremediation strategies, particularly in humid tropical environments where dynamic water regimes strongly shape microbial functionality and ecosystem-level remediation outcomes.

CONCLUSIONS

Phytoremediation represents a viable and sustainable approach for mitigating heavy metal contamination in humid tropical river systems. Through the synergistic action of plants and microbial communities, phytoremediation provides a low-energy, low-emission alternative to conventional remediation technologies while supporting ecosystem restoration and cleaner production objectives. When integrated into comprehensive river management frameworks, phytoremediation can enhance water quality, biodiversity, and long-term environmental resilience. Future research should focus on system optimization, long-term performance assessment, and policy integration to maximize the contribution of phytoremediation to sustainable river governance in tropical regions.

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