Journal of Biomedical Sciences and Health
e-ISSN: 3047-7182 | p-ISSN: 3062-6854
Available online at ejournal.unkaha.ac.id/index.php/jbsh

OPEN ACCESS

Vol. 3, No. 1, 2026 DOI: 10.34310/jbsh.v3.i1.301 Pages 32-41

Narrative Review

Water Jasmine (*Echinodorus palaefolius*): A Phytoremediation Agent for Environmental Health Improvement and Landscape Enhancement

Mellyaning Oktaviani Sonya Kirana Sari[1*]

[1]*Master's Program in Biology, Department of Biology, Faculty of Science and Mathematics, Diponegoro University, Semarang, Indonesia*

*Correspondence: mellyaning16@student.undip.ac.id

ABSTRACT

Background: Heavy metal and organic pollution in water bodies necessitate sustainable, cost-effective remediation. *Echinodorus palaefolius* is a potential aquatic macrophyte that offers a nature-based solution by combining pollutant removal with aesthetic value. **Objective:** This review evaluates the dual-purpose efficacy of *E. palaefolius* in removing contaminants through constructed wetlands (CWs) and its integration into sustainable urban landscapes. **Methods:** The study synthesizes data on *E. palaefolius* performance in subsurface flow (SSF-CW) and free water surface (FWS-CW) systems. It analyzes physiological mechanisms, including rhizofiltration and phytoextraction, as well as the influence of substrates such as zeolite and charcoal on removal rates. **Results:** Findings indicate that *E. palaefolius* achieves over 90% removal efficiency for heavy metals such as mercury (Hg), iron (Fe), copper (Cu), and lead (Pb). The plant's extensive root system facilitates high bioconcentration, particularly for iron in stems and roots, without compromising metabolic functions. Furthermore, its ornamental features, broad leaves, and white inflorescences enhance the visual and ecological integrity of urban water features. **Conclusion:** *E. palaefolius* is a highly effective, multifunctional agent for water quality management. Its implementation as a tertiary treatment in industrial and urban settings provides an eco-friendly strategy for environmental health and landscape beautification.

Keywords: *Echinodorus palaefolius*; Phytoremediation; Constructed wetlands; Heavy metals; Landscape enhancement

Received: 2 February 2026 | **Revised:** 22 February 2026 | **Accepted:** 24 February 2026 | **Published:** 26 February 2026

Cite this article: Mellyaning Oktaviani Sonya Kirana Sari (2026). Water Jasmine (*Echinodorus palaefolius*): a Phytoremediation Agent for Environmental Health Improvement and Landscape Enhancement. *Journal of Biomedical Sciences and Health*, *3*(1), 32-41. https://doi.org/10.34310/jbsh.v3.i1.301

1. INTRODUCTION

Environmental pollution, particularly from heavy metals and organic contaminants, poses significant threats to aquatic ecosystems and human health worldwide. Traditional water treatment methods, while effective, often involve high operational costs and secondary environmental impacts. Phytoremediation, the use of plants to remove, degrade, or stabilize contaminants from soil and water, has emerged as a sustainable and cost-effective alternative for environmental restoration (Syeed et al., 2022).

Constructed wetlands (CWs) represent one of the most widely applied nature-based solutions for wastewater management, offering robust treatment performance at relatively low costs (Syeed et al., 2022). These systems integrate physical, chemical, and biological processes to remove pollutants, with vegetation playing a central role in contaminant uptake and transformation. Among aquatic macrophytes employed in CWs, *Echinodorus palaefolius*, commonly known as water jasmine, has gained attention for its exceptional phytoremediation capacity and ornamental characteristics.

E. palaefolius features broad leaves, hollow stems for oxygen transport, and white flowers, demonstrating remarkable tolerance to heavy metal stress. Studies have shown its effectiveness in reducing lead (Pb) in river environments (Nafi'ah, 2021) and removing mercury (Hg) through zeolite-integrated subsurface flow systems (Prasetya et al., 2020). Furthermore, it has demonstrated high potential in treating leachate, specifically in removing iron (Fe) (Sari et al., 2019).

However, despite its potential, there is a notable research gap regarding the integrated study of its dual-functionality. Most existing literature focuses strictly on its technical efficiency in removing specific pollutants. There is a lack of comprehensive analysis that simultaneously bridges these phytoremediation capabilities with their practical application in aesthetic landscape enhancement. This study aims to fill this gap by evaluating how the synergistic attributes of *E. palaefolius* can be optimized for both environmental remediation and the beautification of sustainable urban water management systems.

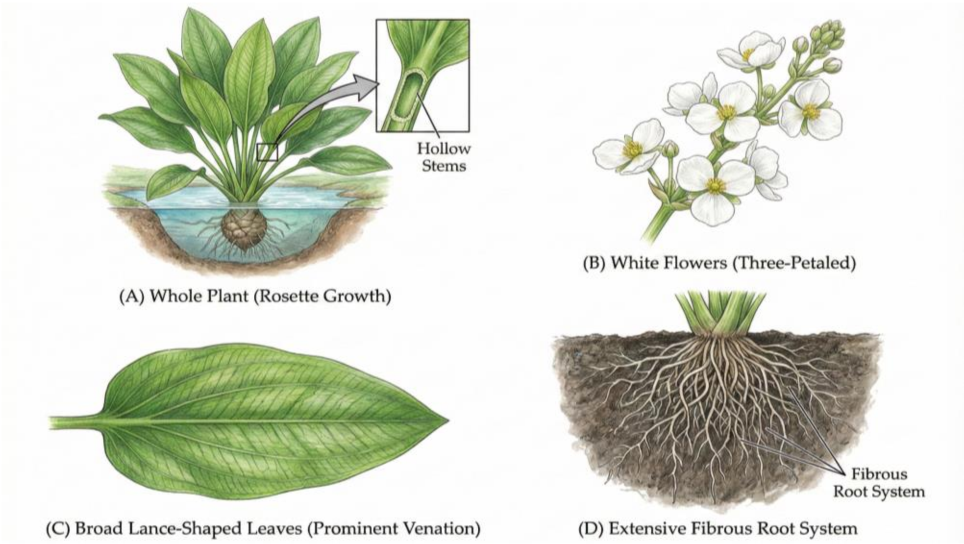

Figure 1. Morphological characteristics of *Echinodorus palaefolius*: (A) Whole plant showing rosette growth habit with emergent leaves and hollow stems, (B) White flowers with characteristic three-petaled structure and yellow stamens, (C) Broad lance-shaped leaves with prominent venation, (D) Extensive fibrous root system enabling efficient contaminant uptake. These morphological features contribute to both phytoremediation capacity and ornamental value.

2. PHYTOREMEDIATION MECHANISMS AND HEAVY METAL REMOVAL EFFICIENCY

2.1 Mercury Removal

Mercury (Hg) contamination, primarily stemming from artisanal small-scale gold mining (ASGM) and industrial effluents, poses a severe global environmental threat due to its high neurotoxicity and tendency for biomagnification. Recent advancements demonstrated by Prasetya et al. (2020) revealed that subsurface flow constructed wetlands (SSF-CW) utilizing *Echinodorus palaefolius* in conjunction with natural zeolite substrates achieved a remarkable Hg removal efficiency of 91.84% from an initial concentration of 14.94 mg/L. This performance is largely attributed to the synergistic interaction between the ion-exchange capacity of the zeolite and the robust rhizofiltration mechanisms inherent in *E. palaefolius* (Herath & Vithanage, 2015; Prasetya et al., 2020).

In a comparative context, *E. palaefolius* exhibits distinct advantages over conventional macrophytes such as Phragmites australis, Typha latifolia, and Pistia stratiotes. While P. australis is a staple in vertical flow wetlands for its high biomass, its effectiveness in high-concentration Hg environments is often limited to rhizosphere stabilization rather than efficient systemic translocation (Tlili et al., 2024). Similarly, floating species like P. stratiotes are highly effective for rapid nutrient uptake in domestic wastewater but remain susceptible to toxicity-induced chlorosis and root decay when exposed to heavy metal spikes (Ali et al., 2024; Singh et al., 2024).

The superiority of *E. palaefolius* lies in its specialized physiological resilience and compartmentalization strategy. Unlike Typha species, which may experience metabolic inhibition under significant metal stress, *E. palaefolius* utilizes apoplastic pathways to sequester Hg in root tissues before translocating it to aerial organs via the xylem (Lorensia & Rachmadiarti,2024; Sari et al., 2019). This hyperaccumulation potential extends to other metals such as lead (Pb), copper (Cu), and iron (Fe) (Nafi'ah, 2021; Pasaribu et al., 2021). Furthermore, while most high-efficiency remediators are strictly functional.

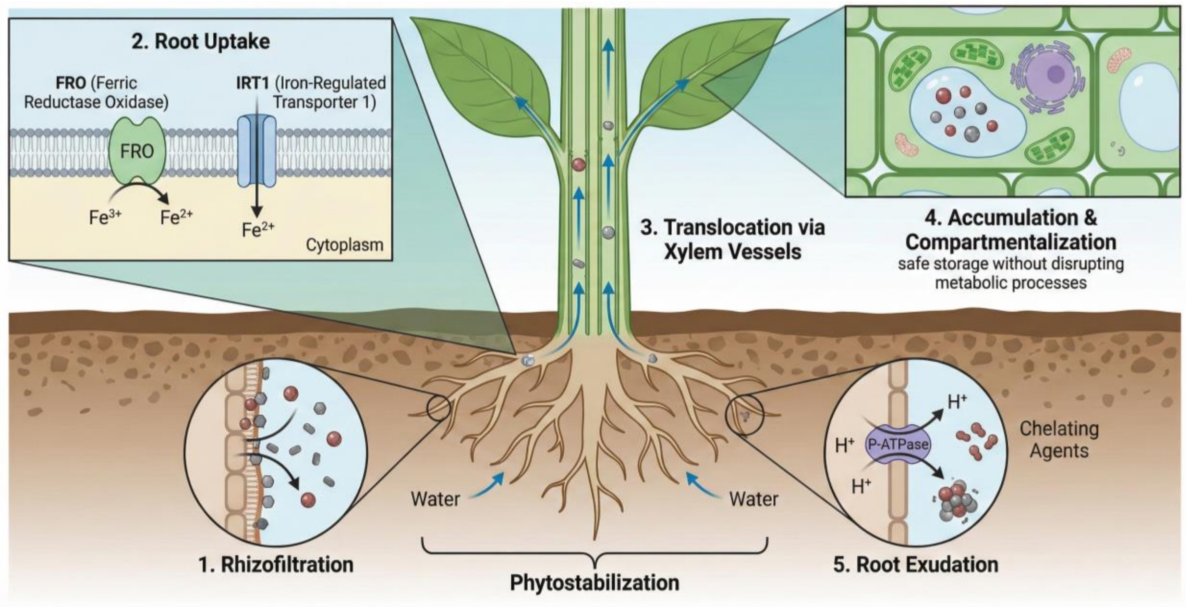

Figure 2. Schematic diagram of heavy metal uptake and accumulation mechanisms in *E. palaefolius*. The diagram illustrates: (1) Rhizofiltration at root surface where contaminants are filtered from water, (2) Root uptake through ion channels including IRT1 (Iron-Regulated Transporter 1) following reduction of Fe^{3+} to Fe^{2+} by ferric reductase oxidase (FRO), (3) Translocation of metals via xylem vessels from roots to aerial tissues, (4) Accumulation and compartmentalization in stems and leaves without disrupting metabolic processes, (5) Root exudation of protons (H^+) via P-ATPase pumps and chelating agents that enhance metal solubility and availability. The mechanisms shown include rhizofiltration, phytoextraction, and phytostabilization processes that enable *E. palaefolius* to function as a hyperaccumulator species.

2.2 Iron Removal from Landfill Leachate

Landfill leachate typically contains elevated concentrations of iron (Fe) and other heavy metals resulting from the complex decomposition of heterogeneous waste. Sari et al. (2019) investigated the capacity of *E. palaefolius* to sequester iron from Jatibarang Landfill leachate using a constructed wetland system. Their findings revealed significant accumulation, with peak concentrations observed in the plant stems (571 mg/kg) and roots (10.86 mg/kg). The bioconcentration factor (BCF) reached 3144.54, indicating a robust phytoextraction capacity. Furthermore, the optimal absorption rates were recorded at 7 days after planting (DAP) for roots (1.56 mg/kg/day) and 14 DAP for stems (63.71 mg/kg/day) (Sari et al., 2019).

The physiological mechanism of iron uptake in *E. palaefolius* involves a sophisticated multi-stage process. Initially, the roots secrete protons (H?) via P-ATPase pumps to acidify the rhizosphere, followed by the reduction of Fe? to Fe? facilitated by ferric reductase oxidase (FRO). Finally, Fe? is internalized through iron-regulated transporter 1 (IRT1). This specialized system enables *E. palaefolius* to function as a hyperaccumulator, predominantly storing iron in leaf tissues without compromising photosynthetic efficiency or metabolic vitality (Sari et al., 2019; Syeed et al., 2022).

2.3 Copper and Lead Removal

Recent investigations have broadened the understanding of *E. palaefolius* efficacy against a wider spectrum of heavy metals. Lorensia and Rachmadiarti (2024) demonstrated that *E. palaefolius* effectively absorbs copper (Cu) from growth media, with uptake increasing proportionally to the external Cu concentration. Although elevated Cu levels were found to negatively impact chlorophyll content, a paradoxical increase in wet biomass was observed, suggesting a resource reallocation strategy to maintain structural integrity under metallic stress.

Similarly, Pasaribu et al. (2021) evaluated the performance of *E. palaefolius* in mitigating lead (Pb) contamination in the upper Citarum River. A combined treatment involving *E. palaefolius* achieved a 90.32% reduction in Pb, decreasing concentrations from 0.068 mg/L to 0.0066 mg/L over a 14-day period. These results confirm the plant's broad-spectrum phytoremediation capacity, making it a versatile tool for treating multi-metal contaminated water (Nafi'ah, 2021; Pasaribu et al., 2021).

2.4 Organic Pollutant and Emerging Contaminant Removal

Beyond heavy metal sequestration, *E. palaefolius* demonstrates significant potential for degrading organic pollutants and emerging contaminants (ECs). Studies have documented substantial reductions in biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS), alongside nutrient removal (nitrogen and phosphorus) (Yadav et al., 2022). The plant's dense root system facilitates an expansive surface area for microbial colonization, which is critical for the biodegradation of complex organic compounds through rhizosphere interactions (Carvalho, 2020; Singh et al., 2024).

In the context of industrial applications, such as batik wastewater treatment, systems employing *E. palaefolius* have shown superior performance. The plant s aerenchyma tissue allows for the efficient transport of oxygen to the rhizosphere, creating aerobic microsites that stimulate microbial activity and promote the oxidative degradation of organic dyes and other persistent pollutants (Herath & Vithanage, 2015).

3. CONSTRUCTED WETLAND APPLICATIONS FOR ENVIRONMENTAL HEALTH

3.1 Subsurface Flow Constructed Wetlands

Subsurface flow constructed wetlands (SSF-CWs) are among the most effective configurations for *E. palaefolius*applications. In these systems, water migrates through porous media such as zeolite, gravel, or charcoal while roots penetrate the substrate to facilitate filtration (Prasetya et al., 2020). *E. palaefolius* thrives in SSF-CWs due to its extensive root development and tolerance to varying hydraulic loads. The synergy between substrate adsorption (e.g., the high cation exchange capacity of zeolite) and plant uptake significantly enhances overall removal efficiency compared to unplanted systems (Prasetya et al., 2020; Syeed et al., 2022).

3.2 Free Water Surface Constructed Wetlands

Free water surface constructed wetlands (FWS-CWs) closely mimic natural ecosystems, where water flows above the substrate surface. *E. palaefolius* is particularly suited for FWS-CWs as its emergent growth habit allows leaves to thrive above the waterline while roots provide a submerged biofilm substrate. FWS-CWs offer unique advantages for urban integration; the visible vegetation and inflorescences provide significant aesthetic value, aligning ecological restoration with urban landscape design (Li et al., 2024; Nowak et al., 2024). These "Living Water Parks" not only treat urban runoff but also enhance local biodiversity and provide recreational spaces for the community (Li et al., 2024).

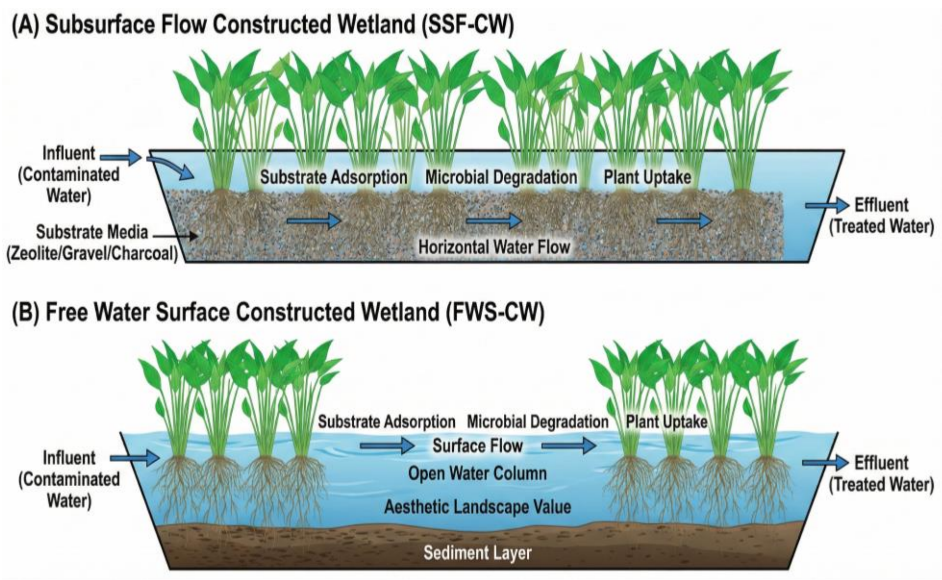

Figure 3. Types of constructed wetlands utilizing *E. palaefolius* for phytoremediation. (A) Subsurface Flow Constructed Wetland (SSF-CW) showing cross-sectional view with horizontal water flow through substrate media (zeolite, gravel, or charcoal). Contaminated water (influent) enters the system, flows through the porous substrate containing submerged roots of *E. palaefolius*, and exits as treated water (effluent). The root zone is completely submerged in substrate while leaves and stems emerge above the surface. (B) Free Water Surface Constructed Wetland (FWS-CW) featuring open water with emergent vegetation. Water flows across the surface while *E. palaefolius* roots extend into the water column and sediment layer below. Both systems facilitate contaminant removal through combined mechanisms of substrate adsorption, microbial degradation, and plant uptake, while FWS-CW additionally provides aesthetic landscape value through visible water and vegetation.

3.3 Performance Optimization and Operational Considerations

The operational efficacy of *E. palaefolius*-based constructed wetlands is contingent upon the precise calibration of several physicochemical parameters. Hydraulic Retention Time (HRT) emerges as a critical determinant of removal efficiency; empirical evidence suggests that a contact time of 7 21 days is required to facilitate adequate pollutant sequestration for most wastewater profiles (Syeed et al., 2022). Furthermore, thermal conditions dictate both the metabolic rate of the macrophyte and the kinetic activity of associated rhizospheric microorganisms, with peak performance typically observed within the 20 30 C range. The management of pH is equally vital, as *E. palaefolius* exhibits optimal nutrient and metal uptake capacity within a circumneutral range of 6.0 7.5 (Herath & Vithanage, 2015).

Plant density and spatial distribution are fundamental to system design. While high-density plantings generally enhance removal rates by increasing the active surface area for biofilm attachment, they may concomitantly escalate maintenance complexity. Experimental studies have identified that a spacing interval of 30-40 cm between specimens provides an effective balance between biomass growth and contaminant uptake (Sari et al., 2019). System performance should be continuously evaluated through the monitoring of plant health indicators, such as foliar coloration, growth kinetics, and reproductive vigor, which serve as proxies for physiological stress.

A sustainable operational framework necessitates a robust harvesting strategy. As *E. palaefolius* accumulates high concentrations of contaminants within its tissues, periodic harvesting is imperative to prevent the secondary release of pollutants during plant senescence (Prasetya et al., 2020). The resulting contaminated biomass must be managed through appropriate disposal protocols, ranging from composting for low-toxicity organic loads to controlled incineration for hazardous heavy metals (Yadav et al., 2022). The species' rapid growth and high reproductive plasticity, facilitated by both seed production and vegetative propagation, ensure rapid system recovery following biomass removal.

4. AESTHETIC VALUE AND LANDSCAPE INTEGRATION

4.1 Ornamental Characteristics and Morphological Appeal

E. palaefolius possesses distinct morphological attributes that render it highly valuable for ornamental integration within water gardens and urban green infrastructure. The species is characterized by broad, lanceolate leaves that form a symmetrical rosette, typically reaching lengths of 20 40 cm. The foliage exhibits a vibrant green hue with prominent venation, providing significant textural contrast in aquatic assemblages (Nowak et al., 2024). During the anthesis phase, the plant develops elongated inflorescences bearing tri-petaled white flowers with prominent yellow stamens, offering a sophisticated visual aesthetic that complements its ecological function (Nowak et al., 2024).

The versatile growth habit of *E. palaefolius* facilitates diverse applications in landscape design. As an emergent hydrophyte, it thrives in shallow water depths of 10 40 cm but maintains physiological resilience in marginal, saturated soils. This adaptability enables landscape architects to strategically position the species across varying wetland zones, from littoral margins to shallow pond interiors. Its clumping growth pattern is particularly effective for softening hardscape perimeters and creating seamless visual transitions between aquatic and terrestrial environments, thereby enhancing the overall ecological and visual integrity of the landscape (Li et al., 2024; Nowak et al., 2024).

4.2 Integration in Urban Water Features

Modern landscape architecture increasingly prioritizes the synergy between ecological functionality and aesthetic sophistication. Constructed wetlands incorporating *E. palaefolius* exemplify this dual-purpose approach, simultaneously mitigating aquatic contaminants and creating visually engaging public spaces. Current design trends indicate a rising demand for multifunctional water features, such as naturalistic water gardens and biophilic koi ponds, where *E. palaefolius* integrates seamlessly by providing high remediation capacity alongside significant ornamental value (Nowak et al., 2024).

A quintessential case study is the Living Water Park in Chengdu, China, recognized as a global pioneer in integrating wastewater purification with urban park design. This facility utilizes an advanced constructed wetland system where ornamental aquatic plants, analogous in function to *E. palaefolius*, execute the dual roles of pollutant sequestration and landscape enhancement (Li et al., 2024).

Empirical research within such urban wetland contexts reveals a strong positive correlation between aquatic plant diversity, microplastic retention, and public aesthetic appreciation. Layered vegetative configurations not only exhibit superior remediation kinetics but also receive higher evaluative ratings from visitors, underscoring the intrinsic compatibility of ecological health and visual appeal in designed environments (Li et al., 2024; Singh et al., 2024).

4.3 Design Considerations and Companion Planting

The successful integration of *E. palaefolius* into designed landscapes necessitates a strategic adherence to ecological design principles and synergistic plant associations. *E. palaefolius* thrives when paired with aquatic species that occupy distinct ecological niches, thereby creating a multi-tiered planting scheme that enhances both functional biodiversity and visual complexity. For instance, floating macrophytes such as Nymphaea spp. (water lilies) or Nelumbo spp. (lotus) can be utilized to occupy deeper aquatic zones, while marginal species like Juncus spp. (rushes) or Typha spp. (cattails) serve to delineate shallower transition zones (Singh et al., 2024).

Color coordination is fundamental to the aesthetic impact of these systems. The neutral palette of *E. palaefolius*, characterized by deep green foliage and delicate white inflorescences, serves as an ideal backdrop for more polychromatic species. Strategic placement of flowering plants with warm chromatic tones (e.g., reds, oranges, and yellows) against the verdant background of *E. palaefolius* creates compelling visual contrasts that align with contemporary landscape trends favoring earthy tones with bold accents (Nowak et al., 2024).

Operational longevity in ornamental water gardens is further influenced by maintenance protocols. *E. palaefolius* offers distinct advantages due to its high resilience and minimal post-establishment care requirements. Its broad tolerance to fluctuating water quality reduces the necessity for frequent technical interventions. However, the periodic excision of senescent leaves and spent flower stalks remains essential to preserve the visual integrity of the site and to ensure the permanent removal of nutrients from the system (Nowak et al., 2024; Syeed et al., 2022). In temperate climates, strategic management such as winter protection or treating the species as a high-performance annual is required to sustain system efficacy across varying seasons.

5. SUSTAINABILITY AND ENVIRONMENTAL HEALTH BENEFITS

5.1 Cost-Effectiveness and Resource Efficiency

Phytoremediation utilizing *E. palaefolius* within constructed wetland frameworks offers substantial economic advantages over conventional physicochemical water treatment technologies. Empirical data suggest that the capital expenditures (CAPEX) for constructed wetlands are typically 50 80% lower than those of conventional treatment plants with equivalent processing capacities (Yadav et al., 2022). Furthermore, operational expenditures (OPEX) are markedly reduced, as these nature-based systems require minimal energy inputs limited primarily to hydraulic pumping in specific configurations and eliminate the need for continuous chemical additives (Syeed et al., 2022).

The integration of locally sourced materials further optimizes cost-efficiency. Natural substrates such as zeolite and wood charcoal, which demonstrate synergistic effects when paired with *E. palaefolius*, can often be procured regionally at low costs (Prasetya et al., 2020). Moreover, the vegetative stock for wetland establishment can be rapidly propagated from minimal initial populations, thereby mitigating recurring nursery expenses. Maintenance requirements remain modest, focusing on periodic biomass harvesting and system monitoring rather than the high-level technical interventions necessitated by mechanical treatment facilities.

5.2 Ecosystem Services and Biodiversity Enhancement

Beyond its primary function of pollutant sequestration, *E. palaefolius*-based wetlands provide a multifaceted suite of ecosystem services. These systems establish vital habitats for a diverse array of aquatic and semi-aquatic taxa, including macroinvertebrates, amphibians, and avifauna. The structural complexity of the plant s architecture, comprising dense root networks and emergent stems, provides essential refugia and breeding sites, functioning as biodiversity "hotspots" within fragmented urban landscapes (Li et al., 2024; Nowak et al., 2024).

Furthermore, these wetlands contribute significantly to climate change mitigation through carbon sequestration. *E. palaefolius* facilitates the fixation of atmospheric CO2 via photosynthesis, sequestering carbon within its biomass and subsequently within the anaerobic wetland sediments upon decomposition (Syeed et al., 2022). On a microclimatic scale, the evapotranspiration from the dense foliage provides localized cooling effects, thereby alleviating the urban heat island (UHI) phenomenon.

The systemic improvements in water quality extend beyond the removal of heavy metals. The microbial consortia associated with *E. palaefolius* roots facilitate nitrogen transformation via denitrification, addressing critical nutrient enrichment and eutrophication concerns (Singh et al., 2024). Additionally, the physical stand of the vegetation attenuates water velocity, promoting the sedimentation of suspended solids and increasing water clarity. Collectively, these processes yield a superior effluent quality that enhances the ecological integrity of downstream water bodies (Li et al., 2024; Singh et al., 2024).

6. CHALLENGES AND FUTURE PERSPECTIVES

6.1 Current Limitations and Technical Barriers

Despite the robust efficiency demonstrated in laboratory and pilot-scale trials, several challenges hinder the widespread deployment of *E. palaefolius*-based phytoremediation. Transitioning from controlled environments to full-scale operations introduces complexities associated with site-specific variables, including climate variability, seasonal hydraulic fluctuations, and fluctuating contaminant concentrations (Syeed et al., 2022). Currently, longitudinal performance data for these systems operating under diverse and unpredictable environmental conditions remain limited.

A fundamental technical constraint is the finite contaminant uptake capacity of the vegetation. As macrophytes reach saturation points, their remedial efficiency plateaus, necessitating periodic biomass harvesting and replanting (Prasetya et al., 2020). This requirement creates logistical challenges regarding the sustainable disposal or valorization of contaminated plant tissues. Furthermore, regulatory frameworks governing the management of phytoremediation-derived waste are inconsistent across different jurisdictions, complicating long-term operational planning (Carvalho, 2020).

Climatic constraints also significantly modulate the performance of *E. palaefolius*. As a tropical and subtropical species, its metabolic rate and growth kinetics decline sharply at temperatures below 15 C, and it lacks physiological resilience to prolonged freezing (Herath & Vithanage, 2015). This limits its year-round application in temperate or cold regions without supplemental thermal management. Additionally, extreme hydrological events, such as prolonged droughts, can compromise system integrity if water levels fall below the plant s critical tolerance thresholds.

6.2 Research Needs and Opportunities

Future research must prioritize addressing existing knowledge gaps to optimize the scalability of *E. palaefolius* systems. Longitudinal studies monitoring system performance over multiple annual cycles are essential to obtain definitive data on sustainability and long-term maintenance requirements (Syeed et al., 2022). Furthermore, investigating *E. palaefolius* genotypes with enhanced thermal resilience could significantly expand their geographic applicability to temperate regions. Investigating optimal plant-substrate-microbe consortia remains a critical frontier to improve removal kinetics across a broader spectrum of emerging contaminants, including pharmaceuticals and microplastics (Carvalho, 2020; Li et al.,2024).

The valorization of harvested biomass represents a significant opportunity for circular economy integration. Research into phytomining, the safe extraction and recovery of valuable metals from plant tissues, could provide economic incentives while mitigating disposal risks (Yadav et al., 2022). Additionally, converting contaminated biomass into bioenergy via controlled thermochemical processes warrants exploration, provided there is a rigorous assessment of contaminant fate during conversion (Singh et al., 2024).

The integration of *E. palaefolius* wetlands with emerging technologies offers transformative potential. Coupling constructed wetlands with Microbial Fuel Cells (MFCs) could facilitate simultaneous wastewater treatment and bioelectricity generation, enhancing the resource efficiency of the system (Yadav et al., 2022). Moreover, the implementation of Smart Monitoring Systems, utilizing IoT sensors and real-time data analytics, could allow for autonomous operational adjustments to optimize treatment performance under fluctuating environmental loads.

6.3 Policy and Implementation Frameworks

The systemic adoption of *E. palaefolius*-based phytoremediation necessitates robust policy frameworks and regulatory clarity. The development of standardized design guidelines and performance benchmarks is imperative to streamline engineering planning and municipal approval processes. Integrating constructed wetlands into urban planning mandates and green building codes would further catalyze their inclusion in new infrastructure and urban renewal projects (Li et al., 2024; Nowak et al., 2024).

Financial mechanisms, such as ecological grants, green subsidies, and tax credits for nature-based solutions, are essential to accelerate large-scale deployment. Public awareness initiatives that highlight the dual benefits of these systems environmental decontamination and landscape beautification are crucial for building community support. Finally, the establishment of high-visibility demonstration projects in diverse urban and industrial settings will provide empirical evidence of success, helping to refine best practices for global implementation (Li et al., 2024).

7. CONCLUSION

Echinodorus palaefolius represents a highly efficacious aquatic macrophyte that bridges the gap between environmental biotechnology and aesthetic landscape architecture. Empirical evidence confirms its capacity to achieve removal efficiencies exceeding 90% for critical heavy metals, including mercury, iron, copper, and lead, alongside substantial reductions in organic pollutants. Its robust physiological tolerance and sophisticated uptake mechanisms, such as rhizofiltration and phytoextraction, underscore its viability as a primary agent in constructed wetland systems. Unlike traditional remediation species, *E. palaefolius* maintains its metabolic vitality under metallic stress, ensuring that its role as a biofilter does not compromise its ornamental integrity.

Beyond technical remediation, the plant s attractive foliage and inflorescences facilitate the transition from purely functional treatment facilities to multifunctional urban green-blue spaces. This dual-purpose utility aligns with the growing demand for nature-based solutions (NbS) that enhance biodiversity and public well-being while addressing the socio-economic constraints of traditional infrastructure. From a policy perspective, municipal authorities should mainstream green infrastructure by integrating constructed wetland designs into urban planning regulations. Regional managers are encouraged to implement decentralized treatment using *E. palaefolius* in industrial zones, develop circular economy frameworks for biomass valorization (e.g., phytomining), and establish standardized operational guidelines to ensure long-term performance across varying climatic conditions.

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