CONSTRUCTION
E-ISSN: 2785-8731
VOLUME 5, ISSUE 1, 2025, 87 - 95
DOI: https://doi.org/10.15282/construction.v5i1.12168

RESEARCH ARTICLE

Phytoremediation of Heavy Metal Contaminated Groundwater Using Tropical Wetland Plants: *Lepironia articulata* and *Typha angustifolia*

B. Jiang[1,2], N. H. Sa'adon[1], S. I. Doh[1], S. Sulaiman[1], A. S. Abdul Razak[1]*

[1]Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26300 Gambang, Pahang, Malaysia

[2]Faculty of Resources and Environmental Sciences, Hebei Minzu Normal University, 067000 Chengde, Hebei, China

ABSTRACT - This study examines the efficacy of *Lepironia articulata* and *Typha angustifolia* in horizontal subsurface flow constructed wetlands (HSSF-CWs) for removing organic pollutants and heavy metals from contaminated water over a 10-week monitoring period. For *Lepironia articulata*, the average COD, BOD_5, Pb, Zn, Fe, and Cu concentrations were 38.2 mg/L, 13.09 mg/L, 0.0416 mg/L, 0.0368 mg/L, 1.1539 mg/L, and 0.0096 mg/L, with corresponding removal efficiencies of 31.02%, 22.89%, 11.18%, 19.87%, 23.18%, and 22.53%, respectively. For *Typha angustifolia*, they were 50.7 mg/L, 11.43 mg/L, 0.0289 mg/L, 0.0163 mg/L, 0.9795 mg/L, and 0.0095 mg/L, with removal efficiencies of 8.24%, 38.34%, 37.16%, 57.41%, 32.83%, and 34.08%, respectively. FESEM-EDX imaging revealed distinct accumulation patterns, as *Lepironia articulata* tended to sequester more metals in its leaves, whereas *Typha angustifolia* retained a greater proportion in the stem. These findings highlight the complementary strengths of both macrophytes in mitigating organic and metal contaminants through wetland-based treatment.

ARTICLE HISTORY

Received	:	16th Mar. 2025
Revised	:	05th May 2025
Accepted	:	24th May 2025
Published	:	10th June 2025

KEYWORDS

Phytoremediation
Heavy metals
Constructed wetlands
Lepironia articulata
Typha angustifolia

1. INTRODUCTION

Groundwater is an essential resource for domestic, industrial, and agricultural use, yet its quality is increasingly threatened by contamination, particularly from heavy metals [1], [2]. These pollutants, originating from industrial discharge, agricultural runoff, mining activities, and improper waste disposal, pose significant environmental and health risks [3]. Heavy metal contamination disrupts aquatic ecosystems, inhibiting the growth and development of aquatic organisms and plants, while also entering the food chain through bioaccumulation, ultimately posing severe health hazards to humans [4]. Once accumulated in the body, heavy metals can cause neurological disorders, organ damage, and other toxic effects, making groundwater pollution a critical issue requiring urgent remediation [5].

Various physicochemical treatment methods, including adsorption, ion exchange, electrochemical treatment, membrane separation, and chemical precipitation, have been widely employed to remove heavy metals from contaminated water [6]. While these techniques are effective in reducing metal concentrations, they often suffer from high operational costs, significant energy consumption, and the risk of secondary pollution [7]. These limitations hinder their large-scale application and drive the need for sustainable, cost-effective, and environmentally friendly alternatives [8]. Among these, constructed wetlands (CWs) have emerged as a promising green technology for water treatment [9]. This method utilizes the combined physical, chemical, and biological interactions between wetland substrates, plants, and microbial communities to remove pollutants [10]. Through processes such as adsorption, sedimentation, uptake, oxidation-reduction reactions, microbial degradation, and biochemical transformation, CWs can effectively mitigate heavy metal contamination while maintaining ecological balance. The remediation of heavy metal-contaminated water through phytoremediation can employ various mechanisms, either individually or in combination. These mechanisms primarily include phytoextraction [11], phytostabilization [12], phytovolatilization [13], and rhizofiltration [14].

Within constructed wetland systems, wetland plants play a crucial role by absorbing, accumulating, and stabilizing heavy metals. The selection of appropriate plant species is essential to optimize phytoremediation efficiency. Among the various candidate species, *Lepironia articulata* and *Typha angustifolia* have shown significant potential in accumulating heavy metals from contaminated environments [15], [16]. These emergent macrophytes exhibit distinct root structures and biomass accumulation capacities, which may influence their metal uptake and retention efficiency [17]. However, comparative studies on their performance in controlled wetland systems remain limited[18]. Understanding the differences in their heavy metal removal efficiency, as well as the mechanisms governing metal accumulation within different plant tissues, is crucial for optimizing phytoremediation strategies [19].

This study experimentally evaluates the efficiency of *Lepironia articulata* and *Typha angustifolia* in removing biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and heavy metals (Fe, Cu, Zn, Pb) from contaminated groundwater, and the localization and accumulation of heavy metals in different plant structures (roots, stems, and leaves). The findings from this research provide valuable insights into optimizing constructed

***CORRESPONDING AUTHOR | Abdul Syukor Abdul Razak** | ✉ syukor@umpsa.edu.my

wetland systems for sustainable groundwater remediation by identifying plant species with superior metal accumulation capacities, thereby advancing scalable phytoremediation applications and reinforcing the viability of this eco-friendly alternative to conventional heavy metal treatment technologies.

2. METHODS AND MATERIALS

2.1 Experimental Design

A horizontal subsurface flow constructed wetland was established on University Malaysia Pahang Al-Sultan Abdullah (UMPSA) campus (Table 1). The system was designed to maximize contact between contaminated groundwater and plant roots by using baffles to create two distinct compartments, thus optimizing the hydraulic retention time (HRT).

Table 1. Constructed wetland system specifications

Parameter	Value
Length	5.79 m
Width	2.67 m
Total Volume	7.11 m^3
Number of Compartments	2
Baffle Height	0.46 m
Spacing between Baffles	0.97 m

2.2 Sampling and Analytical Methods

Weekly water samples were collected from the inlet and outlet of the treatment pond over a two-month period. Key water quality parameters were measured: Chemical Parameters: Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD). Heavy Metals: lead (Pb), zinc (Zn), iron (Fe), and copper (Cu). All analyses followed APHA Standard Methods. Heavy metal concentrations were determined using Atomic Absorption Spectroscopy (AAS). At the conclusion of the study, representative samples (roots, stems, and leaves) were harvested from both plant species. Samples were prepared by cleaning, drying, and mounting on conductive stubs (using carbon tape) to prevent charging during detection process. Field Emission Scanning Electron Analysis with Energy Dispersion X-ray (FESEM- EDX) was then used to map and quantify heavy metal distribution within plant tissues.

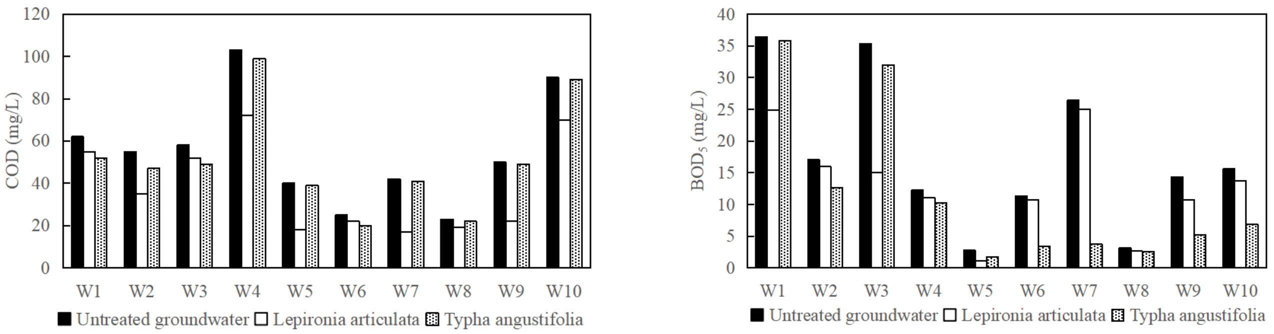
2.3 Data Analysis

Removal efficiency for heavy metals was calculated as the percentage reduction between inlet and outlet concentrations. Statistical analyses (ANOVA) were conducted to assess significant differences in performance between the two plant species and among different compartments. Graphs and charts were generated to illustrate temporal trends and comparative performance metrics.

3. RESULT AND DISCUSSION

3.1 Variation in COD and BOD_5 Concentrations

Chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5) are key parameters for assessing water quality in both natural and engineered aquatic systems [20]. COD quantifies the total oxygen required to chemically oxidize organic (and some inorganic) substances, while BOD_5 measures the amount of dissolved oxygen consumed by microorganisms over five days to break down biodegradable organic matter [21], [22]. Elevated levels of COD and BOD_5 typically indicate higher organic pollution, which can deplete dissolved oxygen and adversely affect aquatic life [23]. Figure 1 summarizes the weekly COD and BOD_5 values (mg/L) recorded in each plant compartment, along with the average concentrations across all sampling points.



(a) COD (b) BOD_5

Figure 1. Variation curves of COD and BOD_5 concentrations (mg/L) in treated effluents from Lepironia articulata and Typha angustifolia compartments, including untreated control values. The figure illustrates weekly fluctuations and highlights the comparative removal performance of both plant species against initial concentrations

For *Lepironia articulata*, COD ranged from 17–72 mg/L (average 38.2 mg/L), with an average removal efficiency of 31.02%. For *Typha angustifolia*, COD ranged from 20–99 mg/L (average 50.7 mg/L), with a lower removal efficiency of 8.24%. Both species demonstrated the ability to reduce COD from higher initial levels to significantly lower concentrations, although the effectiveness varied by week, but *Lepironia articulata* showed markedly higher treatment efficiency. In the *Lepironia articulata* compartment, BOD_5 ranged from (1.10–25.05 mg/L), with an overall average of 13.09 mg/L and a removal efficiency of 22.89%. In the *Typha angustifolia* compartment, BOD_5 varied from (1.75–35.85 mg/L), resulting in an average of 11.43 mg/L, with a higher removal efficiency of 38.34%. Although both species effectively reduced BOD_5 levels, *T. angustifolia* demonstrated greater overall removal performance. These fluctuations suggest that microbial activity, hydraulic conditions, and the growth stage of each plant may have influenced the rate of organic matter decomposition over time.

While *Lepironia articulata* showed lower average COD (38.2 mg/L) than *Typha angustifolia* (50.7 mg/L), its BOD_5 values (13.09 mg/L) were slightly higher overall than those of *Typha angustifolia* (11.43 mg/L). This difference may be due to each species' unique root structures, oxygen transfer mechanisms, and microbial communities associated with their rhizospheres[24]. Both plants displayed marked week-to-week variation in COD and BOD_5 removal, underscoring the dynamic nature of biological treatment processes and the potential influence of external factors. Despite inherent variability, the data indicate that both *Lepironia articulata* and *Typha angustifolia* can significantly reduce organic pollutants, as reflected by the drop in COD and BOD_5 in multiple weeks. Understanding these trends is crucial for optimizing constructed wetland design, particularly in selecting plant species and managing operational conditions (such as hydraulic retention time and loading rates) [25].

3.2 Variation in Heavy Metals Concentrations

Heavy metals such can have detrimental effects on plant physiology, growth, and overall ecosystem stability when present in excessive concentrations. While some of these metals (Fe, Cu, Zn) are essential micronutrients, their toxicity emerges when accumulated beyond optimal levels. Although Fe is crucial for chlorophyll synthesis and electron transport in plants, excessive Fe accumulation leads to oxidative stress, root browning, and impaired nutrient uptake. High Fe concentrations can cause cell membrane damage due to excessive reactive oxygen species (ROS) production [5]. Cu plays a vital role in enzyme activation and photosynthesis, but excessive Cu disrupts metabolic activities by damaging proteins and enzymes. It also leads to chlorosis, root growth inhibition, and reduced water uptake, ultimately affecting plant productivity[26]. Zn is essential for enzyme function and protein synthesis; however, an overabundance of Zn disrupts ion homeostasis, interfering with Fe and Mn uptake, leading to stunted growth, leaf chlorosis, and root abnormalities. Excess Zn may also inhibit seed germination [27]. Unlike Fe, Cu, and Zn, Pb has no known biological function in plants and is highly toxic even at low concentrations. Pb accumulation impairs photosynthesis, reduces root elongation, and disrupts enzymatic processes. It also induces ROS production, leading to oxidative damage and potential plant mortality [28].

Figure 2 presents the weekly measurements of four heavy metals—Fe, Cu, Zn, and Pb—within two separate wetland compartments planted with *Lepironia articulata* and *Typha angustifolia*. The dataset, spanning a 10-week monitoring period, provides both weekly fluctuations and overall averages for each species, offering insights into their respective heavy metal retention and removal capabilities.

Pb concentrations ranged from 0.029–0.051 mg/L in *Lepironia articulata* (average 0.0416 mg/L, removal efficiency 11.18%) and 0.016–0.039 mg/L in *Typha angustifolia* (average 0.0289 mg/L, removal efficiency 37.16%). The consistently higher Pb concentrations in the *Lepironia articulata* compartment suggest a lower removal capacity, potentially due to limited uptake. In contrast, *Typha angustifolia* demonstrated more effective Pb removal, indicating greater phytoextraction potential. Despite these variations, both compartments consistently maintained Pb concentrations below 0.06 mg/L, demonstrating the wetland's effectiveness in preventing excessive Pb accumulation in effluent water.

Zn concentrations followed a similar pattern, with *Lepironia articulata* exhibiting higher retention, ranging from 0.003–0.059 mg/L (average 0.0368 mg/L, removal efficiency 19.87%), while *Typha angustifolia* ranged from 0.001–0.043 mg/L (average 0.0163 mg/L, removal efficiency 57.41%). The relatively elevated Zn levels in *Lepironia articulata* compartments suggest a lower translocation and uptake efficiency relative to *Typha angustifolia*, which exhibited markedly better Zn removal performance.

Fe concentrations showed the most substantial fluctuations throughout the study, with *Lepironia articulata* ranging from 0.003–3.262 mg/L (average 1.1539 mg/L, removal efficiency 23.18%) and *Typha angustifolia* from 0.045–4.372 mg/L (average 0.9795 mg/L, removal efficiency 32.83%). Although *Typha angustifolia* showed a slightly higher average removal efficiency, both species demonstrated comparable Fe treatment performance overall. The substantial week-to-week fluctuations are likely influenced by external factors such as sediment resuspension, biofilm dynamics, and variable redox conditions within the wetland compartments, all of which can significantly affect Fe mobility and availability.

Cu concentrations, though comparatively lower, ranged from 0.002–0.033 mg/L for *Lepironia articulata* (average 0.0096 mg/L, removal efficiency 22.53%) and 0.001–0.034 mg/L for *Typha angustifolia* (average 0.0095 mg/L, removal efficiency 34.08%). Despite nearly identical average effluent concentrations, *Typha angustifolia* achieved a significantly higher removal efficiency, suggesting it was more effective in reducing Cu from a higher initial concentration. This discrepancy indicates a stronger uptake or adsorption capacity in *Typha angustifolia*, possibly due to more active root-microbe interactions or greater surface area for metal binding.

Across both wetland compartments, heavy metal concentrations exhibited a general downward trend over time, despite occasional spikes. This progressive decline underscores the ability of constructed wetlands to mitigate heavy metal pollution through a combination of plant uptake, microbial biofilm activity, metal precipitation, and sedimentation processes. The observed variations in metal retention between the two species likely stem from differences in root morphology, biomass production, and tolerance thresholds for specific metals [29].

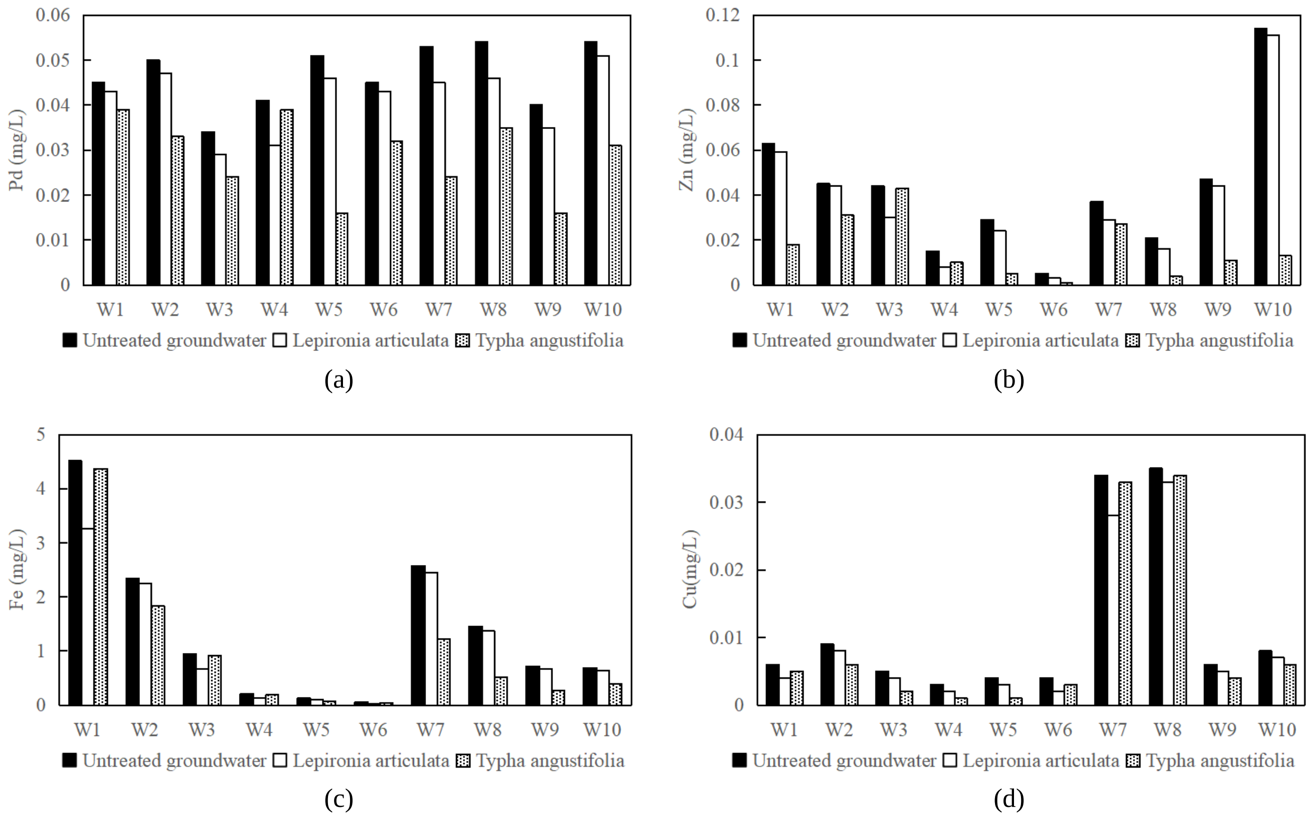


Figure 2. Weekly variations in heavy metal concentrations (mg/L) of Control and after phytoremediation with *Lepironia articulata* and *Typha angustifolia* over a 10-week period. The bar charts illustrate the temporal removal patterns of (a) Pb, (b) Zn, (c) Fe, and (d) Cu

Comparative analysis indicates that *Lepironia articulata* retained higher average concentrations of Zn and Fe, whereas *Typha angustifolia* exhibited lower Pb levels overall. The root structure of *Typha angustifolia*—characterized by an extensive rhizome network—may enhance Pb sequestration within belowground tissues, thereby limiting its translocation to aerial parts. Conversely, the relatively higher Zn and Fe retention in *Lepironia articulata* suggests a different sequestration mechanism, potentially linked to its fibrous root system and cell wall binding properties. Previous studies have highlighted *Typha angustifolia*'s superior ability to remove a broad range of contaminants due to its rapid biomass accumulation and its rhizosphere's role in supporting microbial interactions that facilitate metal immobilization [30]. Meanwhile, *Lepironia articulata* has been reported to be particularly effective in trapping suspended particles and associated metal pollutants, which may explain its higher Zn and Fe retention [31]. These findings suggest that integrating multiple macrophytes in constructed wetlands—either through co-planting or rotational use—could enhance overall heavy metal removal efficiency by leveraging the complementary strengths of different species.

From a practical perspective, these results emphasize the importance of species selection, compartmental configuration, and long-term operational strategies for optimizing wetland performance. Key management interventions, such as maintaining stable hydraulic retention times, monitoring water chemistry (e.g., pH, redox potential), and periodically harvesting aboveground biomass, can improve removal efficiency while sustaining plant health. By capitalizing on the synergistic effects of different plant species, constructed wetlands provide a cost-effective and ecologically viable alternative to more energy-intensive remediation technologies, offering resilience against fluctuating influent loads and environmental conditions [32]. Beyond individual heavy metal retention patterns, interactions among Fe, Cu, Zn, and Pb within constructed wetlands may influence their bioavailability, mobility, and overall removal efficiency. These interactions occur through various physicochemical and biological mechanisms, including competition for adsorption sites, precipitation, redox transformations, and complex formation. Understanding these inter-metallic relationships provides deeper insight into how constructed wetlands regulate heavy metal sequestration [33].

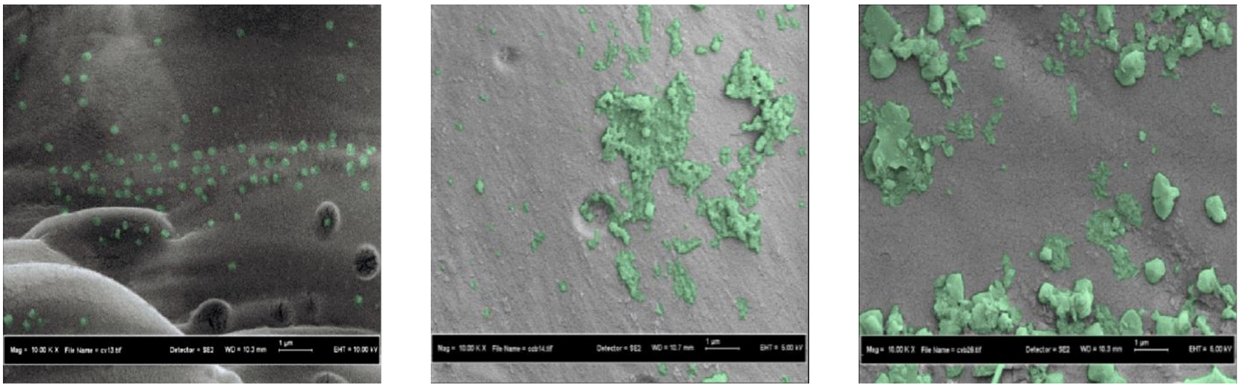
Metals with similar ionic properties often compete for binding sites in plant roots, microbial biofilms, and sediment surfaces. In this study, Fe and Zn showed relatively high concentrations in *Lepironia articulata*, which may indicate competitive inhibition affecting other metals. Fe, being a dominant and highly reactive metal, can outcompete Zn and Pb for adsorption sites on organic matter and clay minerals [30]. This competition can reduce Zn availability, potentially explaining why *Typha angustifolia* exhibited lower Zn retention compared to *Lepironia articulata*. Similarly, Cu and Zn often exhibit antagonistic behavior in plant uptake. Cu has a higher affinity for root binding sites due to its stronger complexation ability, potentially limiting Zn absorption in *Typha angustifolia* and leading to its lower Zn retention. In contrast, *Lepironia articulata*, which accumulated more Zn, may have been less affected by Cu interference, possibly due to differences in root exudate composition or rhizosphere chemistry.

Heavy metals do not exist in isolation in wetland environments; instead, they form various complexes that affect their solubility and transport. Fe and Pb, for instance, are prone to hydrolysis and precipitation under oxidizing conditions, forming insoluble hydroxides or carbonates. The observed fluctuations in Fe and Pb concentrations may be attributed to periodic shifts in oxidation-reduction conditions, leading to cycles of metal precipitation and re-solubilization [34]. Moreover, Cu and Pb can form stable organic complexes with humic substances present in wetland sediments. These complexes may reduce free Cu and Pb ion availability, leading to lower uptake by plants. This could partly explain why *Typha angustifolia* retained lower Pb levels in its tissues—organic complexation may have sequestered Pb in sediment or biofilms, reducing its translocation to plant compartments. Certain metals can facilitate or inhibit the removal of others. For example, Fe oxides are known to act as co-precipitants, adsorbing Cu, Zn, and Pb onto their surfaces. The relatively higher Fe retention in *Lepironia articulata* suggests that Fe oxides might have contributed to enhanced Zn and Pb adsorption, preventing their further mobility. Conversely, excess Fe in water can also lead to competitive exclusion, decreasing Zn and Cu uptake efficiency by plants.

Antagonistic interactions were also likely present between Pb and Zn. Pb tends to compete with Zn for cation exchange sites in sediments, which may have affected Zn retention dynamics between the two plant species. In *Typha angustifolia*, Pb concentrations remained lower, possibly due to stronger affinity for organic ligands in the root zone, preventing Pb from interfering with Zn removal. In contrast, *Lepironia articulata* had higher Zn levels, suggesting less Pb competition in its compartment [28]. Understanding these inter-metallic interactions is crucial for optimizing constructed wetlands for heavy metal removal. Designing systems that promote favorable redox conditions, regulate pH stability, and enhance microbial activity can improve metal complexation and co-precipitation, reducing free metal ion toxicity. Additionally, pairing macrophytes with complementary metal sequestration abilities can minimize competitive inhibition and maximize overall removal efficiency.

3.3 Comparative Analysis of Heavy Metal Accumulation Using FESEM-EDX

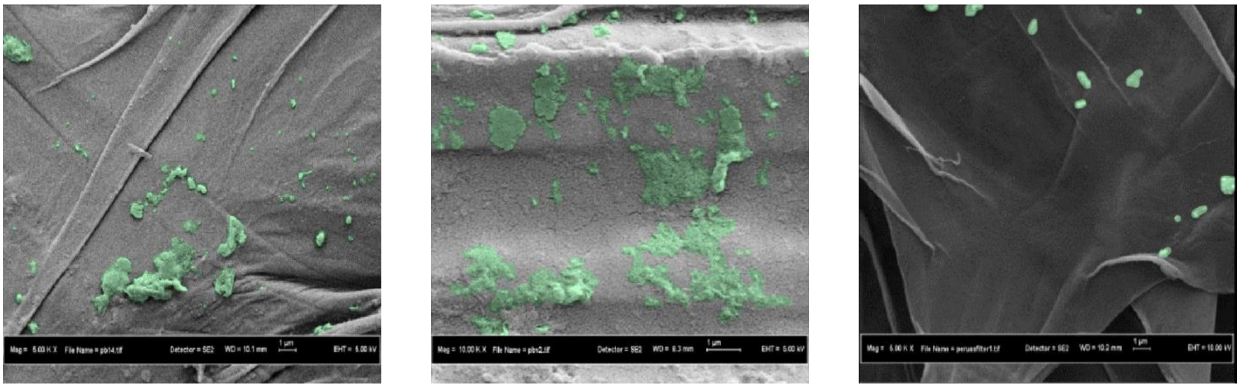
The FESEM-EDX micrographs (Figures 3 and 4) reveal the spatial distribution of metal particulates (highlighted in green) on the root, stem, and leaf surfaces of both *Lepironia articulata* and *Typha angustifolia*. These observations are reinforced by the quantitative data in Table 2, which shows the weight percentage of Fe, Cu, Zn, and Pb retained in each plant section.



(a) (b) (c)

Figure 3. FESEM-EDX images of (a) *Lepironia articulata*'s root, (b) stem and (c) leave surface at 10k magnification, showing metal particle deposition (green spots). The images indicate significant metal accumulation on stems and leaves, suggesting active metal translocation within the plant

The root surfaces, particularly in *Lepironia articulata*, appear well-suited for early metal capture, while the stem tissues in *Typha angustifolia* facilitate metal retention via internal aeration structures or specialized cells. Understanding these tissue-level accumulation patterns is crucial for phytoremediation system design—particularly if selective harvesting of above-ground biomass is employed to remove metals. Mixed-species wetlands could leverage each plant's strengths, with *Lepironia articulata* targeting metals through robust leaf translocation and *Typha angustifolia* sequestering metals in the stem, potentially reducing stress on its leaves. FESEM images also indicate that, in the root sections of both species, heavy metal particles appear smaller and more dispersed, whereas in the stem they tend to form larger, more complex compounds (e.g., metal chelates or precipitates). These morphological differences suggest varying chemical environments and binding sites across plant tissues.



(a) (b) (c)

Figure 4. FESEM-EDX images of (a) *Typha Angustifolia*'s root, (b) stem and (c) leave surface at 10k magnification, highlighting metal deposits mainly on roots and stems (green spots). This pattern suggests metal retention primarily in belowground and stem tissues, limiting leaf exposure

Table 2. Percentage of heavy metals weight retained in different section of plants (%)

Heavy metals	*Lepironia articulata*			*Typha Angustifolia*		
	Root	Stem	Leave	Root	Stem	Leave
Fe	1.97	0.16	2.95	0	1.48	0
Cu	0.51	0.04	0.31	0.38	0	0.30
Zn	0.49	0.63	0.07	0.42	0	0
Pb	0.71	0.65	0.93	0.13	0.36	1.08
Sum	3.68	1.48	4.26	0.93	1. 84	1.38

Lepironia articulata exhibits its highest total metal retention in the leaf (4.26%), followed by the root (3.68%) and the stem (1.48%). Iron (Fe) and lead (Pb) dominate in the leaf, whereas copper (Cu) and zinc (Zn) are more uniformly distributed between the root and leaf. While *Typha angustifolia*, in contrast, shows the greatest total metal retention in the stem (1.84%), followed by the leaf (1.38%) and the root (0.93%). Iron (Fe) concentrates in the stem, while lead (Pb) is more prevalent in the leaf. *Lepironia articulata* demonstrates a notable capacity to translocate metals to the leaf, as evidenced by the elevated Fe and Pb percentages in leaf tissues. This stronger translocation capability can help remove metals from the root zone but may increase the physiological burden on leaves [35]. *Typha angustifolia*, on the other hand, retains a larger fraction of metals (especially Fe) in the stem, effectively shielding its leaves and potentially supporting healthier growth and photosynthetic efficiency.

Species selection and compartmental design can be tailored to address specific contaminants. Where higher Fe or Pb concentrations are present, *Lepironia articulata* might offer an advantage by moving these metals to leaf tissues for easier removal. Conversely, *Typha angustifolia* could help maintain plant vitality by confining a portion of the metals to its stem. By capitalizing on each plant's specific uptake and retention patterns, a multi-species configuration in constructed wetlands can take advantage of their complementary strengths, thereby enhancing overall metal removal from contaminated water [34].

4. CONCLUSION

Both *Lepironia articulata* and *Typha angustifolia* demonstrated the capacity to remove organic pollutants and heavy metals from contaminated water, as evidenced by reductions in COD, BOD_5, and key metal concentrations (Pb, Zn, Fe, and Cu), albeit with differing efficiencies across parameters. On average, *Lepironia articulata* achieved removal efficiencies of 31.02% for COD, 22.89% for BOD_5, 19.87% for Zn, 23.18% for Fe, 22.53% for Cu, and 11.18% for Pb. In contrast, *Typha angustifolia* demonstrated higher average removal efficiencies for BOD_5 (38.34%), Pb (37.16%), Zn (57.41%), Fe (32.83%), and Cu (34.08%), but showed relatively lower COD removal (8.24%). FESEM-EDX analysis revealed that *Lepironia articulata* tends to translocate a higher proportion of metals to its leaves, reflecting robust mobility of contaminants within its tissues, whereas *Typha angustifolia* retains more metals in its stems, potentially preserving leaf health. These contrasting strategies underscore the potential benefits of integrating multiple macrophytes with distinct uptake and accumulation patterns into constructed wetlands, thereby enhancing overall contaminant removal. The results reinforce the feasibility of using cost-effective, nature-based approaches to address water pollution and pave the way for more sustainable, eco-friendly wastewater treatment practices.

AUTHOR CONTRIBUTIONS

Baiyang Jiang: Writing- Original draft preparation, Visualization and Investigation.

Noor Hijrah Sa'adon: Data curation. Shu Ing Doh: Co-Supervision, and validation.

Suryati Sulaiman: Writing- Reviewing and Editing.

Abdul Syukor Abdul Razak: Supervision.

FUNDING

The support provided by the Science and Technology Special Project for the Construction of Innovative Demonstration Areas in the National Sustainable Development Agenda of Chengde(202302F006), 2024 Science and Technology Program of Chengde (No.202404B103) and 2023 Science and Technology self-financing Program of Chengde (No.202303A097) are highly appreciated.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] A. Ismanto, T. Hadibarata, S. Widada, E. Indrayanti, D. H. Ismunarti, N. Safinatunnajah, et al., “Groundwater contamination status in Malaysia: level of heavy metal, source, health impact, and remediation technologies,” *Bioprocess and Biosystems Engineering*, vol. 46, no. 3, pp. 467–482, 2023.

[2] A. R. A. Syukor, Z. N. Azzimah, R. Norbaizurah, and S. Suryati, “Assessment of physico-chemical analysis of ground water quality in rural area: Kampung Chendrawasih, Pekan Pahang for drinking purpose,” in *Proceedings of International Conference on Knowledge Transfer (ICKT’15)*, Putrajaya Marriott Hotel, Malaysia, pp. 223–228, 2015.

[3] P. B. Angon, M. S. Islam, A. Das, N. Anjum, A. Poudel and S. A. Suchi, “Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain,” *Heliyon*, vol. 10, no. 7, p. e28357, 2024.

[4] T. A. Saleh, M. Mustaqeem and M. Khaled, “Water treatment technologies in removing heavy metal ions from wastewater: A review,” *Environmental Nanotechnology, Monitoring & Management*, vol. 17, p.100617, 2022.

[5] R. Shrestha, S. Ban, S. Devkota, S. Sharma, R. Joshi, A. P. Tiwari, et al., “Technological trends in heavy metals removal from industrial wastewater: A review,” *Journal of Environmental Chemical Engineering*, vol. 9, no. 4, p. 105688, 2021.

[6] S. Kataki, S. Chatterjee, M. G. Vairale, S. Sharma, S. K. Dwivedi, and D. K. Gupta, “Constructed wetland, an eco-technology for wastewater treatment: A review on various aspects of microbial fuel cell integration, low temperature strategies and life cycle impact of the technology,” *Renewable and Sustainable Energy Reviews*, vol. 148, p. 111261, 2021.

[7] S. F. Ahmed, M. Mofijur, S. Nuzhat, A. T. Chowdhury, N. Rafa, M. A. Uddin, et al., “Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater,” *Journal of Hazardous Materials*, vol. 416, p. 125912, 2021.

[8] F. Younas, N. K. Niazi, I. Bibi, M. Afzal, K. Hussain, M. Shahid, et al., “Constructed wetlands as a sustainable technology for wastewater treatment with emphasis on chromium-rich tannery wastewater,” *Journal of Hazardous Materials*, vol. 422, p. 126926, 2022.

[9] A. S. Abd Razak, N. Rahman, N. A. Zamri, S. Sulaiman, N. A. A. Burhanudin, and E. Abd Aziz., “COD, BOD and heavy metal removal from ground water treatment by using WASRA System: A case study on Universiti Malaysia Pahang Mosque.,” *Advances in Environmental Biology*, vol. 9, no. 1, pp. 26–29, 2015.

[10] T. Kamilya, A. Majumder, M. K. Yadav, S. Ayoob, S. Tripathy, and A. K. Gupta, “Nutrient pollution and its remediation using constructed wetlands: Insights into removal and recovery mechanisms, modifications and sustainable aspects,” *Journal of Environmental Chemical Engineering*, vol. 10, no. 3, p. 107444, 2022.

[11] S. Haq, A. A. Bhatti, Z. A. Dar, and S. A. Bhat, *Phytoremediation of heavy metals: An eco-friendly and sustainable approach*. Springer International Publishing, 2020.

[12] Sabreena, S. Hassan, S. A. Bhat, V. Kumar, B. A. Ganai, and F. Ameen, “Phytoremediation of heavy metals: An indispensable contrivance in green remediation technology,” *Plants*, vol. 11, no. 9, p. 1255, 2022.

[13] M. A. Oyuela Leguizamo, W. D. Fernández Gómez, and M. C. G. Sarmiento, "Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands — A review," *Chemosphere*, vol. 168, pp. 1230–1247, 2017.

[14] P. Sharma, "Efficiency of bacteria and bacterial assisted phytoremediation of heavy metals: An update," *Bioresource Technology*, vol. 328, p. 124835, 2021.

[15] N. H. A. L. Sbani, S. R. S. Abdullah, M. Idris, H. A. Hasan, M. I. E. Halmi, O. H. Jehawi, et al., "PAH-degrading rhizobacteria of Lepironia articulata for phytoremediation enhancement," *Journal of Water Process Engineering*, vol. 39, p. 2021.

[16] Y. Lei, L. Carlucci, H. Rijnaarts, and A. Langenhoff, "Phytoremediation of micropollutants by Phragmites australis, Typha angustifolia, and Juncus effuses," *International journal of phytoremediation*, vol. 25, no. 1, pp. 82-88, 2023

[17] N. H. Al-Sbani, S. R. S. Abdullah, M. Idris, H. A. Hasan, O. H. Jehawi, and N. Ismail, "Sub-surface flow system for PAHs removal in water using Lepironia articulate under greenhouse conditions," *Ecological Engineering*, vol. 87, pp. 1-8, 2016.

[18] A. R. Abdul Syukor and S. Suryati, "Treatment of Industrial Wastewater using Eichornia Crassipes, Pistia Stratiotes and Salvinia Molesta in Phytogreen System," *Energy Education Science and Technology Part A: Energy Science and Research*, vol. 32, no. 1, pp. 339–346, 2014.

[19] S. F. Ahmed, P. S. Kumar, M. R. Rozbu, A. T. Chowdhury, S. Nuzhat, N. Rafa, et al., "Heavy metal toxicity, sources, and remediation techniques for contaminated water and soil," *Environmental Technology & Innovation*, vol. 25, p. 102114, 2022.

[20] A. R. Abdul Syukor, A. W. Zularisam, M. I. M. Said, S. Suryati, and A. H. Hasmanie, "The effectiveness of phytogreen system in phytoremediation and bioremediation process to enhance the quality of domestic wastewater," in *IWA Malaysia Young Water Professionals Conference*, Kuala Lumpur, Malaysia, vol. 65, no. 3, pp. 1–11, 2015.

[21] A. R. Abdul Syukor, A. W. Zularisam, I. Zakaria, M. S. Mohd. Ismid, S. Sulaiman, H.A. Halim, et al., "Potential of aquatic plant as phytoremediator for treatment of petrochemical wastewater in Gebeng Area, Kuantan," *Advances in Environmental Biology*, vol. 7, no. 12, pp. 3808–3814, 2013.

[22] A. A. Syukor, A. W. Zularisam, Z. Ideris, M. M. Ismid, H. Nakmal, S. Sulaiman, et al., "Performance of phytogreen zone for BOD5 and SS removal for refurbishment conventional oxidation pond in an integrated phytogreen system," *International Journal of Environmental, Earth Science and Engineering*, vol. 8, no. 3, pp. 11–16, 2014.

[23] A. R. Abdul Syukor, "Performance of conventional oxidation pond using integrated phytogreen system by aquatic plants for achieving standard an effluent," Universiti Malaysia Pahang, 2020.

[24] D. Arivukkarasu and R. Sathyanathan, "A sustainable green solution to domestic sewage pollution: Optimizing floating wetland treatment with different plant combinations and growth media," *Water Cycle*, vol. 5, pp. 185–198, 2024.

[25] A. R. Abdul Syukor, A. W. Zularisam, Z. Ideris, M. S. Mohd. Ismid, S. Suryati, and A. H. Hasmanie, "Treatment of industrial wastewater at Gebeng Area using Eichornia Crassipes Sp.(Water Hyacinth), Pistia Stratiotes Sp.(Water Lettuce) and Salvinia Molesta Sp.(Giant Salvinia)," *Advances in Environmental Biology*, vol. 7, no. 12, pp. 3802–3808, 2013.

[26] W. Xu, Y. Jin, and G. Zeng, "Introduction of heavy metals contamination in the water and soil: a review on source, toxicity and remediation methods," *Green Chemistry Letters and Reviews*, vol. 17, no. 1, p. 2404235, 2024.

[27] M. M. Uddin, M. C. M. Zakeel, J. S. Zavahir, F. M. M. T. Marikar, and I. Jahan, "Heavy metal accumulation in rice and aquatic plants used as human food: A general review," *Toxics*, vol. 9, no. 12, p. 360, 2021.

[28] K. H. Hama Aziz, F. S. Mustafa, K. M. Omer, S. Hama, R. F. Hamarawf, and K. O. Rahman, "Heavy metal pollution in the aquatic environment: efficient and low-cost removal approaches to eliminate their toxicity: A review," *RSC advances*, vol. 13, no. 26, pp. 17595-17610, 2023.

[29] D. Majid, M. Al Kholif, M. N. Arif, J. Sutrisno, and J. W. Zhang, "Eco-friendly solutions for urban wastewater: evaluating constructed wetlands and filtration methods," *Advances in Environmental Technology*, vol. 11, no. 2, pp. 182–194, 2025.

[30] K. K. Lawal, I. K. Ekeleme, C. M. Onuigbo, V. O. Ikpeazu, and S. O. Obiekezie, "A review on the public health implications of heavy metals," *World Journal of Advanced Research and Reviews*, vol. 10, no. 3, pp. 255–265, 2021.

[31] F. Ismail, A. S. A. Razak, A. Z. A. M. Termizi, M. A. S. Nasarudin, and S. Sulaiman, “Enhanced phytoremediation of domestic wastewater using lepironia articulata, monochoria vaginalis and typha angustifolia: Comparative performance and efficacy,” *Construction*, vol. 4, no. 2, pp. 244–254, 2024.

[32] T. Sricoth, W. Meeinkuirt, J. Pichtel, P. Taeprayoon, and P. Saengwilai, “Synergistic phytoremediation of wastewater by two aquatic plants (Typha angustifolia and Eichhornia crassipes) and potential as biomass fuel,” *Environmental Science and Pollution Research*, vol. 25, no. 6, pp. 5344–5358, 2018.

[33] L. T. Maranho and M. P. Gomes, “Morphophysiological adaptations of aquatic macrophytes in wetland-based sewage treatment systems: Strategies for resilience and efficiency under environmental stress,” *Plants*, vol. 13, no. 20, p. 2870, 2024.

[34] Q. Wang, Y. Hu, H. Xie, and Z. Yang, “Constructed wetlands: A review on the role of radial oxygen loss in the rhizosphere by macrophytes,” *Water*, vol. 10, no. 6, p. 678, 2018.

[35] S. K. Malyan, S. Yadav, V. Sonkar, V. C. Goyal, O. Singh, and R. Singh, “Mechanistic understanding of the pollutant removal and transformation processes in the constructed wetland system,” *Water Environment Research*, vol. 93, no. 10, pp. 1882-1909, 2021.