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Phytoremediation Potential of Native Aquatic Macrophytes in Heavy Metal-Contaminated Ecosystems

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Abstract

This study assessed metal accumulation and distribution to evaluate the phytoremediation potential of native macrophytes in heavy metal-contaminated wetlands around the Sincan Organized Industrial Zone. *Phragmites australis* (Cav.) Trin. ex Steud., *Typha latifolia* L., and *Polygonum lapathifolium* L. were sampled, and Pb, Zn, Cd, Cu, Mn, and Ni concentrations in sediment and plant tissues (roots, stems, and leaves) were determined by ICP-OES. Data were analyzed using Spearman correlation and principal component analysis (PCA), while bioaccumulation (BAF) and translocation factors (TF) were calculated and differences tested by ANOVA. Heavy metal accumulation patterns differed significantly by species and tissue type rather than sediment concentrations. *P. australis* reflected sediment metal load, particularly Cu and Pb, with parallel accumulation patterns across tissues, whereas *T. latifolia* was characterized by pronounced metal–metal interactions and predominantly root-associated accumulation. *P. lapathifolium* stood out, exhibiting the highest concentrations for five of six metals, with four reaching their highest concentrations in roots (Zn, 223.68 ppm; Cu, 146.50 ppm; Pb and Cd, 7.66 ppm), and displaying metal-dependent translocation patterns. These findings indicate that macrophytes do not exhibit uniform phytoremediation behavior and that species-, tissue-, and metal-specific strategies are important for environmental monitoring, phytostabilization, and controlled phytoextraction.

Introduction

Water and soil pollution have become one of the most significant environmental problems of the 21st century, linked to increasing global population, intensive agricultural activities, technological advancements, mining, and industrialization processes. Industrial activities, which accelerated particularly with the Industrial Revolution, have resulted in waste containing heavy metals, which has become a significant source of pollution in aquatic ecosystems and stands out as one of the main problems threatening environmental sustainability (Fu et al., 2017; Dinaki et al., 2023). This process disrupts the chemical and biological balance of ecosystems, leading to reduced soil fertility and contamination of water resources.

A large proportion of inorganic pollutants, such as toxic heavy metals and radionuclides, including actinides (Sharma et al., 2015) cannot be removed from the environment by chemical or biological processes, unlike some organic pollutants (Rajakaruna et al., 2006; Tripathi and Ranjan, 2015; Yan et al., 2020) and can accumulate in soil, water, sediment, and living organisms. The accumulation of these pollutants throughout the food chain can lead to toxic effects at high trophic levels, including humans (Taylan & Özkoç, 2007; Farooq et al., 2008), through the biomagnification effect (Fu et al., 2017). When the distributions in natural environments are examined, it is seen that heavy metal concentrations are higher in soil and aquatic ecosystems compared to the atmospheric particulate phase. (Rai, 2009). Pollutants reaching surface waters interact with

water in particulate form and settle into sediments, a process that makes sediments major sinks for heavy metals and other pollutants (Sanches et al., 2015). However, this process may vary depending on environmental conditions, including pH, metal solubility, and the density of macrophytes, which may contribute to the biological uptake and retention of metals in aquatic systems.

The persistence of heavy metals in the environment increases the need for sustainable and environmentally friendly remediation approaches in the restoration of contaminated sites. Although various technologies have been developed for the remediation of environments contaminated with heavy metals (Alaboudi et al., 2018), interest in more sustainable alternative methods for the restoration of these areas has increased in recent years. In this respect, phytoremediation using plants stands out as an effective, low-cost, and environmentally friendly cleaning technology (Sharma et al., 2015; Naz et al., 2022; Saha et al., 2022). The success of phytoremediation depends on the availability of plant species with high metal tolerance and accumulation capacity (Rajakaruna et al., 2006). Recent studies highlight a shift in phytoremediation research beyond conventional plant-based remediation toward multidisciplinary and technology-driven approaches that integrate advances in biotechnology, including genome editing and omics-based approaches, with improved understanding of plant metal uptake, root biology, and plant–microorganism interactions (Acharya et al., 2025). Within this emerging framework, Wang et al. (2026) provide a comprehensive roadmap and theoretical foundation for modern phytoremediation research by emphasizing synergistic integration of genetic engineering, microbiology, nanotechnology, and soil chemistry.

Wetland macrophytes are reliable bioindicators due to their sediment-rooted growth habit, their capacity to accumulate chemical substances in their tissues, and their ability to reflect environmental conditions through long-term exposure to pollutants (Ghosn et al., 2020; Serafini et al., 2023). In addition, due to their broad environmental tolerance and high growth and biomass production capacities, they are widely used in phytoremediation applications aimed at monitoring and removing pollutants accumulated in aquatic environments (Kumar et al., 2008; Fu et al., 2017; Muthusaravanan et al., 2018; Özçelik & Tekin-Özan, 2023).

The potential of plants to remove pollutants from the environment varies among species depending on their capacity to accumulate heavy metals and the levels of tolerance they develop against these metals (Sharma et al., 2015). In the selection of macrophytes to be used in phytoremediation, morphological and physiological characteristics involved in the uptake and transformation of pollutants are decisive, in addition to growth traits. In this context, species with a well-developed root–shoot system, capable of tolerating multiple pollutants and exhibiting high metal-binding capacity, provide an advantage. In aquatic plants, metal accumulation behavior may differ among tissues; in some species accumulation is concentrated in roots, whereas in others translocation to shoot tissues may be more pronounced. (Kumar et al., 2008). While species- and tissue-specific metal uptake is important in phytoremediation, how naturally occurring macrophytes differ in metal accumulation and translocation remains poorly understood. We hypothesized that the three macrophyte species would exhibit distinct metal accumulation and translocation patterns, reflecting differences in their phytoremediation potential. Accordingly, this study aimed to (i) determine the tissue-specific distribution of Pb, Zn, Cd, Cu, Mn, and Ni in Phragmites australis, *Typha latifolia*, and *Polygonum lapathifolium*; (ii) examine sediment–plant metal relationships and overall accumulation patterns; and (iii) evaluate their phytoremediation potential using BAF and TF.

Materials and Methods

Study Area

The study area consists of five stations identified along the Ankara Stream, which flows through the Sincan Organized Industrial Zone, an area under environmental pressure due to intensive industrial activities (Figure 1). The distance between stations was planned to be approximately 750 m, taking into account the density of riparian macrophytes, flow velocity associated with the stream gradient, and the occurrence of stagnant or pooled water sections. The hydrological structure of the study area is shaped by the point where the Çubuk Streammerges with the Hatip Streamto form the Ankara Stream. The Ankara Stream can be used to irrigate surrounding agricultural areas and may facilitate the transport of potential pollutants through aquatic environments and the food chain. For this reason, the study area was chosen as a representative system for evaluating the impacts of industrial activities on aquatic ecosystems.

Sample Preparation and Chemical Analysis

As part of the study, plant samples of the naturally dominant species *T. latifolia*, *P. australis*, and *P. lapathifolium* were collected at each station simultaneously with bottom sediment samples. Sampling was carried out in shallow areas suitable for the growth of *P. lapathifolium*, where water depth at the sampling sites ranged from approximately 0 to 50 cm. At each station, three samples were randomly collected from the superficial sediment (0–10 cm). Plant samples were washed in the laboratory, separated into root, stem, and leaf tissues, dried at 65°C for 48 hours, and ground. A total of 45 plant tissue samples were prepared

from different organs of plant samples obtained from five stations. Sediment samples were dried and passed through a 2 mm sieve prior to elemental analysis. For elemental analysis of plant samples, approximately 0.5 g of dried and ground material was subjected to closed-vessel microwave-assisted acid digestion. Samples were digested using 10 mL of concentrated nitric acid (65%, Merck) in accordance with EPA Method 3052. Following digestion, the solutions were cooled, diluted to volume with ultrapure water, filtered through Whatman filter paper, and elemental concentrations were determined using an ICP-OES (Varian 720 ES).

Calculations of Bioaccumulation and Translocation Factors

To evaluate the capacity of three macrophyte species selected from the study area to accumulate metals in sediments and translocate them from roots to shoot organs, the bioaccumulation factor (BAF) and translocation factor (TF) were calculated. These indices were computed to quantitatively assess the uptake of metals from sediments and their internal transport within plant tissues.

The bioaccumulation factor (BAF) was defined as the ratio of the metal concentration in plant tissues to the metal concentration in sediments collected from the same sampling point and was calculated using the following equation (Alhaithloul et al., 2024). In this study, metal contents in different plant tissues were considered for BAF calculations:

$$BAF = C_{\text{plant tissue}} / C_{\text{sediment}}$$

The translocation factor (TF) was defined as the ratio of the metal concentration in the shoot organs to that in the roots, indicating the efficiency of metal transport from roots to shoots (Yoon et al., 2006; Netshiongolwe et al., 2020):

$$TF = C_{\text{shoot}} / C_{\text{root}}$$

Statistical Analysis

All statistical analyses were performed using the R programming language (version 4.5.1). Data analysis and visualization were performed using the ggplot2, tidyverse, vegan, ggrepel, reshape2, stats, emmeans, and multcomp packages. Species-based Spearman rank correlation analysis was applied to determine the relationships between heavy metal concentrations in plant tissues and metal concentrations in sediments from the stations where the plants were collected.

To examine the relationships of heavy metals in plant tissues with plant species, plant organs, and station factors, multivariate ordination (Principal Component Analysis, PCA) and permutation-based analysis of variance (PERMANOVA) were applied. The multivariate dispersion assumption of PERMANOVA was tested using the betadisper and permutest.betadisper functions in the vegan package. The relationships between heavy metal concentrations in sediments and metals in plant tissues were evaluated using ENVFIT

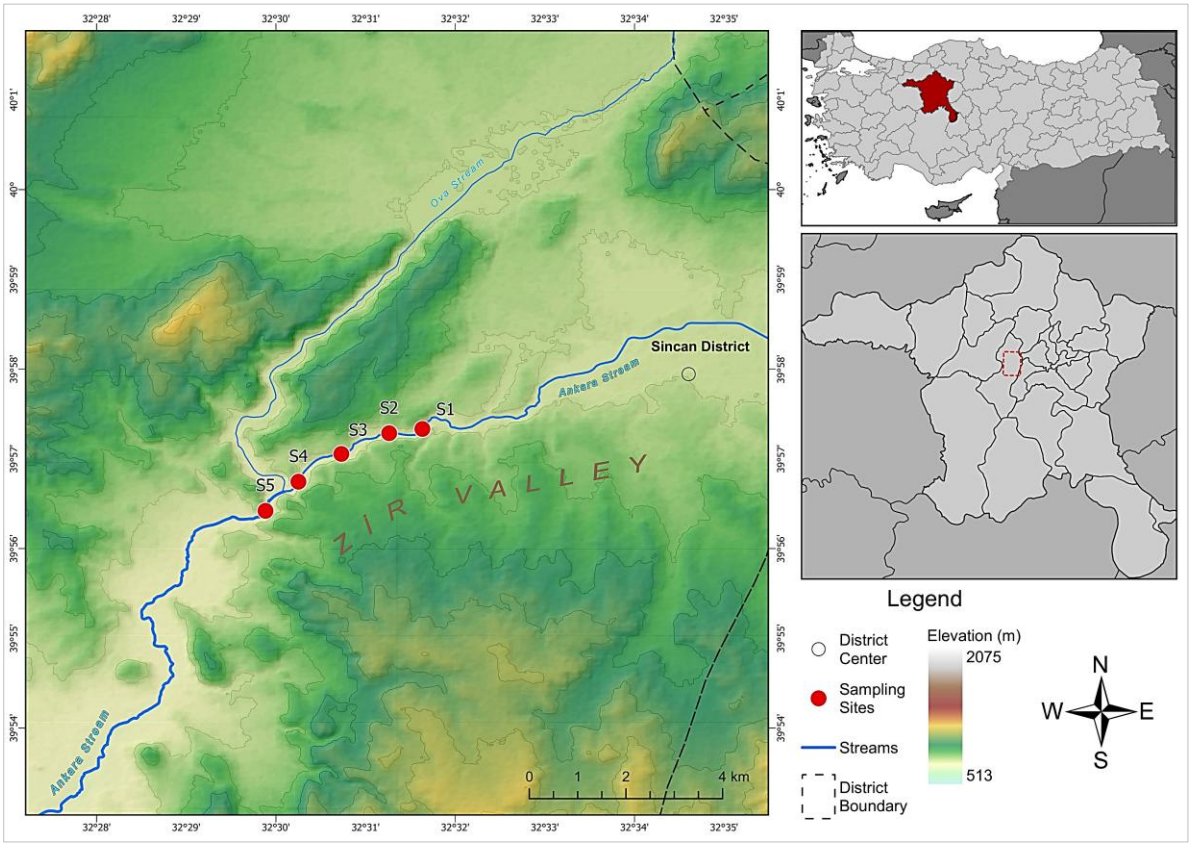

Figure 1. Map of the study area (sampling sites used in this study are marked in red).

analysis, which was incorporated into PCA ordination as environmental vectors. Tissue heavy metal concentrations were subjected to log10 transformation to reduce right-skewness in the distribution, and a small positive constant was added to zero values to enable calculation. These transformed values have been used in all multivariate analyses.

Additionally, BAF, which indicates heavy metal accumulation, and TF, which indicates the transport of the related metals, were given as mean±standard error. To improve the distributional properties of these values, a log10 transformation was applied, and ANOVA assumptions were evaluated by examining the distribution of model residuals. Two-way ANOVA models including plant species and plant organ were applied for each heavy metal in BAF values, while one-way ANOVA was used to test interspecific differences in TF values. Significant differences among groups were assessed using Tukey's HSD multiple comparison test. All statistical analyses were performed at a significance level of $P<0.05$.

Results

In order to determine heavy metal pollution in plant samples (root, stem and leaves) and sediment from Ankara Stream flows through the Industrial Zone, the levels of total Cu, Zn, Pb, Ni, Mn and Cd elements were analyzed. The heavy metal concentrations (Cd, Cu, Mn, Ni, Pb, Zn) determined in plant and soil samples collected from five stations in the research area are given in Figure 2. Metal accumulation in macrophyte species varied depending on the species, metal, and tissue type. Mn, Zn, and Cu were determined to have the highest concentrations; Ni had medium concentrations, while Cd and Pb had the lowest concentrations. *P. lapathifolium* showed the highest accumulation for all metals, while Mn was particularly concentrated in leaf tissues. *P. australis* was observed to accumulate other metals in the roots, except for Cd. In *T. latifolia,* accumulation was generally concentrated in the roots, while Ni and Zn were mainly detected in the leaves. Cd and Pb were predominantly retained in the roots of all species.

When considering the average values obtained at each station, the heavy metal concentrations measured in sediment samples showed the following order: Mn>Zn>Cu>Ni>Cd=Pb. Furthermore, sediment concentrations were found to be higher than plant tissue levels for all metals examined (Figure 2).

Analysis of Correlation Between The Accumulation of Heavy Metals and Sediment

Spearman correlation matrices revealed complex relationships between heavy metal concentrations across different plant compartments and sediments, separately for each plant species. According to

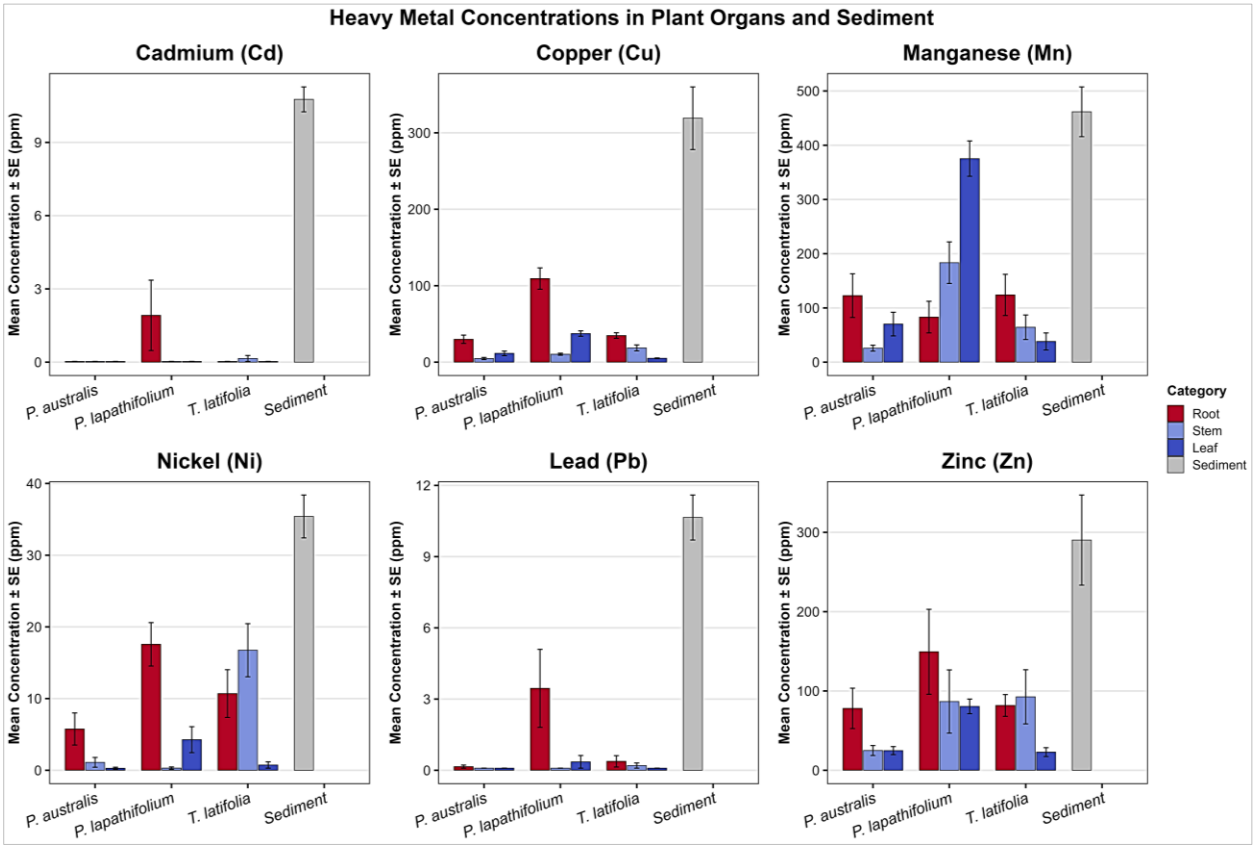

Figure 2. Heavy metal (Cd, Cu, Mn, Ni, Pb, Zn) concentrations measured in plant tissues (roots, stems, leaves) at the studied stations and in sediment samples.

Spearman correlation analysis, strong positive relationships were identified in *P. australis* between sediment Cu concentration and Cu levels in root, stem, and leaf tissues, with P=0.900 (P<0.05), P=0.900 (P<0.05), and P=1.000 (P<0.001), respectively. A very high positive correlation was also found between sediment Cd and sediment Pb (P=1.000, P<0.001). A strong positive correlation was found between stem Zn and sediment Mn (P=0.900, P<0.05), while similarly strong positive correlations were observed between leaf Cu and root and stem Cu levels (P=0.900, P<0.05). A strong positive correlation was found between stem Zn and sediment Mn (P=0.900, P<0.05), while similarly strong positive correlations were observed between leaf Cu and root and stem Cu levels (P=0.900, P<0.05). Leaf Mn showed a very high positive correlation with stem Ni (P=0.975, P<0.01); conversely, it exhibited a strong negative relationship with root Cu (P=–0.900, P<0.05). A similar negative relationship was also identified between sediment Ni and sediment Mn. These findings indicate that *P. australis* strongly reflects sediment–tissue relationships particularly for Cu, Cd, and Pb, while the negative associations observed for the Mn–Ni and Mn–Cu pairs point to species-specific metal selectivity (Figure 3).

Spearman correlation analysis performed on *T. latifolia* revealed a very strong positive correlation between sediment Cd and Pb (P=1.000, P<0.001; Figure 4). The positive correlation between sediment Cu and root Cu (P=0.900, P<0.05) supports Cu uptake by

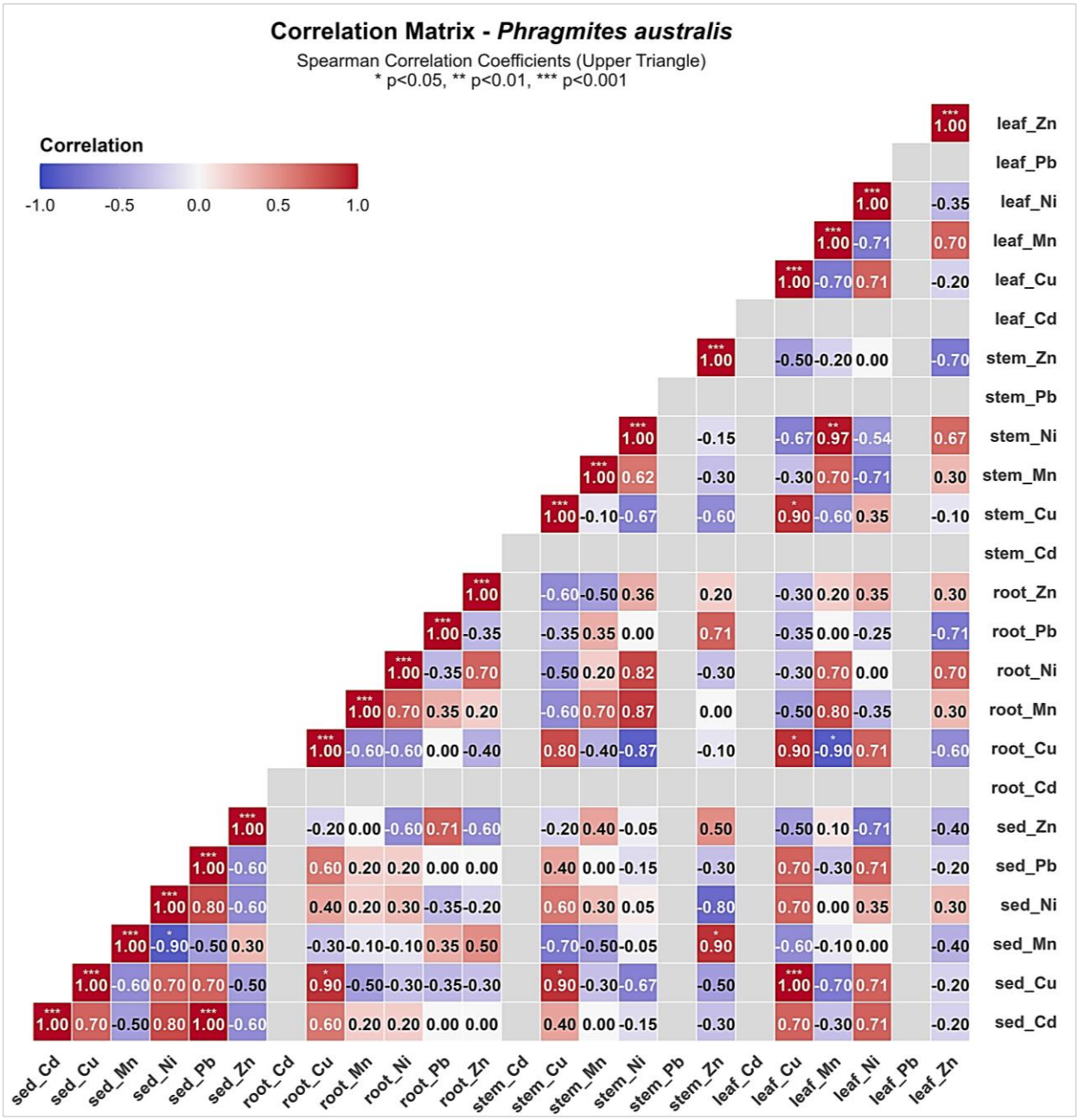

Figure 3. Spearman correlation heatmap illustrating the relationships between heavy metal concentrations in root, stem, and leaf tissues of *P. australis* and sediment metal levels at the sampling stations. Statistical significance is indicated at three levels (*P<0.05; **P<0.01; ***P<0.001).

roots, while the negative relationship with leaf Zn (P=– 0.900, P<0.05) indicates tissue-specific metal interactions. Leaf Mn showed a very strong positive correlation with root Mn (P=1.000, P<0.001) and a positive correlation with stem Ni (P=0.900, P<0.05); conversely, it showed a strong negative correlation with leaf Cu. Ni in the stem exhibited a positive correlation with Mn in the roots (P=0.900, P<0.05), whereas it showed a negative correlation with Cu in the stem (P=– 0.900, P<0.05), indicating transport-level interactions among these metals. Furthermore, the very strong positive correlation between stem Pb and stem Cd (P=1.000, P<0.001) indicates that these metals exhibit parallel behavior in plant tissue as well. A strong positive correlation was observed between leaf Ni and sediment Zn concentrations (P=0.894, P<0.05), indicating a consistent association between these variables. Negative correlations identified between the sediment Mn– sediment Ni, root Zn–sediment Ni, and stem Ni–stemCu pairs (P=–0.900, P<0.05) reveal the presence of inverse accumulation patterns among certain metals.

Spearman correlation analysis performed for *P. lapathifolium* revealed that the most significant relationships occurred at the sediment level (Figure 5). The very strong positive correlation between sediment Cd and both sediment Pb and root Cd (P=1.000, P<0.001) indicates that these metals behave in parallel in plant

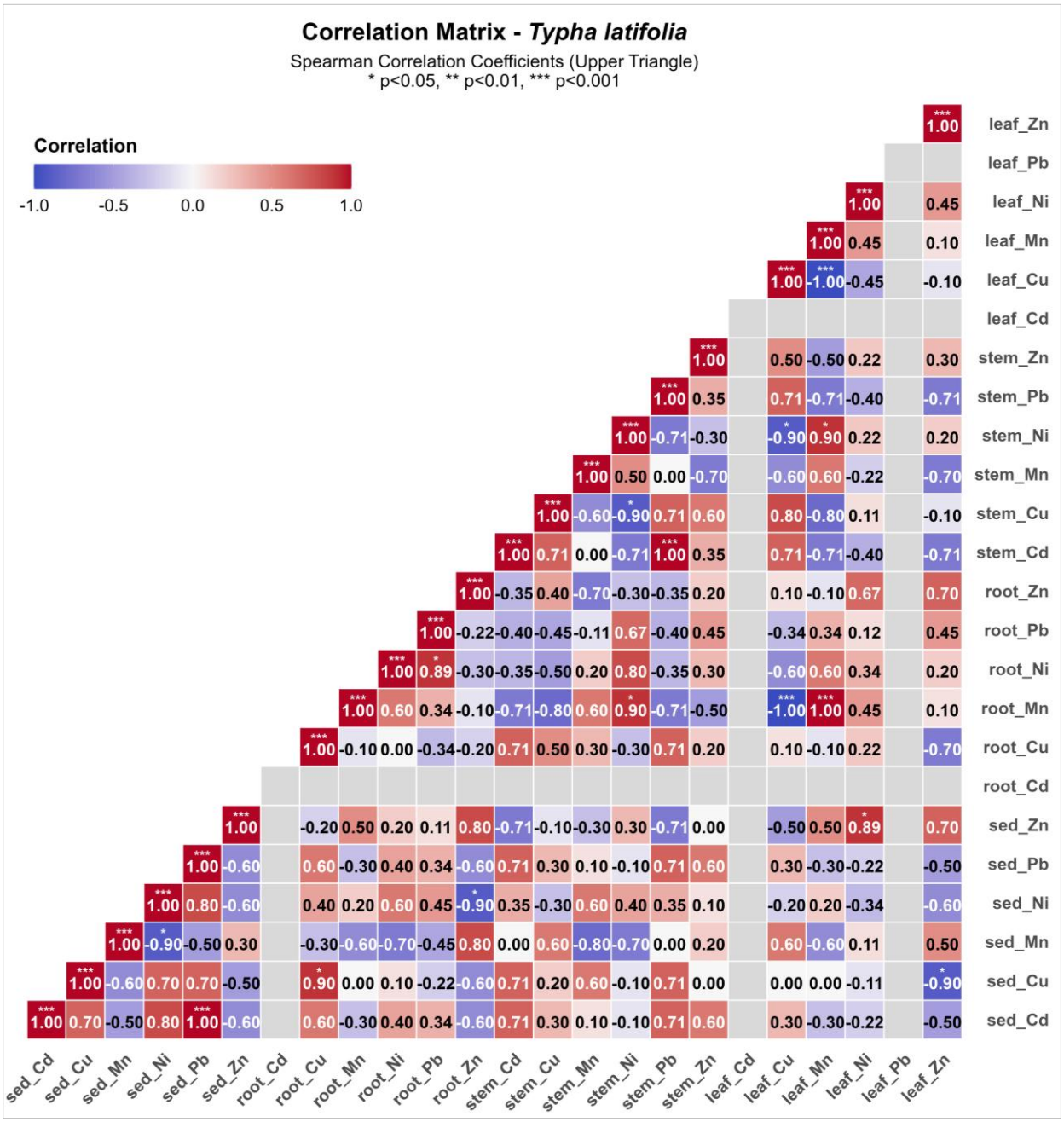

Figure 4. Spearman correlation heatmap illustrating the relationships between heavy metal concentrations in root, stem, and leaf tissues of *T. latifolia* and sediment metal levels at the sampling stations. Statistical significance is indicated at three levels (*P<0.05; **P<0.01; ***P<0.001).

uptake processes. Sediment Cd also showed strong positive associations with leaf and root Ni and root Cu (P=0.900, P<0.05). Sediment Cu showed a positive correlation with leaf and root Cu (P=0.900, P<0.05), while it exhibited a negative relationship with leaf Zn (P=–0.900, P<0.05). The positive correlation of sediment Mn with leaf Mn (P=0.900, P<0.05) and the negative correlation with sediment Ni (P=-0.900, P<0.05) reveals that these two metals may exhibit contrasting behavior in sediment-to-plant transfer. The strong positive relationship between sediment Ni and leaf Ni, root Ni, and root Cu (P=0.900, P<0.05) supports the view that the metal follows a consistent accumulation pattern within the plant. The very strong correlation of sediment Pb with root Cd (P=1.000, P<0.001) and its positive relationships with leaf Ni, root Ni, and root Cu (P=0.900, P<0.05) suggest that this metal exhibits parallel behavior in sediments and plant tissues. Furthermore, the negative correlation between sediment Zn and stem Zn (P=-0.900, P<0.05) indicates tissue-specific distribution differences in Zn.

In *P. lapathifolium,* root tissue was identified as the tissue that responds most strongly to sediment metals. Root Cd showed strong positive correlations with root Cu, root Ni, and leaf Ni (P=0.900, P<0.05). The very strong positive correlation between root Ni and leaf Ni (P=1.000, P<0.001) indicates that the metal is effectively transported from roots to leaves.

The positive correlations between root Mn and stem Cu, as well as between root Cu and stem Cu

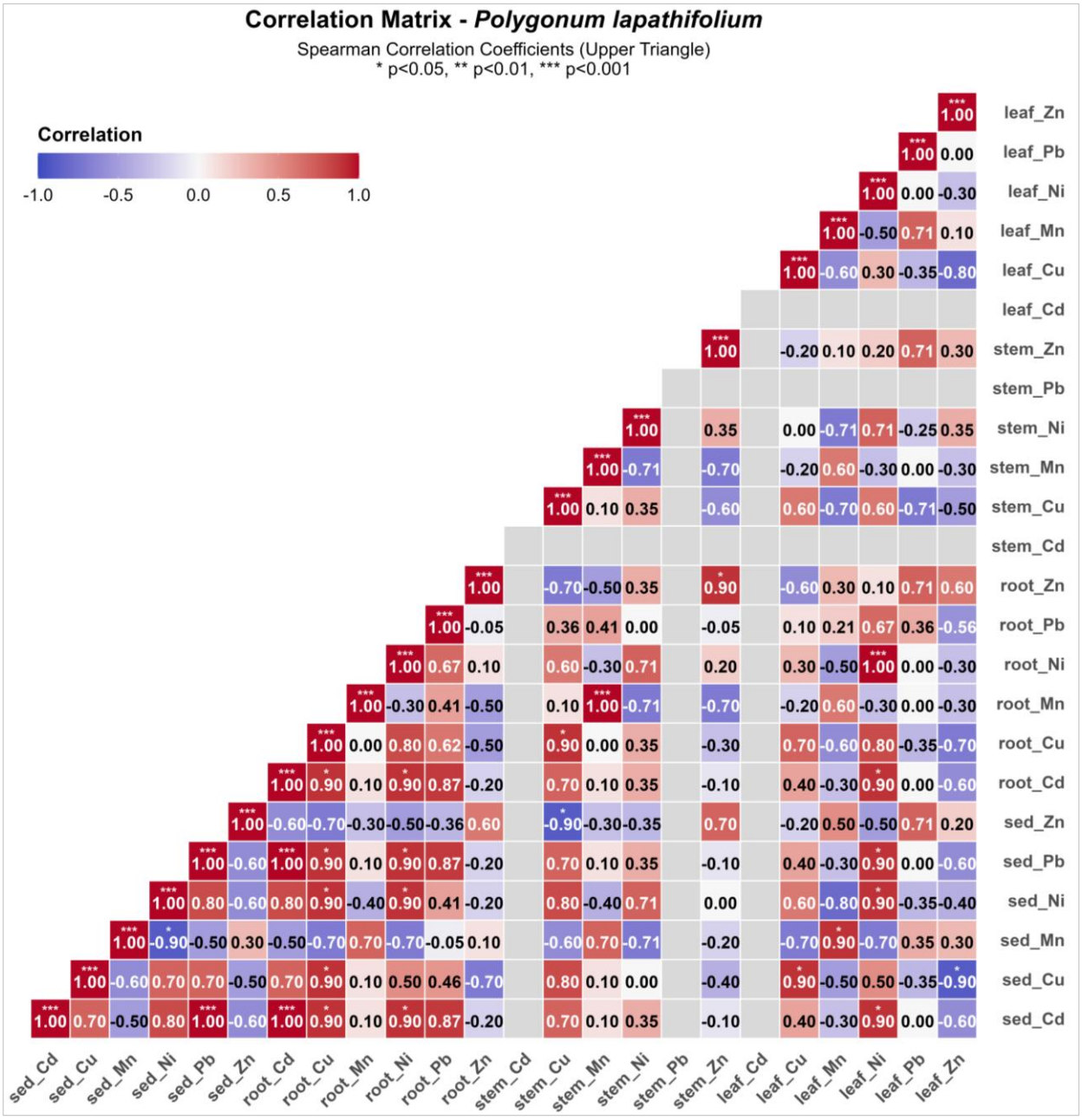

Figure 5. Spearman correlation heatmap illustrating the relationships between heavy metal concentrations in root, stem, and leaf tissues of *P. lapathifolium* and sediment metal levels at the sampling stations. Statistical significance is indicated at three levels (*P<0.05; **P<0.01; ***P<0.001).

(P=0.900, P<0.05), indicate that Cu exhibits a consistent and predictable distribution within the plant (Figure 5). On the other hand, root Zn showed a significant relationship only with stem Zn (P=0.900, P<0.05). While a limited number of significant correlations were identified in stem tissue, Ni was particularly noteworthy in leaf tissue. The strong positive correlations of leaf Ni with sediment Cd, Ni, and Pb, as well as with root Cd and root Ni, indicate that metal loading is effectively transferred from sediments to aerial tissues.

Multivariate Analysis of Heavy Metal Accumulation Patterns

PCA analyses were applied to evaluate how these relationships form a pattern in a multivariate structure. Accordingly, this has shown that the majority of the variation in plant tissues is explained by the first two components (Figure 6). PC1 explains 51.5% of the total variance, and PC2 explains 20.3%, together accounting for 71.8% of the total variance. This situation demonstrates that heavy metal accumulation exhibits a distinct multivariable structure according to species–organ–station combinations. All metals exhibited positive loadings on PC1, and since Cu, Ni, Pb, Cd, and Zn contributed particularly high loadings, PC1 was interpreted as the dominant gradient representing the "total heavy metal load" (PC1 loading: 1.37 for Cu; 1.29 for Ni; 1.29 for Pb). On the PC2 axis, Cd and Pb are positive, while Mn and Zn exhibit distinct negative charges, creating a secondary separation between Cd–Pb-rich tissues and Mn–Zn-dominant tissues.

The PCA biplot (Figure 6) revealed a distinct separation of plant organs in ordination space. Root samples were mostly clustered on the positive side of PC1 and were associated with higher total heavy metal accumulation, following the direction of high loadings for Cu, Ni, Pb, and Cd. On the other hand, leaf samples, with relatively negative PC1 scores, represented low-metal-load samples, while stem samples were positioned between these two extremes. A partial divergence has also been observed between species. The positioning of some *P. lapathifolium* and *T. latifolia* root samples away from the axis along the Cd, Pb, Cu, and Ni vectors indicated tissue profiles enriched in these metals. The PC2 axis, in turn, reflects a secondary compositional gradient separating tissues enriched in Cd–Pb from those dominated by Mn–Zn.

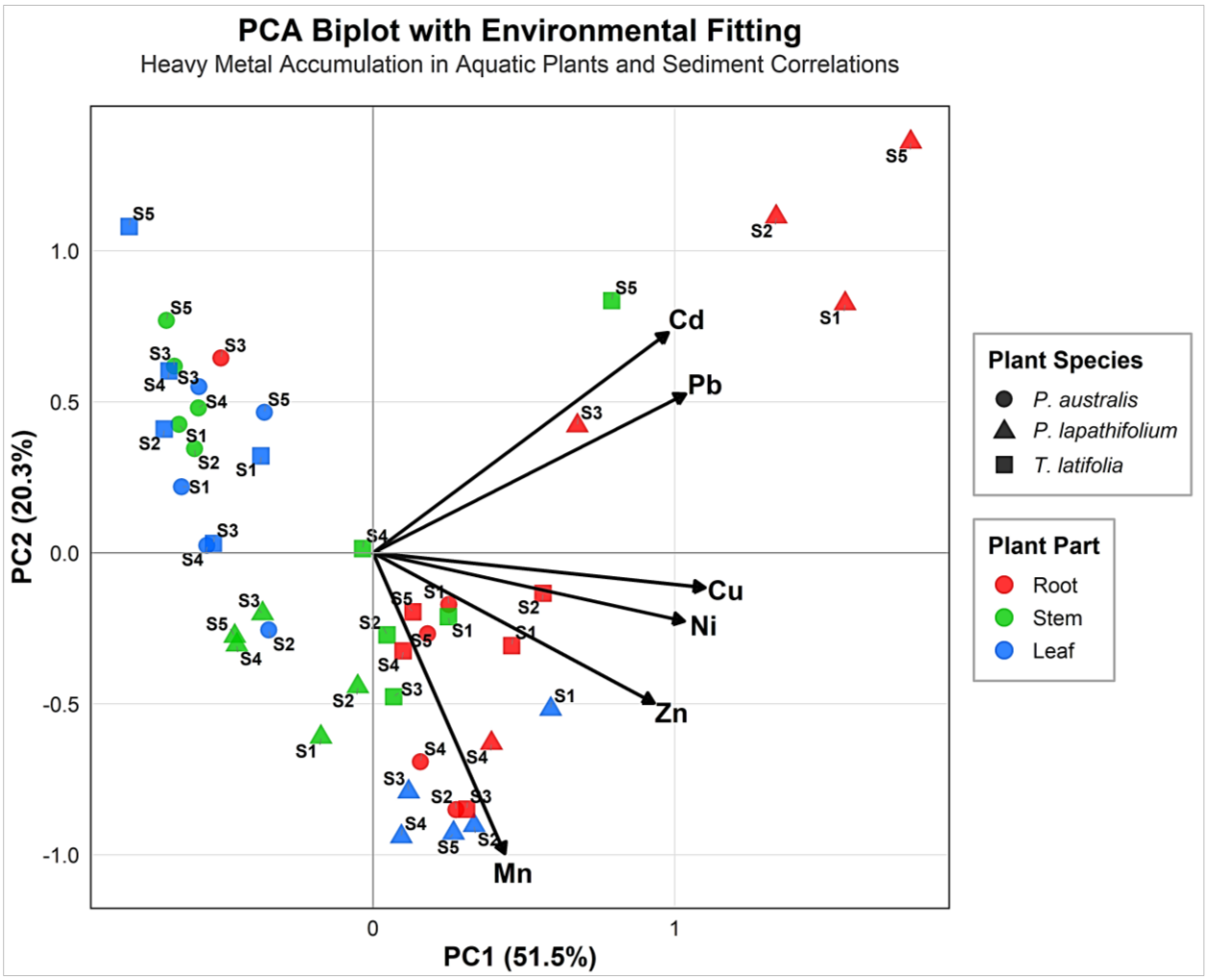

Figure 6. PCA biplot showing heavy metal accumulation patterns in plant tissues and their relationships with sediment metal concentrations (with envfit vector fitting).

PCA and PERMANOVA analyses indicated that sediment metals are strongly reflected in plant tissues, with root tissues providing particularly significant metal retention. The results revealed that heavy metal accumulation in plant tissues differed significantly depending on biotic factors. According to the analysis results, plant species produced significant differences in metal accumulation ($F=3.98$, $R^2=0.159$, $P=0.003$) and was found to explain approximately 16% of the total variance. The plant organ factor exhibited the strongest effect, with significant differences in metal accumulation detected among root, stem and leaf tissues ($F=6.64$, $R^2=0.240$, $P=0.001$), explaining 24% of the variance. In contrast, no significant differences in metal accumulation were observed among the sampling stations ($F=0.83$, $R^2=0.076$, $P=0.593$), indicating that spatial variability did not play a determining role in heavy metal distribution. Marginal tests from the multiple model evaluating species, organ, and station together also confirmed this pattern, indicating that plant organ was the most dominant explanatory variable for metal accumulation ($F=8.25$, $R^2=0.240$, $P=0.001$). The BETADISPER test indicated no multivariate dispersion differences among plant species ($F=2.04$, $P=0.131$), plant organs ($F=0.38$, $P=0.686$), and stations ($F=0.56$, $P=0.709$). Thus, the homogeneity of dispersion assumption for PERMANOVA was met for all factors, confirming that the results were not affected by dispersion heterogeneity.

ENVFIT analysis, however, showed that sediment metals could not meaningfully explain the metal composition in plant tissues. None of the sediment metals showed a statistically significant relationship with the PCA axes (all $P>0.05$). Therefore, sediment metal concentrations did not constitute a primary environmental gradient driving metal accumulation patterns in plant tissues; instead, the observed variation was more strongly associated with species- and organ-specific characteristics. Although sediment metal concentrations showed some numerical variation among sampling stations, no consistent site-specific enrichment pattern was evident across metals. Similarly, sampling station did not significantly explain the overall variation in heavy metal accumulation patterns in plant tissues (PERMANOVA, $P>0.05$).

Calculation of Metal Indices: Bioaccumulation Factor (BAF) and Translocation Factor (TF)

One-way ANOVA results showed significant differences in TF values for Cd ($F=10.29$, $P=0.0025$), Mn ($F=47.98$, $P<0.001$), and Ni ($F=11.74$, $P=0.0015$) varied significantly depending on plant species, whereas no significant difference was found between species for Pb, Zn, and Cu ($P>0.05$). When species averages were examined, the TF values for Cd in *P. lapathifolium* averaged 0.23±0.19, which was significantly lower than the other two species ($P<0.05$, Figure 7). The highest TF value was determined in *T. latifolia*, with an average of 3.03±2.03. For Ni metal, TF values were determined to be significantly higher in *T. latifolia* compared to both other species (average 0.95±0.17, $P<0.05$). Additionally, the Tukey test showed that *P. lapathifolium* had significantly higher Mn TF values than the other two species (average 4.72±1.04, $P<0.001$). According to these analysis results, *P. lapathifolium* was found to be particularly prominent in Mn translocation, while *T. latifolia* was prominent in Ni translocation. *T. latifolia* and *P. australis* were identified as effective species in the transport of Cd from roots to above-ground plant organs.

Results of two-way ANOVA results, the bioaccumulation levels of heavy metals differed significantly among plant species and plant parts (Figure 7). BAF values varied significantly for Cd according to plant species ($F=6.65$, $P<0.05$), plant parts ($F=6.65$, $P<0.05$), and the combined effect of both factors ($F=9.08$, $P<0.001$). Post-hoc comparisons revealed that root tissues of *P. lapathifolium* had significantly higher BAF values for Cd than other species and tissues ($P<0.001$). In contrast, no notable differences among species were observed in stem and leaf tissues ($P>0.05$).

ANOVA results for BAF values of Cu identified that plant species ($F=61.52$, $P<0.001$), plant organs ($F=124.59$, $P<0.001$), and the interaction of both factors ($F=25.02$, $P<0.001$) were highly significant (Figure 7). The highest Cu accumulation was observed in the root tissue of *P. lapathifolium*, which, according to Tukey test data, was significantly higher than the BAF values in the root tissues of *P. australis* and *T. latifolia* species ($P<0.001$). For *P. australis*, Cu accumulation in the stem is significantly lower than BAF values in both species ($P<0.05$). BAF values, which represent Cu accumulation in leaves, differed significantly among the three species, with the highest BAF value observed in *P. lapatifolium* (average 0.120±0.01).

When BAF values were examined for Mn metal accumulation, ANOVA results showed that the effect of plant species was significant ($F=11.71$, $P<0.001$), while the effect of plant parts was insignificant ($P>0.05$) On the other hand, the interaction between plant species and plant parts was also determined to be statistically significant ($F=7.23$, $P<0.001$). The highest Mn-BAF value was observed in the leaf tissues of *P. lapathifolium* (mean 0.819±0.04), which was significantly higher than the values in the leaves of *P. australis* and *T. latifolia* ($P<0.001$). According to the analysis of variance, BAF values for Ni were found to vary significantly with both species ($F=10.23$, $P<0.001$) and plant part ($F=24.12$, $P<0.001$) as well as the combined effect of both factors ($F=12.10$, $P<0.001$; Figure 7). Root tissue of *P. lapathifolium* and stem tissue of *T. latifolia* exhibited the highest BAF values for Ni (respectively 0.49±0.06 and 0.47±0.08). The Tukey test revealed that the stem tissue of *T. latifolia* accumulated significantly higher levels of Ni than the stem tissues of *P. australis* and *P. lapathifolium* ($P<0.001$). Tukey test for BAF values in

root tissue showed that the three species had similar BAF levels for Ni (P>0.05). The highest BAF value for Ni in leaf tissue was observed in *P. lapathifolium* (0.11±0.04), showing a significant difference from *P. australis* (P<0.05) but not from *T. latifolia* (P>0.05).

Two-way ANOVA analysis showed that BAF values for Pb varied according to plant species (F=3.48, P=0.0417) and plant parts (F=5.68, P=0.0072; Figure 7). The highest BAF values for this metal were detected in the root tissue of *P. lapathifolium*, and this value is significantly higher than that of *P. australis* root tissue (P<0.05). There was no significant difference between species in other tissues (P>0.05).

The variance analysis for Zn showed that both species (F=6.31, P<0.05) and plant parts (F=5.67, P<0.05) had a significant effect on BAF values (Figure 7). For this metal, the highest BAF value was observed in the root tissues of *P. lapathifolium* (mean 0.50±0.11); however, BAF values in root tissues did not differ significantly among the three species (P>0.05). Additionally, a significant difference in BAF values was not observed between species in stem and leaf tissues (P>0.05).

When BAF values for heavy metals were evaluated overall, the root tissues of *P. lapathifolium* were found to exhibit higher bioaccumulation capacity for Cd, Cu, Ni, Pb, and Zn (Figure 7). *T. latifolia* stands out particularly in terms of Ni accumulation in the stem, while *P. australis* showed relatively low bioaccumulation in all metals. In general, BAF values have varied across all metals depending on the plant species. The effect of the plant part was found to be significant in all metals except Mn (P<0.05). In addition, the interaction between plant species and plant part is statistically significant for Cd, Cu, Mn, and Ni (P<0.05). The fact that BAF values remained below 1 for all metals indicates that the transfer of metals from sediments to plant tissues is limited in these species.

Discussion

The Ankara Stream and its associated river systems represent suitable aquatic ecosystems for monitoring anthropogenic metal pollution, and several previous studies have investigated metal concentrations in their waters (Girgin et al., 2010; Kayadelen and Demir, 2024). Comparison of these water data with a previous sediment study from Ankara Stream (Eker and Özkan, 2017) showed that the relative metal rankings were generally not similar between water and sediment. However, Cd occurred at relatively low levels in both previous water and sediment studies, consistent with the sediment results of the present study. This difference may be related to differences in metal solubility, interactions with suspended matter, sedimentation behavior, and chemical stability, which may prevent water-column metal patterns from being directly reflected in sediment accumulation.

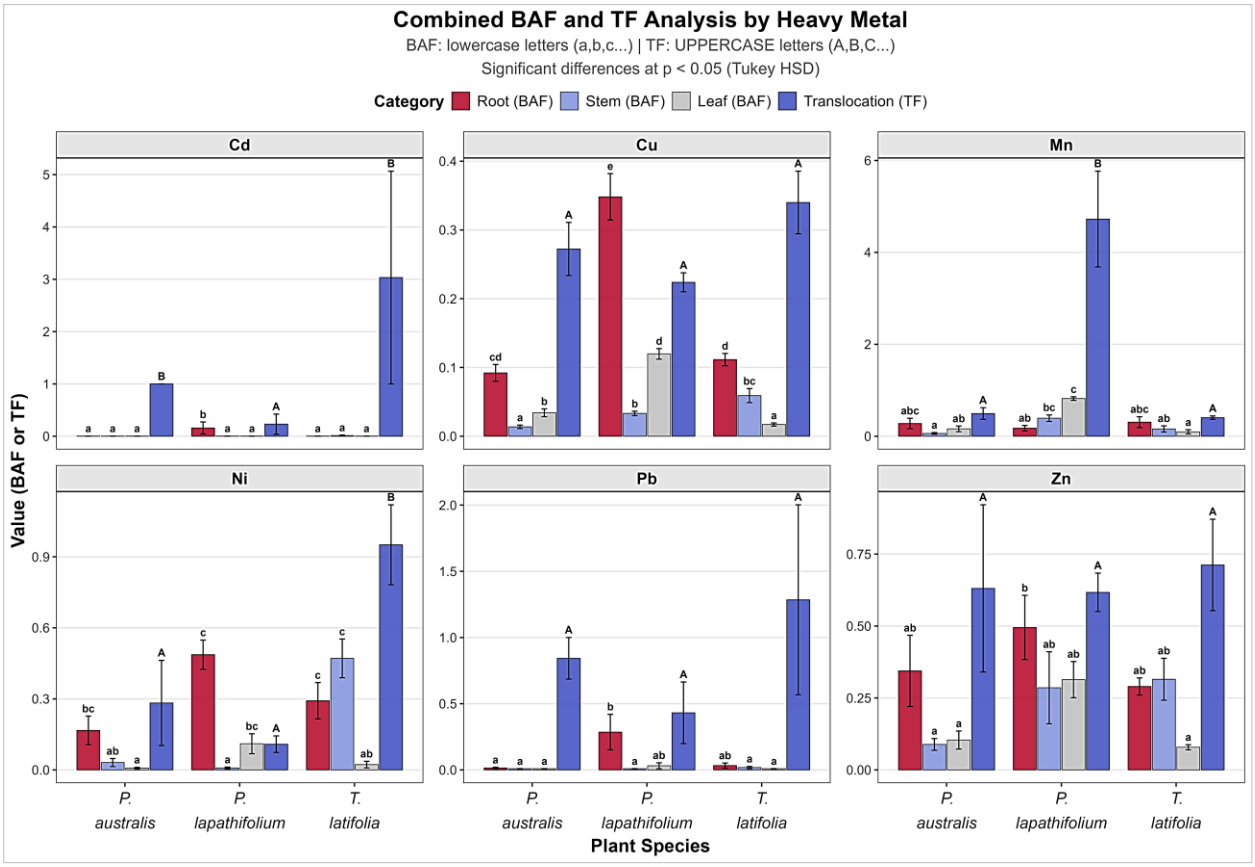

Figure 7. Comparative BAF (root, stem, leaf) and TF values for Cd, Cu, Mn, Ni, Pb and Zn in *P. australis*, *P. lapathifolium*, and *T. latifolia* (Mean±SE). Different lowercase letters (for BAF) and uppercase letters (for TF) indicate statistically significant differences (Tukey HSD, P<0.05).

The strong positive correlation between sediment Cu and all plant organs in *P. australis* indicates that the species is highly sensitive to environmental copper levels and that sediment Cu load directly drives its accumulation in the plant. Effective metal transport from roots to above-ground organs is consistent with Klink et al. (2019), who reported that *P. australis* is a reliable bioindicator reflecting sediment metal levels. This parallel accumulation pattern supports the species' potential in monitoring Cu pollution and in phytoremediation applications. Similarly, the strong positive correlation between Pb and Cd in *P. australis* sediments indicates that these metals can accumulate together from common contaminant sources or through similar geochemical binding processes. (Baran & Tarnawski, 2015; Zhang et al., 2024).

In *T. latifolia,* the accumulation of Mn, Cu, and Pb in the roots, and Ni, Zn, and Cd primarily in the stem tissue, indicates that the species follows a tissue-selective strategy for metal uptake and distribution. This finding is consistent with a study reporting that Cd can accumulate in the upper tissues due to its high mobility, while many other metals are retained in the roots. (Parzych & Sobisz, 2018). This distribution pattern, characterized by the preferential accumulation of Mn, Cu, and Pb in the roots, suggests a tendency toward phytostabilization, as the retention of these metals in belowground tissues may limit their movement to aboveground plant parts. Pb and Cd are known to be translocated to and accumulated in the stems of *T. latifolia* (Klink et al., 2016). Our findings revealed a positive correlation between Pb and Cd concentrations in the stems, suggesting that these metals may exhibit a closely associated accumulation pattern. Consistently, a positive correlation between Pb and Cd has also been reported in a study of aquatic macrophytes (Abdelaal et al., 2021).

Spearman correlation analyses revealed that within-plants metal interactions are more dominant than sediment-to-plant interactions in *T. latifolia*. The strong positive relationship between Mn and Ni suggests that these metals may share similar uptake and translocation mechanisms (Saşmaz, 2008; Klink, 2016), whereas the negative relationship between Cu and Mn indicates the presence of physiological competition mechanisms (Parzych & Sobisz, 2018). These patterns demonstrate that metal uptake and tissue distribution in *T. latifolia* are regulated by synergistic and antagonistic interactions, which determine the species' potential for phytoremediation and bioindicator applications.

The strong positive correlations between *P. lapathifolium* sediment metals and especially root Cd, Cu, and Ni indicate that metal accumulation in the roots closely reflects metal concentrations in the sediment. Kim et al. (2003) similarly determined a positive correlation between lead, copper, and zinc content in plant tissues and habitat soil of P. thunbergii. They also stated that the bioaccumulation of cadmium, lead, copper, and zinc was highest in the root tissue. The strong correlation between sediment Cd and Pb supports the possibility that these metals may be linked to common sources of contamination (Bai et al., 2011). The limited presence of Zn and its negative correlation in some tissues suggest that this metal may have competitive or independent transport pathways within the species (Li et al., 2020). Furthermore, the strong reflection of sediment and root metals by Ni in the leaf tissue indicates that Ni has high mobility.

PCA results revealed that variation in heavy metal accumulation originate more from physiological differences at the plant species and organ level than from sediment concentrations. These results are consistent with Netshiongolwe et al. (2024), who reported that the metal composition of macrophytes in polluted wetlands is greatly controlled by physiological processes.

The fact that Cd and Pb show positive charges and Mn and Zn show negative charges on the PC2 axis suggests that different metal groups are separated. The association of Cd and Pb reflects heavy metal pressure related to industrial and urban inputs (Loska et al., 2003), whereas the separation of the Mn–Zn group indicates that macrophytes have developed different accumulation strategies for essential and toxic metals. (Kabata-Pendias & Pendias, 2000).

The fact that Cd and Pb predominantly exhibit phytostabilization, while Mn and Zn display more mobile bioindicator behavior, indicates that toxic and essential metals follow different uptake and translocation strategies in plants (Di Toppi & Gabbrielli, 1999; Broadley et al., 2012). The ability of non-essential metals to enter plant cells by interacting with essential metal transport systems explains why the Cd–Pb and Mn–Zn metal groups observed in the PCA exhibit distinct accumulation patterns across tissues (Clemens, 2006; Huang et al., 2024). In addition, the regulation of essential metals such as Mn and Zn through homeostatic mechanisms indicates that these metals can either be retained in photosynthetic tissues depending on the species or stabilized in roots to protect aboveground tissues (Page & Feller, 2015).

The association of *P. lapathifolium* roots with Cd and Pb on the PC2 axis indicates that these metals are retained in root cells and their transport to shoots is limited, revealing that the species has a distinct phytostabilization potential (Clemens, 2006). Low translocation potential and high bioaccumulation in roots are associated with advanced detoxification mechanisms linked to the retention of heavy metals in root tissues (Klink, 2016; El-Amier et al., 2020).

When BAF and TF indices were evaluated together, it was observed that plant species was a determining factor in the translocation behavior of Cd, Mn, and Ni. The high TF values for Cd in *T. latifolia* indicate that this species efficiently transports Cd from the roots to the upper organs, and consistent with the translocation capacity reported in Typha species (Rolón-Cárdenas et

al., 2022). For Ni, TF values below 1 (but close to 1) indicate that the metal is largely retained in the roots but that limited translocation occurs (Klink, 2016; Bonanno & Cirelli, 2017).

Values of TF<1 for Cd and TF>1 for Mn in *P. lapathifolium* reveal that the species develops different physiological responses depending on the metal type. The reported high shoot accumulation and growth increase for Mn support the potential of this species to be a hyperaccumulator for Mn (Liu et al., 2016). Root-based accumulation of Cd indicates a tendency for phytostabilization, while *P. lapathifolium* has been reported to exhibit condition-dependent physiological and phenotypic plasticity under heavy metal stress, with the potential for enhanced phytoextraction capacity under environmental or microbial interactions (Li et al., 2020).

P. lapathifolium exhibits higher BAF values in its roots compared to other species for Cd, and Cd concentration accumulates more in root tissue than in leaves and stems, indicating that roots form a protective barrier against metal toxicity (Clemens, 2006). The predominant accumulation of Cd in the root is related not only to the chemical properties of the metal, but also to species-specific root physiology and cellular sequestration capacity. In this study, although BAF values for Cd were below 1, the highest concentrations were detected in root tissues, consistent with previous studies reporting that the root system in Polygonum species plays an active role in Cd retention (Li et al., 2020; Kim et al., 2003).

The BAF values obtained for Cu showed that metal accumulation is shaped by the combined effect of species-specific uptake capacity and tissue-specific distribution. In *P. lapathifolium,* despite higher Cu-BAF values, the predominance of Cu accumulation in root tissues across all species indicates that the metal undergoes controlled and limited translocation within the plant and reflects interspecific differences in metal distribution strategies (Yu et al., 2020; Kaur et al., 2018).

Ultimately, the fact that *P. lapathifolium* exhibits TF>1 but BAF<1 values for Mn indicates that metal uptake and intraplant transport are independent physiological processes. This situation demonstrates that, despite limiting the plant's Mn uptake, it can effectively direct the absorbed metal to shoot tissues (Zhenggang et al., 2023). Similarly, a comprehensive meta-analysis reported BAF values below 1 and TF values above 1 for Pb and Fe, a pattern interpreted as indicating that metal uptake is limited while internal translocation within the plant remains physiologically effective (Huang et al., 2025). The essential nature of Mn and its high translocation potential support the high TF–low BAF combination observed in this study as a controlled adaptive strategy linked to metal homeostasis (Alejandro et al., 2020).

Conclusion

The strong positive correlations observed between different metals in the same plant tissue indicate that these elements are regulated through similar uptake and transport pathways within the plant and that the species studied have a high capacity to reflect environmental metal contamination. BAF and TF analyses revealed that heavy metal bioaccumulation behaviors differ significantly between plant species and tissue types, and that species develop ecologically distinct uptake, transport, and storage strategies for metals. These results indicate that species selection based on target metals or metal groups is critically important in phytoremediation applications and that the studied species may play potential functional roles in phytostabilization and controlled phytoextraction processes.

Ethical Statement

Ethics approval and consent to participate not applicable for this study.

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Author Contribution

EÖ: Data Curation, Methodology, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing. **MÖ:** Data Curation, Formal Analysis, Methodology, Software, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing. **YK:** Investigation, Methodology, Resources. **LK:** Conceptualization, Project Administration, Supervision, Writing – Review & Editing.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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