

# ECOLOGICAL RISK AND PHYTOREMEDIATION ASSESSMENT OF HEAVY METAL CONTAMINATION IN THALE NOI LAKE, THAILAND

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**Abstract.** Thale Noi Lake is a part of the Songkhla Lagoon in Phatthalung Province, Thailand and is home to many different types of water animals. This research studies the levels and location of aluminum (Al), arsenic (As), and lead (Pb) in water, sediments, and aquatic plants. The study involved two aquatic plants, water lettuce (*Pistia stratiotes*) and water primrose (*Ludwigia adscendens*), which are macrophytes capable of absorbing metals from water and sediment. The analysis was conducted using ICP-OES on samples from four stations (ST01-ST04). The amount of Al, As, and Pb in the water at the four stations were found to be below the established maximum standards in Thale Noi Lake, indicating acceptable water quality. However, Al concentrations were highest in sediments, followed by Pb and As. Lead concentrations exceeded the sediment standard at all stations, and arsenic levels exceeded both USEPA and MacDonald standards. Statistical differences in heavy metal concentrations were confirmed by ANOVA followed by Tukey's post hoc test. Al and As in water and sediment varied significantly among the stations, while differences were also observed between plant species and plant parts. High EF values for Pb and As at ST02 confirmed human influence, similar to Igeo results showing Pb contamination at all stations, while As remained unpolluted. The highest metal concentrations in ST01 were linked to the lowest sediment pH and DO. Both plants showed low BAF and BCF values, indicating limited metal accumulation from soil, but higher metal uptake from the water column, especially for arsenic and lead. Translocation factors remained below 1, suggesting metals were retained in roots, minimizing potential entry into the food chain. These findings support the potential of both species for phytoremediation, particularly in arsenic- and lead-contaminated waters.

**Keywords:** *water lettuce, water primrose, sediment pollution, the Songkhla lagoon, phytoremediation*

## Introduction

The Songkhla Lagoon, the largest lagoon in Thailand, and Thale Noi Lake have a rich biodiversity. Thale Noi, a natural pan-shaped wetland, acts as a natural sink, absorbing contaminants such as heavy metals from its surrounding environment (Pradit et al., 2024). These bodies of water support a diverse array of aquatic species and local communities are heavily reliant on these bodies of water for transportation, fishing, and agriculture for their livelihoods (Treeudom, 2016). Common aquatic plants found in Thale Noi include those that serve as food for aquatic animals, such as hydrilla and water lettuce, as well as plants consumed by local communities, such as lotus and water primrose (Treeudom, 2016). Thale Noi is particularly vulnerable to heavy metal contamination from sediment transport, urban runoff, fisheries, and agriculture. Recent studies in Southeast Asia have found accumulation of As, Pb, and even aluminum (Al) in sediments and aquatic plants, raising concerns about long-term ecological impacts and potential exposure through food chains. It is crucial to study heavy metal contamination because locals depend on these waters for food, water, and their livelihoods.

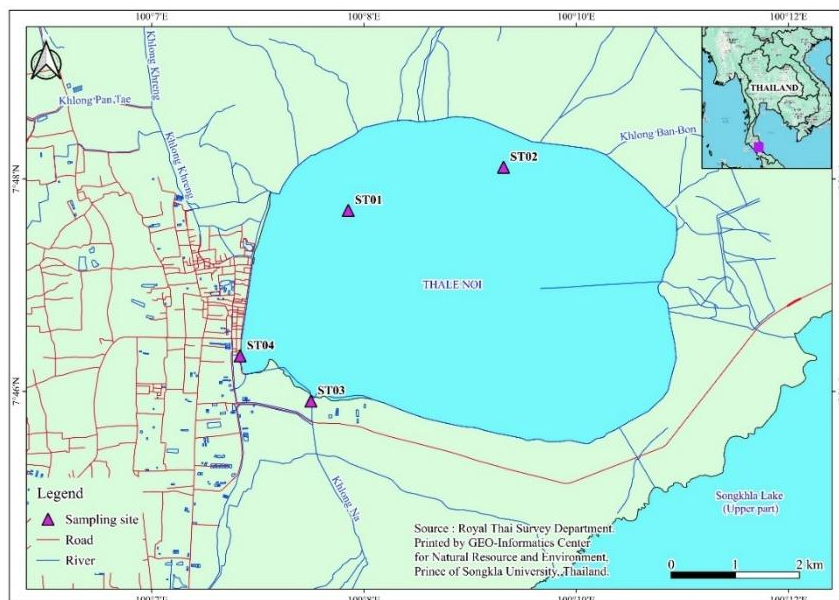
Heavy metal pollution from agricultural runoff, industry, and urbanization threatens human health and aquatic ecosystems (Masindi et al., 2021). These dangerous chemicals, such as the carcinogen arsenic (As) and heavy metals like lead (Pb), accumulate in water and soil, causing long-term health and environmental problems (Jaishankar et al., 2014). Among the dangerous heavy metals in aquatic environment are arsenic (As) and lead (Pb), which are persistent and bioaccumulate. Chronic exposure to arsenic has been linked to several types of cancer and cardiovascular diseases, while lead exposure can cause neurodevelopmental damage, particularly in children. Metals in the environment can be especially harmful to aquatic life as well as to animals and humans if they enter food chains. Water and sediment both frequently contain heavy metals such as As and Pb, with sediment serving as a long-term reservoir and possible secondary source of contamination. When their surroundings of the lake change, small particles and organic matter allow these metals to remain and enter the water column (Pradit et al., 2016b). During the rainy season, runoff increases metal input in Pattani Bay, the Setiu Wetlands, and the Kelantan Delta sediments in Thailand and Malaysia (Pradit et al., 2016b). Although Al is safe, it is used in enrichment factor (EF) estimates to differentiate between anthropogenic and natural inputs (Pradit et al., 2016b). Assessing ecological concerns and establishing long-term wetland management plans requires understanding metal-sediment dynamics and identifying aquatic plants with high metal uptake.

This research aims to determine the concentration of heavy metals in the water, sediment, and aquatic plants of Thale Noi. Two sediment-related variables, organic matter and pH, were included for investigation regarding metal accumulation (Aljumaily and Al-Hamndi, 2022). Sediment characteristics impact heavy metal adsorption, which could influence bioavailability to aquatic organisms. This research also examines using aquatic plants for phytoremediation to reduce pollution effects. Aquatic plants in these wetlands function as valuable bioindicators due to their ability to absorb and accumulate heavy metals from their surroundings (Kushwaha et al., 2025). Phytoremediation may offer a natural, sustainable response to heavy metal pollution by using plants to remove, transfer, or maintain pollutants (Kushwaha et al., 2025). This study's findings can serve a management plan of heavy metals, which combined with an assessment of the efficiency of phytoremediation will guide future monitoring plans. Combining phytoremediation techniques with environmental monitoring could improve the health and sustainability of the lagoon, therefore helping local communities as well as the environment.

## Materials and methods

### *Study area*

Thale Noi is a freshwater lake located in the Phanang Tung and Thale Noi subdistricts within the Khuan Khanun district of Phatthalung province. Covering around 8 km<sup>2</sup>, the region has an average depth between 1.2 and 1.5 m. With a remarkable number of waterbirds, this area shows great biodiversity with a range of habitats, animals, aquatic species, and plants. Various villages surround the lake, with locals participating in water transportation, fishing, and boat-based tourism. Samples were taken from four stations (ST01-ST04) (*Fig. 1*) which were selected based on varying levels of human activity, including fishing, tourism, and proximity to residential areas, to capture the spatial variability of heavy metal contamination within Thale Noi Lake. Three samples of water, sediment, and aquatic plants were collected to ensure three duplicates at every station.



**Figure 1.** Map of the study area and sampling station locations

### **Sample collection and preparation**

Sampling was conducted in January 2025, with three replicates per station for each sample type, including water, sediment, and aquatic plants. During sampling, in situ parameters including water temperature, total dissolved solids (TDS), salinity, and water depth were measured at each station using a YSI™ Professional Plus Multiparameter Meter. The process of collecting the water samples involved two steps. First, a 1 L sampling bottle was rinsed twice with water from the sampling station, then 1 L of surface water was collected from 30 cm below the water surface. Concentrated  $\text{HNO}_3$  was added to the sample until the pH was below 2. If suspended particles were present, it was filtered at room temperature. The filtered water was then stored at room temperature until heavy metal analysis. Sediment samples were collected using a sediment grab sampler, with three replicates per station. The samples were transferred into a bag and stored in an icebox. After arriving at the laboratory, the samples were dried in an oven at  $60^\circ\text{C}$  until completely dry. The samples were then weighed, finely ground, and sieved through a 0.63 mm mesh for chemical analysis. The processed samples were stored in a sealed bag and placed in a desiccator until heavy metal analysis. Aquatic plant samples were collected by hand and stored in an icebox. Water lettuce (*Pistia stratiotes*) and water primrose (*Ludwigia adscendens*) were selected based on their abundance and ecological relevance in the study area. After arriving at the lab, they were cleaned with deionized water, dried, split into above-ground (shoot) and below-ground (root) parts, and chopped into small pieces. The samples were then dried in an oven at  $60^\circ\text{C}$  until a consistent weight was obtained and then stored in a sealed bag for heavy metal analysis.

### **Heavy metals analysis**

One gram of the sediment or aquatic plant sample and 10 mL of water were placed in a test tube. After adding 2 mL of concentrated  $\text{HNO}_3$ , the mixture was heated in a water bath until it became a clear solution. After cooling, the sample was diluted with ultrapure water to a final volume of 10 mL using a volumetric flask. The heavy metal levels of the

prepared sample were determined using ICP-OES to measure absorbance according to the AOAC Official Method (AOAC, 2005).

### ***Sediment-related analysis***

#### *pH*

At the sampling station, the pH value was determined with a portable pH meter (Trans Instrument Senz pH Pro).

#### *Organic carbon content (%OC) analysis by ignition method*

To prepare for organic carbon analysis, a crucible was preheated at 103°C for 1 h, left to cool down in a desiccator, and weighed using an analytical balance. Meanwhile, 5 g of the oven-dried and ground sediment sample was weighed and placed into a preheated crucible and burned for 4 h at 550°C. After letting the sample cool in a desiccator, it was weighed again using an analytical balance and the weight was tracked. Total organic carbon content was calculated using the Loss on Ignition (LOI) (Eq. 1).

$$\%LOI = \frac{Mb - Ma}{100} \quad (\text{Eq.1})$$

where Mb is the mass before combustion and Ma is the mass after combustion.

The estimate of organic carbon content (%OC) based on LOI was as follows:

If %LOI < 0.20, use: %OC = 0.21 + 0.40(%LOI)

If %LOI > 0.20, use: %OC = 0.33 + 0.43(%LOI)

### ***Water-related analysis***

#### *pH*

At the sampling station, the pH value was determined using a portable pH meter (Trans Instrument Senz pH Pro).

#### *Dissolved oxygen (DO)*

Dissolved oxygen (DO) was measured using a multiparameter device (YSI™ Professional Plus Multiparameter Meter).

### ***Ecological risk calculation***

#### *Enrichment factor (EF)*

Metal contamination was evaluated by comparing its concentration to a reference element (e.g., Al or Fe). The enrichment factor was calculated using Equation 2 (Akoto et al., 2008; Pradit et al., 2024).

$$EF = \frac{\left(\frac{M}{Al}\right)_s}{\left(\frac{M}{Al}\right)_b} \quad (\text{Eq.2})$$

where  $(M/Al)_s$  is the ratio of heavy metal content in the sediment to the concentration of Al and  $(M/Al)_b$  is the ratio of heavy metal content in baseline values to the concentration of Al.

### *Geoaccumulation index (I<sub>geo</sub>)*

Metal pollution was measured by comparing current levels to pre-industrial background values. The geoaccumulation index was calculated using *Equation 3* (Akoto et al., 2008; Pradit et al., 2024).

$$I_{geo} = \log_2 \left( \frac{C_n}{1.5B_n} \right) \quad (\text{Eq.3})$$

where  $C_n$  is the concentration of heavy metals in the sediment being studied and  $B_n$  is the concentration of heavy metals in natural conditions. The baseline values ( $B_n$ ) used for the geoaccumulation index calculation were as follows: Al = 80,000  $\mu\text{g/g}$ , As = 15  $\mu\text{g/g}$ , and Pb = 20  $\mu\text{g/g}$  (Turekian and Wedepohl, 1961).

### *Phytoremediation capability in aquatic plants*

#### *Bioaccumulation factor (BAF)*

The bioaccumulation factor (BAF) describes the ability of a plant to accumulate heavy metal in its above-ground tissues (shoots). BAF was calculated using *Equation 4* (Hosseini et al., 2020; Rachmadiarti and Sholikhah, 2020).

$$BAF = \frac{C_{shoot}}{C_{sediment}} \text{ and } BAF = \frac{C_{shoot}}{C_{water}} \quad (\text{Eq.4})$$

where  $C_{shoot}$  is the heavy metal concentration in above-ground tissues,  $C_{sediment}$  is the heavy metal concentration in sediment, and  $C_{water}$  is the heavy metal concentration in water.

#### *Bioconcentration factor (BCF)*

The bioconcentration factor (BCF) describes the ability of a plant to accumulate heavy metal in below-ground tissues (roots). BCF was calculated using *Equation 5* (Hosseini et al., 2020; Rachmadiarti and Sholikhah, 2020).

$$BCF = \frac{C_{root}}{C_{sediment}} \text{ and } BCF = \frac{C_{root}}{C_{water}} \quad (\text{Eq.5})$$

where  $C_{root}$  is the heavy metal concentration in below-ground tissues,  $C_{sediment}$  is the heavy metal concentration in sediment, and  $C_{water}$  is the heavy metal concentration in water.

#### *Translocation factor (TF)*

The translocation factor (TF) evaluates the metal movement from above-ground tissues to below-ground tissues (roots to shoots). TF was calculated using *Equation 6* (Hosseini et al., 2020; Rachmadiarti and Sholikhah, 2020).

$$TF = \frac{C_{shoot}}{C_{root}} \quad (\text{Eq.6})$$

where  $C_{shoot}$  is the heavy metal concentration in above-ground tissues and  $C_{root}$  is the heavy metal concentration in below-ground tissues.

### **Statistics analysis**

Heavy metal concentrations (Al, As, Pb) were analyzed using descriptive statistics (mean and standard deviation, SD). Pearson or Spearman correlation analysis was applied to examine the relationships between heavy metal concentrations and environmental parameters (water quality and sediment characteristics), depending on the distribution of the data. Multivariate analysis (MANOVA) was performed to assess the effects of sample type (water, sediment, and aquatic plants), plant species, plant part, and sampling station on metal concentrations. Statistical significance was set at  $p < 0.05$ .

## **Results and discussion**

### **Study area observation**

The sampling sites were located in the upper Thale Noi area, representing varied environmental conditions. ST01 (Khlung Khwai Yai) had an oily water surface and foul-smelling sediment. ST02 (Khlung Na Laem) was surrounded by intensive fishing activity and was reported by locals as biologically productive. ST03 (Khlung Yuan) was near a protection area with little litter observed. ST04 (Ao Chao jetty area) was adjacent to boat landings and accommodation. Aquatic macrophytes such as water primrose (*Ludwigia adscendens*) and water lettuce (*Pistia stratiotes*) were present at all sites (Fig. 2). In addition to sediment and water quality, *in situ* parameters recorded during sampling showed that water temperature ranged from 26.7 to 30.2°C, total dissolved solids (TDS) from 40.3 to 78 mg/L, salinity from 0.03 to 0.05 ppt, and water depth from 0.7 to 1.3 m across all stations.



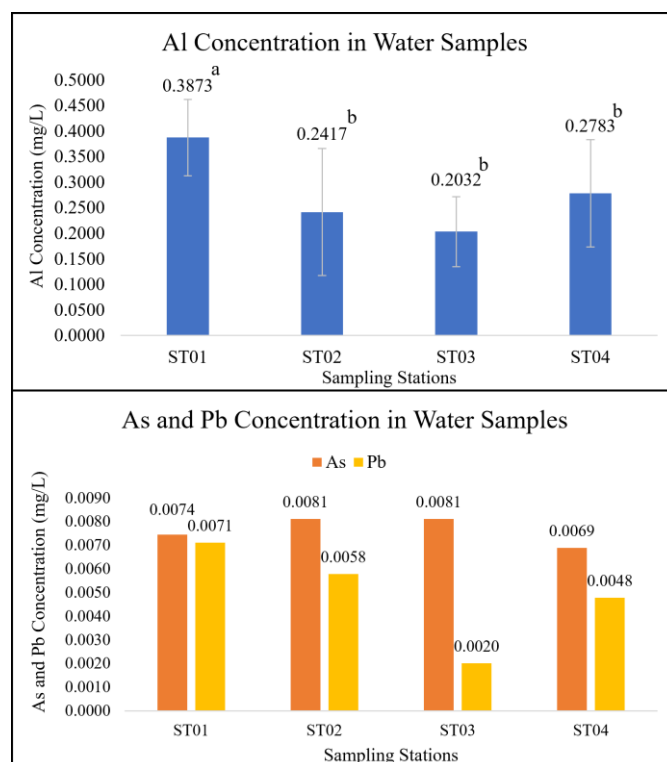
**Figure 2.** Aquatic plants used in this study: (a) water lettuce (*Pistia stratiotes*), (b) water primrose (*Ludwigia adscendens*) (yellow arrow)

### **Heavy metal concentration**

#### **Water**

Descriptive statistics of heavy metal concentrations (Al, As, and Pb) in water samples are presented in Figure 3. The bar graphs illustrate the mean values with standard deviations ( $\pm$ SD) across different sampling stations, providing a visual representation of the distribution and variability of each metal. Based on Figure 3, the water samples from the study area exhibited a trend in heavy metal concentrations, with

Al ( $0.2776 \pm 0.0669$ ) > As ( $0.0076 \pm 0.0005$ ) > Pb ( $0.0049 \pm 0.0019$ ). Lead (Pb) showed the lowest concentration, whereas water samples demonstrated the highest concentration of aluminum (Al). Al concentration varied throughout the several stations; the peak was recorded at ST01 (0.3873 mg/L), while the lowest value was recorded at ST03 (0.2032 mg/L). The elevated Al levels are consistent with findings from Pattani Bay and Setiu Wetlands, where aluminum presence is linked to both natural weathering and anthropogenic sources, such as agriculture and industry (Pradit et al., 2016a). Arsenic concentrations are much lower than various areas such as the Seu'um Geothermal Manifestation Area, Aceh, Indonesia (Irnawati et al., 2021). Meanwhile, Pb concentrations are higher than the global median Pb concentration in inland waters (Wei et al., 2023). Water samples indicated both As and Pb concentrations below the permissible limits based on Thailand's Pollution Control Department (Thailand's Pollution Control Department, 2010) (Table 1), but continuous monitoring is recommended to prevent future contamination risks and maintain ecological balance. Natural waterways often show higher aluminum levels, particularly in areas shaped by geological processes and human activities like industry and agriculture. Arsenic (As) and lead (Pb) are known as harmful substances, showing detrimental effects even in small amounts. They can accumulate in aquatic life, which may harm both ecosystems and human health. Natural releasing systems, agricultural runoff, and industrial discharges allow these metals to enter the environment. Monitoring the release and accumulation of heavy metals over time will help us to understand aquatic ecosystems and water quality.



**Figure 3.** Al, As, and Pb concentrations (mg/L) in water samples collected from ST01–ST04 in Thale Noi. Different letters (a, b) indicate significant differences between sampling stations according to Tukey's post hoc test ( $p < 0.05$ )

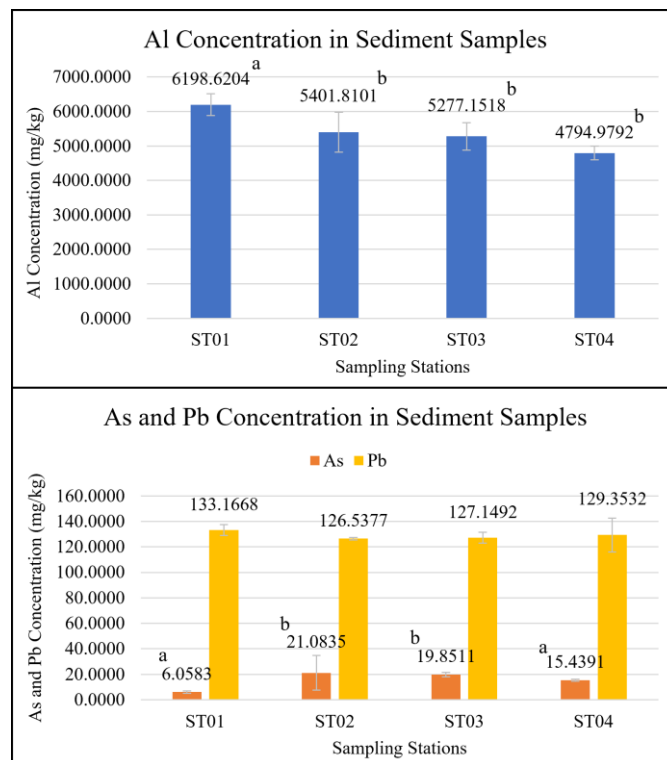
**Table 1.** Historic details of heavy metal of the Songkhla Lagoon and relevant environmental standards

Location	Year	Sample type	Metal range (mg/kg dry wt or mg/L)			References
			Al	As	Pb	
Thale Noi Lake, Phatthalung	2025	Sediment	4794.98-6198.62 mg/kg	6.06-21.08 mg/kg	126.54-133.17 mg/kg	This study
Thale Noi Lake, Phatthalung	2025	Water	0.2032-0.3873 mg/L	0.0069-0.0081 mg/L	0.0020-0.0071 mg/L	This study
The Songkhla Lagoon, Songkhla	2023	Sediment	-	1.20-13.74 mg/kg	3.26-39.02 mg/kg	Pradit et al., 2024
Thale Noi, Phatthalung	2007	Surface sediment	-	5.7-10.8 mg/kg	-	Sompongchaiyakul and Sirinawin, 2007
PCD Thailand (standard)	2010	Water	-	10 mg/L	8.5 mg/L	Thailand's Pollution Control Department, 2010
USEPA (sediment std.)	1996	Sediment	-	11 mg/kg	37 mg/kg	USEPA, 1996
MacDonald standard	2003	Sediment	-	7.79 mg/kg	35.80 mg/kg	MacDonald et al., 2003
NOAA standard	1991	Sediment	-	85 mg/kg	110 mg/kg	Long and Morgan, 1991

### Sediments

Figure 4 presents the distribution, average concentrations and standard deviations of heavy metals (Al, Pb, As) within the study area. The average concentrations (mg/kg) show the following trend: Al ( $5418.1404 \pm 582.42$ ) > Pb ( $129.35322 \pm 6.81$ ) > As ( $15.4391 \pm 6.81$ ). Aluminum (Al), the most common metal, is sourced from natural weathering, industrial discharges, and urban runoff. Aluminum concentrations vary by station, ranging from 4794.98 mg/kg (ST04) to 6198.62 mg/kg (ST01). Lead (Pb) concentrations, ranging from 126.54 to 133.17 mg/kg, indicate considerable human influence, including domestic and agricultural waste. High Pb levels indicate localized contamination, comparable to the situation in the Songkhla Lagoon, which is impacted by aquaculture and mining (Pradit et al., 2009). Arsenic (As) concentrations were lower than Al and Pb but still exceeded levels recorded in certain international coastal areas, such as the Arabian Gulf and parts of China (Amin and Almahasheer, 2022; Liu et al., 2022). Compared to the previous study by Sompongchaiyakul and Sirinawin (2007) which reported As concentrations of 5.7–10.8 mg/kg in surface sediments from Thale Noi, our findings show considerably higher values at certain stations, indicating a marked increase in contamination over time. The findings highlight the necessity for continuous monitoring of Pb and As to protect aquatic ecosystems. Based on sediment quality guidelines from NOAA, USEPA, and MacDonald standard, the sediment samples showed Pb concentrations that exceeded the standard limit with the highest concentration at ST02 (Long and Morgan, 1991; USEPA, 1996; MacDonald et al., 2003) (Table 1). Meanwhile, As levels were below the NOAA standard but exceeded the USEPA and MacDonald standards, indicating potential contamination from human activities. These findings increase concerns about long-term environmental impacts and potential metal transfer to aquatic organisms.

Based on historical data of heavy metal of Songkhla Lagoon (Table 1), concentrations of arsenic (As) and lead (Pb) in the sediments show a decreasing trend over time. However, when focusing specifically on Thale Noi Lake, an increase in both As and Pb concentrations is observed in the most recent sampling. This suggests that while overall contamination in the broader lagoon may be declining, localized pollution in Thale Noi is intensifying, possibly due to differences in hydrology, land use, or surrounding human activities.



**Figure 4.** Al, As, and Pb concentrations (mg/kg) in sediment samples collected from ST01–ST04 in Thale Noi. Different letters (a, b) indicate significant differences between sampling stations according to Tukey's post hoc test ( $p < 0.05$ )

#### Aquatic plants

Figures 5.1 and 5.2 show the concentration of heavy metals (Al, Pb, As) in the roots and shoots of water lettuce and water primrose, using the same descriptive statistical format (mean  $\pm$  SD). Overall, both species exhibit greater heavy metal accumulation in their roots than their shoots. In water lettuce shoots, Al ranged from 101.19 to 611.60 mg/kg, while the highest Pb and As concentrations were found at ST03 (2.78 and 1.05 mg/kg, respectively). In roots, Al ranged from 1018.45 to 3353.96 mg/kg, with the highest Pb (16.11 mg/kg) and As (10.80 mg/kg) also recorded at ST03 (Fig. 5.1). In water primrose shoots, Al ranged from 23.51 to 154.71 mg/kg, with the highest Pb (0.36 mg/kg) and As (0.04 mg/kg) at ST03. In roots, Al ranged from 614.57 to 2110.92 mg/kg, and Pb (6.59 mg/kg) and As (8.23 mg/kg) peaked at ST03 and ST01, respectively (Fig. 5.2). Both plants' roots had high Al and Pb levels, especially water lettuce, indicating metal absorption. This root-accumulation pattern aligns with previous studies reporting that floating aquatic plants tend to store metals in their roots rather than transport them to shoots (Lu et al., 2011; Rachmadiarti and Sholikah, 2020; Wang et al., 2020). Previous studies found that water lettuce roots could absorb and retain large quantities of heavy metals like Al and Pb (Lu et al., 2011). Another work discovered that water primrose collected Cd mostly in the roots rather than the leaves, supporting the present observation (Rachmadiarti and Sholikah, 2020). Furthermore, researchers reported that water primrose, a similar species, hyperaccumulated zinc (Zn) and copper (Cu) and lead (Pb), suggesting it could be a multi-heavy metal treatment plant (Wang et al., 2020). Local consumption of water primrose, which accumulates lead (Pb), causes major health

problems. Roots are an important part for metal buildup, so water lettuce might be useful for the phytoremediation of metal-polluted waterways.

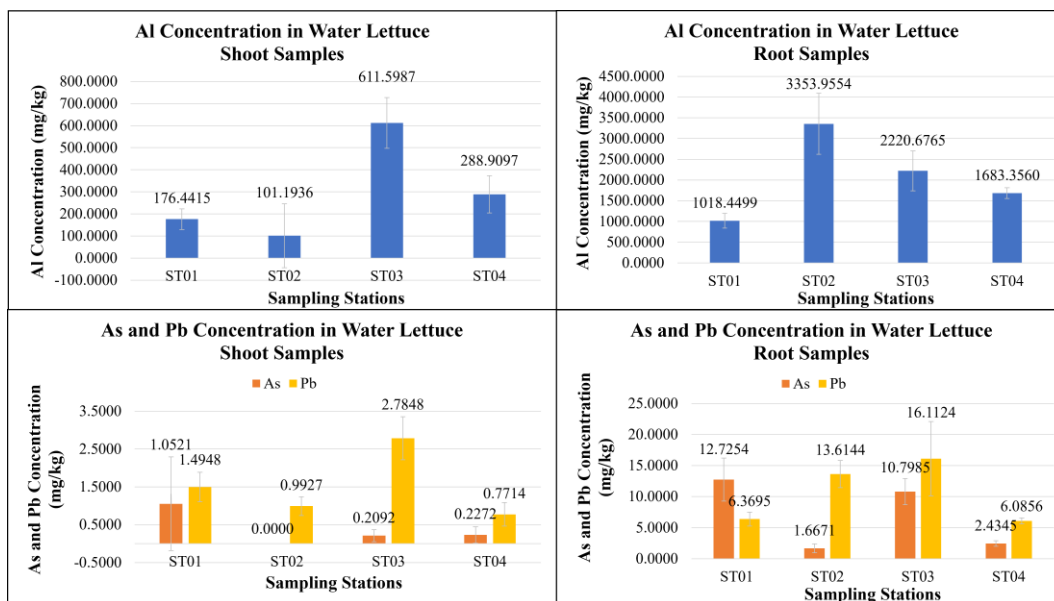


Figure 5.1. Al, As, and Pb concentrations (mg/kg) in water lettuce shoots and roots from ST01–ST04

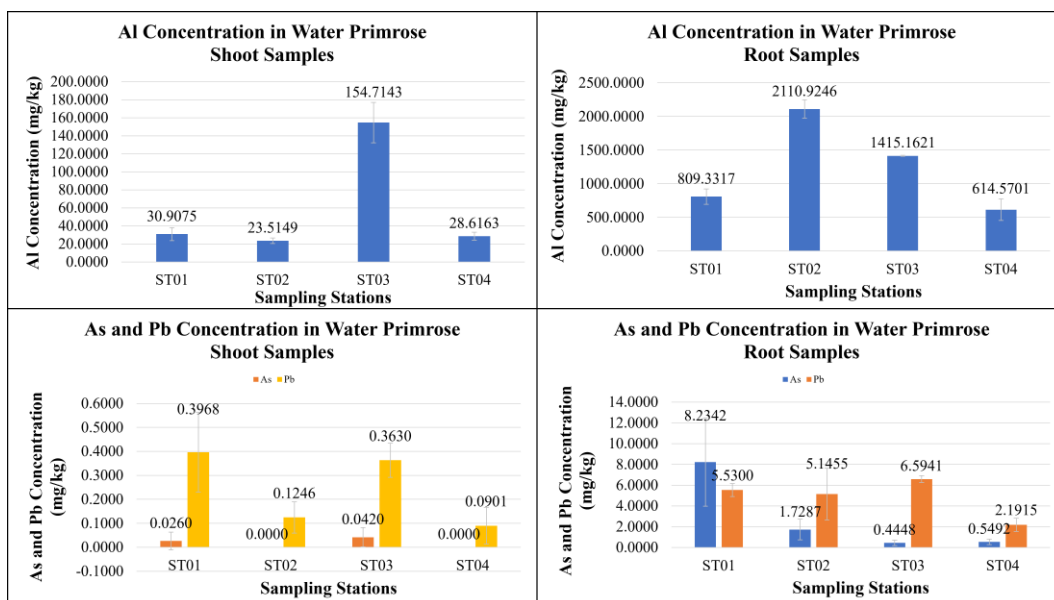


Figure 5.2. Al, As, and Pb concentrations (mg/kg) in water primrose shoots and roots from ST01–ST04

### Statistical evaluation: multivariate analysis variance (MANOVA) and Tukey's post hoc test

Multivariate analysis of variance (MANOVA) revealed that the sampling station, plant species, and plant part had a statistically significant effect on the overall concentrations

of aluminum (Al), arsenic (As), and lead (Pb) ( $p < 0.001$ ) (*Table A1*). In addition, significant interaction effects were observed between these factors, including station  $\times$  plant, station  $\times$  part, plant  $\times$  part, and station  $\times$  plant  $\times$  part, suggesting that both spatial and biological factors contribute to the variation in metal accumulation. Further analysis using between-subjects effects in *Table A2* indicated that metal concentrations in plant tissues (PAI, PAS, PPb) were significantly influenced by all three main factors and their interactions ( $p < 0.05$ ). In contrast, metal concentrations in water and sediment were affected only by the sampling station. Since “plant part” is biologically irrelevant to non-plant samples, it was excluded from subsequent analyses of water and sediment. These findings emphasize that spatial variability plays a key role in determining metal concentrations in water and sediment, while species-specific and tissue-specific biological characteristics primarily drive metal accumulation in aquatic plants.

Significant differences in Al and As concentrations in both water and sediment samples among stations were detected by one-way ANOVA followed by Tukey’s post hoc test ( $p < 0.05$ ). In water samples, ST01 showed significantly higher Al concentrations than ST02, ST03, and ST04, while As concentrations at ST01 were also significantly higher than at the other stations (*Fig. 3*). For sediment samples, ST01 showed significantly higher Al concentrations compared to the other stations. For As, ST01 and ST04 constituted one group with higher concentrations, while ST02 and ST03 constituted another group with decreased numbers. No significant variations in Pb values were observed across the stations (*Fig. 4*).

Significant differences in heavy metal concentrations in aquatic plants were observed according to plant species and plant parts. The results of two-way ANOVA showed that both plant species (water lettuce and water primrose) and plant parts (shoot and root) significantly affected Al, As, and Pb concentrations ( $p < 0.05$ ). Tukey’s post hoc test indicates that aluminum (Al) concentrations in water primrose roots were significantly higher than in all other groups, followed by the water lettuce roots, but the shoots of both species showed the lowest values. The root parts of both species had significantly higher values of arsenic (As) compared to the shoot parts, with water primrose roots showing the highest levels of As. Additionally, for lead (Pb), roots collected significantly more Pb than shoots, particularly in water primrose. The findings indicate that root structures are the principal location for heavy metal buildup, with water primrose exhibiting better phytoremediation capabilities compared to water lettuce (*Fig. 5*).

### ***Sediment-related factors and water-related factors***

*Table 2* indicates that Station ST01 exhibited the lowest sediment pH (4.16) with a comparatively high organic carbon content (%OC), suggesting its capacity for heavy metal retention (Aljumaily and Al-Hamndi, 2022). Consequently, aluminum (Al) and lead (Pb) exhibited the highest concentrations in both sediment and water samples at this station. The dissolved oxygen (DO) level was measured at 0.3 mg/L, indicating degraded water quality and a significant potential for pollution accumulation (Chapman, 1992). Station ST02 recorded the lowest water pH at 4.7, signifying strongly acidic conditions, and displayed the highest arsenic (As) concentrations in sediment at 21.08 mg/kg and in water at 0.0081 mg/L, which could be linked to particular pollution sources. Station ST03 exhibited the highest organic carbon content (%OC = 16.86%), which improved the sediment’s capacity to effectively bind heavy metals (Basti et al., 2024; Aljumaily and Al-Hamndi, 2022). As a result, concentrations of heavy metals in the water were decreased, despite relatively high levels in the sediment, especially for arsenic, which

ranked second after ST02. Station ST04 exhibited increased environmental quality, characterized by the highest pH levels in the sediment (5.33) and water (6.8), as well as the highest dissolved oxygen concentration (7.8 mg/L). These factors suggest a well-balanced ecosystem, characterized by the lowest concentrations of heavy metals in both sediment and water. In summary, pH levels in sediment and water significantly influence the mobility and release of heavy metals (Aljumaily and Al-Hamndi, 2022). Sediment pH and organic carbon content (%OC) and water pH and dissolved oxygen (DO) showed significant spatial differences ( $p < 0.05$ ). ST01 and ST02 exhibited lower sediment pH and water pH values compared to ST03 and ST04, indicating more acidic conditions that may enhance metal mobility. ST03 had the highest %OC, suggesting higher metal retention capacity. DO was lowest at ST01 and highest at ST04, reflecting differing water quality conditions among stations. Acidic sediment and high organic carbon content improve the retention of heavy metals, however under high acidic conditions, these metals are released into the aquatic environment. Treatment at ST01 and ST02 is essential to avoid the further spread of heavy metals in the ecosystem.

**Table 2.** Sediment-related factors and water-related factors

Station	Sediment-related part		Water-related part	
	pH	%OC	pH	DO (mg/L)
ST01	4.16 ± 0.07 <sup>a</sup>	10.70 ± 0.47 <sup>b</sup>	5.60 ± 0.06 <sup>a</sup>	0.30 ± 0.05 <sup>c</sup>
ST02	4.54 ± 0.05 <sup>a</sup>	8.83 ± 0.16 <sup>c</sup>	4.70 ± 0.11 <sup>a</sup>	3.12 ± 0.20 <sup>c</sup>
ST03	5.08 ± 0.02 <sup>b</sup>	16.86 ± 1.46 <sup>a</sup>	6.50 ± 0.18 <sup>b</sup>	5.19 ± 1.40 <sup>b</sup>
ST04	5.33 ± 0.13 <sup>b</sup>	9.39 ± 0.81 <sup>b</sup>	6.80 ± 0.12 <sup>b</sup>	7.11 ± 0.64 <sup>a</sup>

Values are expressed as mean ± SD. Different superscript letters indicate statistically significant differences among stations (Tukey's test,  $p < 0.05$ )

Due to the presence of many non-detect values (ND) and non-normal distribution in some variables (especially heavy metal concentrations), Spearman's rank correlation was selected for most analyses to ensure robustness of the results. Spearman's correlation revealed strong interrelationships among environmental factors (Table A3). Dissolved oxygen (DO) was found to have a positive relationship with sediment pH (SpH) ( $\rho = 0.766$ ,  $p < 0.001$ ), likely because of increased photosynthesis, which matches findings from Zhou et al. (2008). Organic carbon (OC) was positively correlated with both SpH and DO. This suggests that these factors rise together in environments that are more productive. DO was found to have a negative relationship with lead in water (WPb), while water pH had negative relationships with aluminum in water (WAl) and arsenic in water (WAs), meaning that more metals dissolve when the conditions are acidic and have low oxygen, which was also reported by Aljumaily and Al-Hamndi (2022). In sediments, organic carbon (OC) was found to have a negative relationship with lead in sediment (SPb), while arsenic in sediment (SAs) had a positive relationship with aluminum in sediment (SAI), indicating that they accumulate together and that organic matter helps bind metals.

### ***Sediment pollution and health status***

This study examined the EF and Igeo of arsenic (As) and lead (Pb) in the Thale Noi Lake (Table 3). The average EF values for As and Pb of all stations were 158.1592 and

1279.7260, respectively, indicating substantial levels of heavy metal pollution. According to previous studies, an EF value of 10 indicates an obvious accumulation of heavy metals from anthropogenic sources or human activities such as agriculture or aquaculture which contribute to both As and Pb in the area Ekissi et al. (2021). The geoaccumulation index (Igeo) was used to find out how much metal was in the sediments at all the sampling stations. Igeo values less than 0 meant that all sites were considered unpolluted for arsenic (As) (Pradit et al., 2024; Shirani et al., 2020). Meanwhile, lead (Pb) always had Igeo values above 2, ranging from 49.2 to 57.2, indicating moderate to strong contamination (Pradit et al., 2024; Shirani et al., 2020). This data shows that lead pollution is a problem that requires more attention and control, while arsenic pollution is not a major threat to the research area. Spatial changes in EF and Igeo values reflected study area observations. ST02 and ST03, located near intensively fished and semi-enclosed canals, showed the highest enrichment levels. ST04, situated near a boat landing and residential area, also exhibited elevated values. In contrast, ST01, which showed signs of surface oil and foul-smelling sediment, had lower EF values, suggesting different pollution sources. Both EF and Igeo values for lead (Pb) indicated the accumulation of heavy metals at levels that can have environmental impacts over time, while arsenic (As) showed unpolluted conditions across all stations. Therefore, continuous situational monitoring and surveillance is needed. These results could be used as baseline data for sediment management, pollution mitigation, and ecological risk assessment in the area.

**Table 3.** Enrichment factor (EF) and geoaccumulation index (Igeo) for As and Pb

Station	Enrichment factor (TF)		Geoaccumulation index (Igeo)	
	As	Pb	As	Pb
ST01	52.13	1145.78	-1.89	2.57
ST02	208.16	1249.34	-0.09	2.49
ST03	200.62	1285.03	-0.18	2.50
ST04	171.73	1438.76	-0.54	2.52

### **Phytoremediation capability**

#### *Aquatic plants compared to sediment*

Table 4 presents the phytoremediation indices of water lettuce and water primrose compared to sediment. The bioaccumulation factor (BAF) and bioconcentration factor (BCF) values of aluminum (Al), arsenic (As), and lead (Pb) were generally low at all sampling stations. Water lettuce and water primrose had the greatest BCF values for arsenic (As) at ST01, 2 and 1, respectively, suggesting that these plants might have the capacity to absorb arsenic from the surroundings. All BAF values remained at 0, while Al and Pb BCF values were also below 1 for both plant species, indicating metal absorption in the roots. The poor quality of these indicators could be related to the growth of floating aquatic plants. Free-floating hydrophytes have roots that float in the water column unanchored in sediment. This biological trait minimizes their sediment interaction, which may limit sediment-bound heavy metal intake. It has been observed that floating species get most of their nutrients and pollutants from the water, not from the ground or sediment (Department of Fisheries, 2019). This ecological characteristic

may explain how there is less metal accumulation in sediment-based comparative studies.

This research found that water lettuce (*Pistia stratiotes*) and water primrose (*Ludwigia adscendens*) roots collected heavy metals with minimal translocation factors. This prevents the direct transmission of metals into the food chain, however plant waste following death may release metals. Under specific environmental conditions, such as low pH, low organic matter content, and fine sediment particle size, metals accumulated in plant debris or sediments may be remobilized into the aquatic environment (Aljumaily and Al-Hamndi, 2022). These remobilized metals can enter the food chain through sediment-ingesting organisms. Although few studies have directly quantified metal release from degraded biomass of these species, frequent harvesting of phytoremediation plants is necessary to minimize secondary contamination (Lu et al., 2011; Ali et al., 2013). Under specific environmental circumstances, plant tissue metals may remobilize. Thus, with proper biomass management, both species may be used for phytoremediation in Thale Noi Lake.

**Table 4.** Phytoremediation capacity of water lettuce and water primrose based on bioaccumulation (BAF), bioconcentration (BCF), and translocation (TF) factors relative to water and sediment samples

Bioaccumulation factor (BAF)					Bioconcentration factor (BCF)				
<b>Phytoremediation capability in water lettuce compared to sediment</b>									
	ST01	ST02	ST03	ST04		ST01	ST02	ST03	ST04
<b>Al</b>	0	0	0	0	<b>Al</b>	0	1	0	0
<b>As</b>	0	0	0	0	<b>As</b>	2	0	1	0
<b>Pb</b>	0	0	0	0	<b>Pb</b>	0	0	0	0
<b>Phytoremediation capability in water primrose compared to sediment</b>									
	ST01	ST02	ST03	ST04		ST01	ST02	ST03	ST04
<b>Al</b>	0	0	0	0	<b>Al</b>	0	0	0	0
<b>As</b>	0	0	0	0	<b>As</b>	1	0	0	0
<b>Pb</b>	0	0	0	0	<b>Pb</b>	0	0	0	0
<b>Phytoremediation capability in water lettuce compared to water</b>									
	ST01	ST02	ST03	ST04		ST01	ST02	ST03	ST04
<b>Al</b>	456	419	3010	1038	<b>Al</b>	2629	13878	10927	6048
<b>As</b>	141	0	26	33	<b>As</b>	1709	206	1331	353
<b>Pb</b>	210	172	1392	161	<b>Pb</b>	896	2356	8056	1274
<b>Phytoremediation capability in water primrose compared to water</b>									
	ST01	ST02	ST03	ST04		ST01	ST02	ST03	ST04
<b>Al</b>	80	97	761	103	<b>Al</b>	2089	8735	6964	2208
<b>As</b>	3	0	5	0	<b>As</b>	1106	213	55	80
<b>Pb</b>	56	22	182	19	<b>Pb</b>	778	891	3297	459
<b>Translocation Factor (TF)</b>									
Phytoremediation capability in water lettuce					Phytoremediation capability in water primrose				
	ST01	ST02	ST03	ST04		ST01	ST02	ST03	ST04
<b>Al</b>	0	0	0	0	<b>Al</b>	0	0	0	0
<b>As</b>	0	0	0	0	<b>As</b>	0	0	0	0
<b>Pb</b>	0	0	0	0	<b>Pb</b>	0	0	0	0

### *Aquatic plants compared to water*

Table 4 provides an overview of how water lettuce and water primrose perform in terms of metal uptake when compared to water. Both species demonstrated a higher capacity to absorb metals from the water column, with bioaccumulation factors (BAF) and bioconcentration factors (BCF) being notably higher compared to sediment. For water lettuce, aluminum (Al) had the highest BCF at ST02 (13,878), while lead (Pb) showed the highest BAF at ST03 (1,392). Arsenic (As) uptake was also significant, with the highest BCF observed at ST01 (1,709). Water primrose also showed good metal uptake ability, particularly for arsenic, with the highest BCF found at ST01 (1,106) and lead peaking at ST03 for both BAF (182) and BCF (3,297). Aluminum BCF was highest at ST02 (8,735). The elevated BCF values for arsenic in both water lettuce and water primrose suggest their potential for use in phytoremediation of arsenic-contaminated water. Additionally, their ability to accumulate lead further supports their potential to reduce Pb contamination in aquatic environments.

### *Translocation factor (TF)*

Translocation factor (TF) values (Table 4) for all metals were consistently below 1 for both plants, indicating that their roots retained metals. This shows that both plant species mostly take in metals through roots, not shoots. Previous research supports this finding that floating plants like water lettuce (*Pistia stratiotes*) get metals such as Al and Pb from the water through their roots (Lu et al., 2011). Additionally, a previous study discovered that *Ludwigia adscendens* and *Ludwigia grandiflora* absorbed metals similarly, with BCF values above 1 and TF values below 1 (Rachmadiarti and Sholikah, 2020). This strongly suggests that metals, including cadmium (Cd), are retained in the roots of these plants.

## **Conclusions**

This study shows that Thale Noi's sediments are highly contaminated with heavy metals, particularly Pb which exceeds the limit at all sample stations, and As which exceeds USEPA and MacDonald standards at many stations. Nonetheless, the water quality still stayed within permissible limits according to national guidelines. Spatial differences in Al and As concentrations were found in water and sediment, with ST01 showing the highest levels, while Pb showed no station difference. In aquatic plants, roots—particularly from water primrose—accumulated the highest Al, As, and Pb, underscoring their role in phytoremediation. The BAF and BCF results of both water lettuce and water primrose were lower than those of sediments, but they were better at absorbing arsenic and lead from the water column. Translocation factors (TF) below 1 indicate that metals were retained primarily in the roots, reducing the risk of transfer into the food chain. These findings show their potential for phytoremediation, especially in waterways polluted with lead (Pb) and arsenic (As). EF indicated anthropogenic heavy metal pollution, especially Pb. Igeo indicated there was no As pollution but moderate to strong contamination of Pb. The accumulation of sediment metals signifies an ongoing problem that requires active treatment and environmental monitoring. The application of native plants for phytoremediation and pollution management may effectively and sustainably reduce metal contamination in the Thale Noi Lake.

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## APPENDIX

*Table A1* is a summary of multivariate test statistics (Pillai's Trace, Wilks' Lambda, Hotelling's Trace, and Roy's Largest Root) for the effects of station, plant species, plant part, and their interactions on heavy metal concentrations. All test results were statistically significant at  $p < 0.001$ .

**Table A1.** Multivariate analysis of variance (MANOVA)

Effect	Statistic	Value	F	Hypothesis df	Error df	Sig.
Station	Pillai's Trace	2.203	37.486	27.000	366.000	0.000
Station	Wilks' Lambda	0.012	46.078	27.000	351.104	0.000
Station	Hotelling's Trace	12.171	53.493	27.000	356.000	0.000
Station	Roy's Largest Root	7.577	102.710	9.000	122.000	0.000
Plant	Pillai's Trace	0.607	20.565	9.000	120.000	0.000
Part	Pillai's Trace	0.904	125.015	9.000	120.000	0.000
Station*plant	Pillai's Trace	0.361	5.428	27.000	366.000	0.000
Station*part	Pillai's Trace	0.450	12.689	27.000	366.000	0.000
Plant*part	Pillai's Trace	0.311	6.013	9.000	120.000	0.000
Station*plant*part	Pillai's Trace	0.745	4.414	27.000	366.000	0.000

*Table A2* shows the significance (p-value) of each factor (station, plant species, plant part) and their interactions on selected heavy metal concentrations (PAI, PAS, PPb) based on between-subjects effects analysis. Only statistically significant effects ( $p < 0.05$ ) are shown.

**Table A2.** Between-subjects effects on heavy metal concentrations

Dependent variable	Source	F	Sig.
PAI	Station	62.754	0.000
PAI	Plant	116.808	0.000
PAI	Part	720.736	0.000
PAI	Station * plant	12.380	0.000
PAI	Station * part	55.225	0.000
PAI	Plant * part	33.615	0.000
PAI	Station * plant * part	11.535	0.000
PAs	Station	15.226	0.000
PAs	Plant	9.680	0.002
PAs	Part	73.807	0.000
PAs	Station * plant	4.083	0.008
PAs	Station * part	11.426	0.000
PAs	Plant * part	4.943	0.028
PAs	Station * plant * part	4.621	0.004
PPb	Station	32.993	0.000
PPb	Plant	96.448	0.000
PPb	Part	398.471	0.000
PPb	Station * plant	15.587	0.000
PPb	Station * part	22.578	0.000
PPb	Plant * part	35.873	0.000

Table A3 shows selected Spearman's correlation coefficients ( $\rho$ ) and significance values (p-value) between key environmental factors and heavy metal concentrations in water and sediment samples.

**Table A3.** Spearman's correlation between environmental factors and heavy metal concentrations

Variable pair	Spearman's rho ( $\rho$ )	p-Value
DO – WPb	-0.330	0.000
SpH – WPb	-0.258	0.002
SpH – WAI	-0.639	0.000
SpH – WAs	-0.308	0.000
OC – SPb	-0.424	0.000
PAI – PAs	0.660	0.000
PAI – PPb	0.940	0.000
SAI – WPb	-0.658	0.000
SAs – SAI	0.545	0.000
SAs – SPb	-0.424	0.000