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Sediment-Macrophyte Interactions in Heavy Metal Contaminated Lakes: Insights into Bioaccumulation and Phytoremediation Potential

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Abstract Heavy metal contamination in freshwater systems has been extensively studied. However, many tropical ecosystems still lack baseline data on metal distribution and effective remediation strategies. Thus, this study investigated sediment-macrophyte metal dynamics, critical for assessing ecological risks and phytoremediation potential. Concentrations of five heavy metals (HM), namely Cadmium (Cd), Lead (Pb), Chromium (Cr), Copper (Cu), and Manganese (Mn) were analyzed in sediments and common macrophytes (*Ludwigia erecta* and *Vossia cuspidata*) from two municipal lakes in North-Central Nigeria. Field sampling was conducted from April to August 2022 in Tagwai and Old Gawu Lakes. Sediment and macrophyte samples were analyzed using standard protocols. Bioaccumulation factors (BAFs), Spearman correlation, and Principal Component Analysis (PCA) were applied to quantify metal uptake efficiency, assess sediment-plant metal relationships, and characterize variations in metal profiles across the lakes. Despite low sediment-based ecological risk (RI < 150), macrophyte bioaccumulation indicated notable HM bioavailability. *Ludwigia erecta* showed high Cd uptake in Old Gawu (BAF = 1.53) and elevated Pb and Cr bioaccumulation in Tagwai, while *Vossia cuspidata* accumulated Mn, Pb, and Cr above sediment levels (BAF > 1). These patterns demonstrate that Cd, Pb, and Cr remain bioavailable revealing a higher ecological concern than is reflected by sediment-based indices alone. These findings highlight species-and site-specific metal accumulation patterns and suggest that *V. cuspidata* holds greater potential for phytoremediation in multi-metal contaminated environments. The study emphasizes the importance of incorporating macrophytes into ecological risk assessments and management strategies for tropical lake systems.

Keywords *Vossia cuspidata* · *Ludwigia erecta* · Biomonitoring · Pollution · And Nigeria

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1 Introduction

Heavy metal (HM) pollution in freshwater systems has become a global environmental concern due to their non-biodegradable nature (Kakade et al., 2023; Maithani et al., 2023). These metals are continuously released into aquatic environments from various anthropogenic sources, including industrial processes, mining activities, agricultural runoff, domestic sewage, and atmospheric deposition. Natural sources, such as the weathering of rocks and volcanic activity, also contribute to HM contamination in freshwater ecosystems (Chen & Yang, 2011; Chukwuemeka et al., 2020; Khan et al., 2008). The primary concern arises from the toxicological impacts of HMs on human health and other organisms. Exposure to elevated concentrations of elements such as chromium (Cr), lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) poses significant health risks to organisms. Notably, Cr, Cd, Pb, As, Hg, and nickel (Ni) are recognized for their carcinogenic potential in humans and are considered among the most hazardous environmental contaminants (Tangahu et al., 2011; Khan et al., 2008). In plants, HMs damage chlorophyll, which lowers photosynthetic efficiency. They also interfere with vital enzymes involved in important physiological processes like carbon fixation and respiration. This disruption can alter metabolic pathways and reduce the plant's ability to effectively produce energy (Asiminicesei et al., 2024; Banaee, 2024; Taiwo et al., 2014). At high concentrations in sediments, HMs can be fatal to benthic organisms such as macroinvertebrates, especially the most sensitive (Qu et al., 2010; Zaynab et al., 2022). Heavy Metals are commonly detected in various components of aquatic ecosystems, including water, sediments, and biota such as aquatic plants and animals (Dixit & Dhote, 2010).

Lake ecosystems are particularly vulnerable to HM pollution due to hydrological and geomorphological factors (Xia et al., 2020). Runoff from the catchment areas, transported via rivers or directly from adjacent land, often carries metal contaminants that accumulate in the lake sediments (El-Sharkawy et al., 2025). These sediments function as long-term sinks for pollutants originating from watersheds (Chiaia-Hernández et al., 2022). The profundal zone, including its benthic communities, is especially affected by HM accumulation due to its role in receiving and storing allochthonous materials (Steinsberger et al., 2017). This accumulation contributes to bioaccumulation and subsequent biomagnification in organisms inhabiting these zones (El-Sharkawy et al., 2025; Phaenark et al., 2024). Indeed, this zone is mainly inhabited by organisms at the lower trophic levels, such as producers (e.g., benthic macrophytes and algae) and primary consumers such as detritivores (Tack et al., 2024).

Benthic organisms play a key role in the transfer of HMs through the food web (Bellante et al., 2016; Phaenark et al., 2024). Many aquatic species interact with sediment either directly or indirectly, making it a crucial medium for contaminant uptake. For instance, benthic macrophytes absorb HMs from the sediment through root absorption and rhizofiltration, and from water through their stem and leaves (epidermal and foliar absorption) (Bai et al., 2018; Skorbiłowicz & Sidoruk, 2025). However, due to the higher metal bioavailability, macrophytes absorb HM more efficiently from sediments than from the water column (Enochs et al., 2023; Li et al., 2023[a]; Oliveira et al., 2024). The HMs accumulated by macrophytes can be transferred into the food web through grazers such as snails, fish, beetles, and birds, resulting in magnified concentrations at higher trophic levels. These macrophytes, as primary producers, initiate and sustain the biomagnification process within aquatic ecosystems (Yan et al., 2024; Wang et al., 2014). Additionally, other organisms such as filter feeders (e.g., bivalves) absorb HMs directly from sediments and the water column through their feeding mechanisms (Bellante et al., 2016). As such, organisms at higher trophic levels, such as carnivorous fish that consume primary feeders, tend to accumulate higher concentrations of pollutants through biomagnification. Therefore, due to these interactions, benthic organisms can serve as effective indicators of HM pollution in aquatic ecosystems.

Macrophytes, as the primary producers in lake ecosystems, are excellent bioindicators of HM contamination due to their ability to accumulate these metals in their tissues (Vardanyan & Ingole, 2006; Khan et al., 2008; Phaenark et al., 2024). The accumulation of HMs in macrophytes portends the extent and potential impact of pollution in the lake environments (Ali et al., 2013; Wang et al., 2014). Some macrophytes, such as *Eichhornia crassipes*, *Pistia stratiotes*, and *Spirodela polyrhiza,* can accumulate large quantities of HMs without exhibiting toxicity symptoms or reduced growth (Mishra & Tripathi, 2008), making them highly suitable for phytoremediation and long-term environmental monitoring.

The potential of macrophytes as bioindicators has driven extensive research into species-specific accumulation capacities. Several freshwater species have been studied and applied in HM monitoring. For instance, *Ceratophyllum demersum* (hornwort), a free-floating submerged plant, shows high accumulation capacity for Cd, Pb, and Cu, making it an effective indicator in eutrophic and contaminated lakes (Ali et al., 2013). Similarly, *Myriophyllum spicatum* (Eurasian watermilfoil) was used in Iranian wetlands due to its broad distribution and significant bioaccumulation potential (Zamani-Ahmadmahmoodi et al., 2020). Emergent species such as *Typha latifolia* (broadleaf cattail) and *Phragmites australis* (common reed) are also effective in monitoring and phytoremediation of sediment-bound metals, particularly in littoral zones where such contamination poses ecological risks (Vymazal, 2011). Beyond their abilities to accumulate contaminants, macrophytes are advantageous for monitoring due to their sedentary nature, high biomass, and ease of sampling and identification (Bhatta & Patra, 2020; Ouma et al., 2022). Macrophytes have limited mobility and are unable to evade the dynamic interactions of hydrodynamic forces, nutrient gradients, and other physicochemical fluctuations that influence their survival within aquatic environments (Bhatta & Patra, 2020). Therefore, their assemblages can effectively indicate the targeted stressor or pressure. Indeed, Macrophytes selectively uptake HMs metals through specialized root systems, metal-specific transporters, and binding molecules (Heisi et al., 2023). This underpins the rationale for selecting particular macrophyte species to target particular metals in phytoremediation applications (e.g., Demarco et al., 2023; Diksha et al., 2022; Preetha & Kaladevi, 2014). In addition, their large size and tolerance to metal exposure make them well-suited for both field-based assessments and controlled laboratory experiments (Afzal, 2023; Samecka-Cymerman & Kempers, 2004). Therefore, these traits, along with their ecological roles and affinity for metal accumulation, highlight the utility of macrophytes as reliable indicators and effective agents in the assessment and remediation of HM pollution.

Although the use of macrophytes as bioindicators of metal pollution has been studied, some regions remain underexplored regarding the potential of adopting this approach. In Nigeria, freshwaters, mainly rivers, streams, and lagoons, have been reported to be threatened by HMs pollution (Bawa-Allah, 2023). While lakes have received comparatively less attention, the few available studies have indicated similar concerns, with anthropogenic activities being identified as a major source of HM enrichment in these ecosystems (e.g., Chukwuemeka et al., 2020; Ogunkunle et al., 2016). However, limited attention has been given to assessing the capacity of macrophytes to indicate pollution levels and potential ecological risk. To address this gap, this study assessed the HM concentration in sediment and selected common macrophytes, *Ludwigia erecta* and *Vossia cuspidata,* from Lake Tagwai and Old Gawu. These are municipal lakes in North-Central Nigeria, vital for the livelihoods of surrounding communities, providing essential water resources for domestic and agricultural use as well as fish (Ndatimana et al., 2023). The findings are expected to provide insight into the ecological health of these water bodies and evaluate the capacity of macrophytes to accumulate HMs, thereby indicating their potential for bioremediation. Ultimately, this research aims to support effective monitoring of municipal lake water quality and promote sustainable water resource management in the region.

2 Materials and Methods

2.1 Study area Description

The study was conducted from two municipal lakes in North-Central Nigeria, Old Gawu, located in the Federal Capital Territory (FCT), Abuja, and Tagwai Lake, located in Minna, Niger State. Old Gawu Lake is located at 6°35′55.6″E longitude and 9°30′41.7″N latitude, whereas Tagwai Lake lies in Minna at coordinates 6°39′40.95″E and 9°33′59.958″N (Fig. 1). These lakes are surrounded by subsistence agriculture supported by dry season irrigation activities (Ndatimana et al., 2023). The lakes offer various services to neighbouring communities through watering livestock, fishing, laundry, and recreation. The north-central region of Nigeria experiences a tropical climate

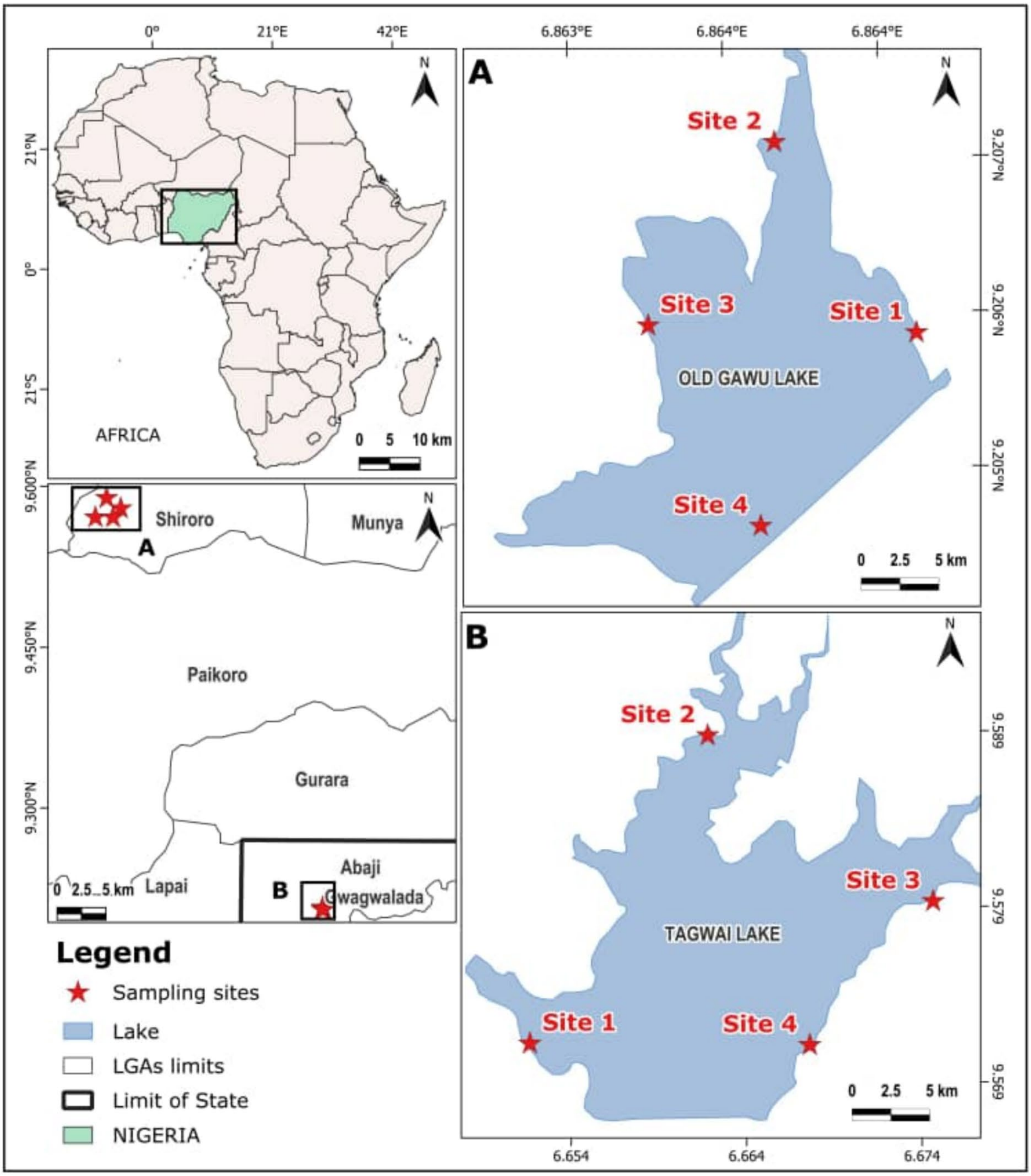

Fig. 1 Map showing sampling sites (in set: Africa (top left), Part of North central Nigeria (bottom left), **A**: Old Gawu Lake, and **B**: Tagwai Lake

with an average temperature of 30 °C, relative humidity of 61%, and approximately 1334 mm of annual rainfall (Chukwuemeka et al., 2020).

2.2 Field Sampling

The sediment and macrophyte samples were collected bimonthly from April to August 2022. The sediments samples were collected from four sites per lake from littoral zone, whereas the common macrophytes, *Ludwigia erecta* and *Vossia cuspidate* were sampled from two sites (site 1 and site 2) of each lake (Fig. 1). The sampling for the two lakes was done on two consecutive days to ensure consistency in sampling effort and timing. The surface sediment samples of approximately one kilogram (per site) were picked from the profile (0–50 cm depth) using a handheld stainless-steel shovel, emptied into Ziploc plastic bags. The macrophytes were manually collected by hand, washed with lake water, and then rinsed with distilled water prior to being placed in Ziploc plastic bags. Samples were transported to the Water Resources, Aquaculture and Fisheries Technology (WAFT) laboratory, Federal University of Technology (FUTMINNA) for further analysis.

2.3 Determination of Heavy Metals from the Sediments and Macrophytes

Sediment samples were air-dried, ground with mortar, and sieved through a 250 µm sieve to obtain a uniform texture before being digested. For each sample, 1.00 g was transferred to a 100 mL tall-form beaker, followed by addition of 30 mL of a 1:1 (v/v) solution of concentrated HNO_3 and deionized water. The mixture was gently heated on a hotplate, magnetic stirring until the volume reduced to approximately 5 ml, then allowed to cool. After cooling, another 10 mL of 1:1 HNO_3 was added, and the digestion was repeated. The solution was then filtered through Whatman Grade 42 (2.5 µm pore size). The filter paper was rinsed with 0.25 M HNO_3. The final filtrate volume was brought to 50 ml with deionized water. Concentrations of HMs (Cd, Cr, Cu, Mn, and Pb) were analyzed using a Microwave Atomic Emission Spectrometer (Agilent 4210 MP-AES, California, USA) with calibration performed using standard solutions. The limits of detection (LOD) and quantification (LOQ) for the analyzed metals were determined from instrument specifications and calibration data. The LODs were as follow: Cd = 0.05 µg/L, Cr = 0.8 µg/L, Cu = 0.5 µg/L, Pb = 1.0 µg/L, and Mn = 0.3 µg/L, with LOQs calculated as three times the respective LODs. Procedural blanks and replicate analyses were included to ensure analytical accuracy. The calibration standards and quality-control checks were performed, and recoveries for the target metals ranged between 90 and 105%. Results were calculated using the formula: metal concentration (mg/kg) = (C × V) ÷ M, where C is the concentration in the digest (µg/mL), V is the final volume (mL), and M is the sample weight (g).

Macrophyte samples were dried in a fan-forced oven at 80 °C for 24 h, then ground into fine powder using a mortar and pestle before being sieved through a 2 mm mesh (Galal & Shehata, 2015a, 2015b). For digestion, 20 mg of the prepared powder sample was mineralized in a Milestone Microwave with a 2:2 (v/v) solution of nitric acid (HNO_3) and hydrochloric acid (HCl) (Kastratović et al., 2018). After digestion, the samples were cooled, and the filtrate was transferred into a 100 mL volumetric flask and diluted to volume with distilled water. Concentrations of HMs (Cd, Cr, Mn, Pb, and Cu) were determined using the same procedures as for sediment.

2.4 Ecological Risk Assessment using Potential Ecological Risk Index

The Potential ecological risk (RI) method developed by Hakanson (1980) was applied. This is a sediment-associated HM contamination index which considers the effects of metals to humans and ecosystems (Hoang et al., 2025; Huang et al., 2020a, 2020b). This index incorporates the contamination factors (C_f^i) of each metal (Eq. 1), the individual ecological risk factor (Er) for each metal (Eq. 2), and the total of these values yields the overall Potential Ecological Risk Index (RI) (Eq. 3; Hakanson, 1980).

$$C_f^i = \frac{C_i}{C_{background}} \tag{1}$$

$$E_r^i = T_r^i \times C_f^i \tag{2}$$

$$RI = \sum_{i=1}^{n} E_r^i = \sum_{i=1}^{n} \left(T_r^i \times C_f^i \right) \tag{3}$$

where C_i stands for measured concentration of metal in sediment, whereas C_f^i is the contamination factor of such metal. E_r^i is the ecological risk factor of metal, whereas T_r^i stands for toxic-response factor of metal. The toxic-response factors (Tr) used for the potential ecological risk calculations followed Hakanson (1980), applying standard values for the assessed metals: Cd (Tr = 30), Pb (Tr = 5), Cu (Tr = 5), Cr (Tr = 2), and Mn (Tr = 1). The ecological risk of each individual metal (E_r) and the cumulative risk (RI) were assessed and categorized following Hakanson (1980) (Table 1). These indices provide complementary insight into metal accumulation relative to natural background levels and the potential ecological implications of the measured concentrations. Due to the absence of region-specific lithogenic baselines for North-Central Nigeria, Post-Archean Australian Shale (PAAS) were applied as reference concentrations (Bau et al., 2018; McLennan, 1989). Consequently, Bioaccumulation factors (Eq. 4), were used to supplement and contextualize the sediment-based indices.

2.5 Calculation of Bioaccumulation Factors

Bioaccumulation factor (BAF) is one of the main indicators of macrophyte efficiency in accumulating HMs from their environment into plant tissues (Xing et al., 2013). It was calculated as the ratio of metal concentration in macrophyte tissues (mg/kg dry weight) to the metal concentration in the sediment of the same biotope. Thus, to calculate the BAF, the following equation (Eq. 4), adopted from Zhai et al. (2016), was applied.

$$Bioaccumulation\ Factor\ \left(BAF_{sediment}\right) = \frac{Cmacrophyte\,(dry)mg/kg}{Csediment\,(dry)mg/kg} \tag{4}$$

2.6 Data Analysis

The comparison of HM concentrations per site for each lake was tested using the Kruskal–Wallis test, followed by Dunn's post hoc test, in case of significant difference ($p < 0.05$). To compare the HM concentrations between sediments and macrophytes of similar sites (biotope), the Mann–Whitney U test was used. Meanwhile, Spearman correlation was applied to assess the relationship between HM concentration in sediment and macrophytes. The Principal Component Analysis (PCA) was conducted to assess the overall variation in HM concentrations among macrophyte species (*L. erecta* and *V. cuspidata*) and sediment samples across the lakes. To test the differences in multi-metal composition among sample media (sediments and macrophytes), a PERMANOVA was performed using Bray–Curtis dissimilarity. All data analyses from descriptive (mean and standard deviations of HM concentration), graphs, and the comparative tests were performed in R software (RCore Team, 2024).

3 Results

3.1 Concentration of Heavy Metals in Sediments of Tagwai and Old Gawu Lakes

The five tested HM were detected at all sampling stations in both lakes. In Tagwai Lake, the order of HM concentration in sediments was Cu > Mn > Cr > Pb > Cd (Table 2). The highest median Cu concentration (7.21 mg/kg) was recorded at Site 4, and the lowest concentration (5.02 mg/kg) was observed at Site 2. Although slight variations in metal concentrations were observed across the sites,

Table 1 Classification of Potential Ecological Risk Index (Hakanson, 1980)

E_r^i value	Level of potential ecological risk	RI value	Level of potential ecological risk
$E_r^i < 40$	Low risk	$RI < 150$	Low ecological risk
$40 \le E_r^i < 80$	Moderate risk	$150 \le RI < 300$	Moderate ecological risk
$80 \le E_r^i < 160$	Considerable risk	$300 \le RI < 600$	Considerable ecological risk
$160 \le E_r^i < 320$	High risk	$RI \ge 600$	Very high ecological risk
$E_r^i \ge 320$	Very high risk		

Table 2 Median and range (Min–Max) of heavy metal contents in sediments at Tagwai and Old Gawu lakes

Lake	Site	Cu	Cr	Cd	Pb	Mn
Old Gawu	S1	3.98 (3.44–4.52)	10.99 (8.26–13.71)	0.495 (0.37–0.62)	2.63 (2.21–3.05)	6.765 (3.33–10.2)
	S2	4.545 (3.98–5.11)	12.925 (10.45–15.4)	0.525 (0.23–0.82)	1.835 (0.46–3.21)	4.785 (4.47–5.1)
	S3	5.07 (3.92–6.22)	14.825 (12.47–17.18)	0.395 (0.17–0.62)	2.315 (2.01–2.62)	7.22 (4.14–10.3)
	S4	5.5 (5.16–5.85)	16.14 (14.06–18.22)	0.58 (0.34–0.82)	2.73 (2.65–2.81)	8.395 (6.43–10.36)
Tagwai	S1	5.785 (4.35–7.22)	3.63 (3.55–3.71)	1.44 (1.4–1.48)	1.9 (1.4–2.4)	7.21 (1.16–13.26)
	S2	5.015 (4.18–5.85)	4.44 (3.01–5.87)	0.415 (0–0.83)	1.88 (1.84–1.92)	2.48 (1.16–3.8)
	S3	6.28 (5.32–7.24)	4.46 (4.2–4.72)	0.215 (0–0.43)	1.31 (1.1–1.52)	6.19 (2.4–9.98)
	S4	7.205 (6.21–8.2)	5.23 (4.16–6.3)	1.35 (0.9–1.8)	2.215 (1.32–3.11)	6.12 (1.82–10.42)

these differences were not statistically significant. Nevertheless, Site 4 showed relatively higher concentrations of all metals, while Site 2 had comparatively lower values (Table 2). Regarding dominant metals per site, Cu was highest at Site 4, Cr and Pb at Site 2, Cd at Site 1, and Mn at Site 1. Meanwhile, the overall order of metal concentrations in the sediments of Old Gawu Lake was Cr > Mn > Cu > Pb > Cd. The highest median concentration of Cr, 16.14 mg/kg, was observed at Site 4, and the lowest, 10.99 mg/kg, at Site 1 (Table 2). Cadmium had the lowest recoded concentration among the studied metals, with a median value of 0.40 mg/kg, recorded at Site 3. Metals were dominant at different sites: Cu at Site 3; Cr, Cd, Mn, and Pb at Site 4 (Table 2). However, there was no significant spatial difference among the sites of Old Gawu Lake ($p > 0.05$). When comparing metal concentrations between the two lakes, only Cr showed a statistically significant difference ($p < 0.05$), with higher levels recorded in Old Gawu Lake.

3.2 Pollution Indices and Ecological Risk

The calculated CF values ranged between 0.006 and 3.53, indicating low contamination for Cu, Cr, Pb, and Mn, and moderate to considerable contamination for Cd. The contamination factor for Cd were above 1 in all sites, reaching up to 3.5 in Tagwai Lake (Table 3). The PLI values for the two lakes were 0.27 and 0.34 for Old Gawu and Tagwai, respectively. Based on PLI, both lakes are considered unpolluted with respect to the studied metals (PLI < 1), although Tagwai Lake expressed slightly higher PLI than Old Gawu lake due to relatively higher Cd concentration. This was emphasized by RI which classified both lakes under low risk, according to Håkanson's classification (RI < 150). Nevertheless, Cd's Er values (50–106) approach the "considerable risk" threshold. Thus, while the total risk index indicates low overall pollution, Cd contributes more than 95% of total RI.

3.3 Concentration of Heavy Metals in Macrophytes of Tagwai and Old Gawu Lakes

In both Tagwai and Old Gawu Lakes, all evaluated HMs were detected in the selected macrophytes. In *L. erecta* from Tagwai Lake, the highest median concentrations were 2.43 mg/kg, 7.25 mg/kg, 0.5 mg/kg, 2.43 mg/kg, and 4.31 mg/kg for Cu, Cr, Cd, Pb, and Mn, respectively, where all are from site two, except Mn from site 1. In the same species from Old Gawu Lake, the highest median concentrations were recorded from sites 1, 2, 2, 1, and site two with 1.88, 5.83, 1.1, 0.83, and 2.21 for Cu, Cr, Cd, Pb, and Mn, respectively (Table 4). On the other hand, in *V. cuspidata* collected from Tagwai Lake showed high

Table 3 Contamination factors (CF), Pollution lead (PLI), and Potential Ecological Risk (RI) for Old Gawu and Tagwai Lakes

Lake	Cu		Cr		Cd		Pb		Mn		PLI	RI	Risk level
	CF	Er	CF	Er	CF	Er	CF	Er	CF	Er			
Old Gawu	0.106	0.53	0.15	0.3	1.67	50.1	0.119	0.6	0.008	0.01	0.27	51.5	Low
Tagwai	0.135	0.68	0.05	0.1	3.53	106	0.091	0.45	0.006	0.01	0.34	107.2	Low–Moderate (Cd)

Table 4 Median and range (Min–Max) of heavy metal concentration (mg/kg) in the macrophyte tissues from Tagwai and Old Gawu lake

Lakes	Species	Site	Cu	Cr	Cd	Pb	Mn
Tagwai	L. erecta	Site1	1.52 (0.78–2.42)^{Aa}	5.7 (4.86–6.62)^{Aa}	0.4 (0.4–0.42)^{Aa}	1.84 (1.28–2.43)^{Aa}	4.31 (1.72–5.44)^{Aa}
		Site2	2.43 (1.9–2.5)^{Aa}	7.25 (6.3–7.83)^{Aa}	0.5 (0.3–0.52)^{Aa}	2.43 (1.74–3.76)^{Aa}	0.5 (0–7.31)^{Aa}
	V. cuspidata	Site1	3.47 (1.34–4.44)^{Aa}	5.12 (4.84–7.32)^{Aa}	0.42 (0–0.72)^{Aa}	2.16 (1.38–2.32)^{Aa}	7.42 (1.42–8.21)^{Aa}
		Site2	1.42 (0.86–2.14)^{Aa}	6.32 (5.55–6.96)^{Aa}	0.1 (0–0.6)^{Aa}	1.46 (1.2–2.43)^{Aa}	6.84 (5.35–7.98)^{Aa}
Old Gawu	L. erecta	site1	1.88 (1.72–2.42)^{Aa}	4.39 (3.42–4.92)^{Aa}	0.41 (0.3–0.95)^{Aa}	0.83 (0.62–1.78)^{Aa}	2.14 (1.66–3.14)^{Aa}
		site2	1.29 (0.85–1.34)^{Aa}	5.84 (4.5–6.28)^{Aa}	1.1 (0.78–1.31)^{Aa}	0.5 (0.3–0.95)^{Aa}	2.21 (2.2–3.14)^{Aa}
	V. cuspidata	site1	1.65 (0.66–3.09)^{Aa}	6.51 (5.4–6.7)^{Aa}	0.2 (0–2.13)^{Aa}	1.2 (0.9–2.44)^{Ab}	4.42 (2.27–6.32)^{Ab}
		site2	1.34 (0.74–1.82)^{Aa}	5.65 (5.16–6.4)^{Aa}	1.35 (0–1.45)^{Aa}	1.73 (1.72–3.27)^{Ab}	3.58 (2.36–4.8)^{Ab}

Values with the same capital letter indicate no significant difference in HM concentrations among macrophyte species at the same site ($P < 0.05$). Values with the same lowercase letter indicate no significant difference among species within the same lake ($P < 0.05$)

median concentration of Cu at site 1 (3.47 mg/kg), Cr at Site 2 (6.32 mg/kg), Cd at Site 1 (0.42 mg/kg), Pb at Site 1 (2.16 mg/kg) and Mn at Site 2 (7.42 mg/kg). In Old Gawu Lake, *V. cuspidata* showed particularly high median concentrations of HMs at certain sites: 1.65 mg/kg of Cu and 6.51 mg/kg of Cr at site 1, 1.35 mg/kg of Cd and 1.73 mg/kg of Pb at site 2, and 4.42 mg/kg of Mn at site 1 (Table 4). There was no significant difference in HM concentrations among different sampling sites within the same lake. However, *V. cuspidata* accumulated significantly higher Pb in Old Gawu Lake compared to Tagwai Lake, while Mn was significantly higher in *V. cuspidata* from Tagwai Lake than from Old Gawu Lake (Table 4).

3.4 Correlations and Multivariate Patterns of Heavy Metal Concentrations in Sediments and Macrophytes

Spearman correlation analysis between macrophyte and sediment metal concentration of the same biotope revealed that most metals showed weak to moderate correlation (r ranged from −0.73 to 0.69, $p > 0.05$). Heavy metal concentrations in macrophytes showed slight correlations with those in the sediments of the same site. In both lakes, Cr concentration in *L. erecta* and sediments showed a moderately positive correlation ($r = 0.68$ in Tagwai Lake and $r = 0.69$ in Old Gawu Lake). The same species also showed a low positive correlation with Pb in both lakes. In Tagwai Lake, *L. erecta* demonstrated low positive correlations with Cd and Mn, while a negative correlation with Mn was observed at Old Gawu Lake (Fig. 2). Meanwhile, HM in *V. cuspidata* and sediments showed a moderate positive correlation in Tagwai Lake. Low positive correlations for Pb were also recorded in both lakes for V. *cuspidata* ($r = 0.31$ in Tagwai and $r = 0.27$ in Old Gawu). Additionally, negative correlations with Cd and Cr were observed for *V. cuspidata* in Old Gawu Lake (Fig. 2).

To further explore the overall patterns in metal distribution and identify group trends among samples, PCA was performed. The first two principal components (PC1 and PC2) accounted for 53.6% of the total variation in the data (PC1 = 31.8%, PC2 = 21.8%). The biplot showed a degree of distinction between sediment and macrophyte samples. Sediment clustered toward the positive end of PC1, opponent to the macrophyte samples. Meanwhile, PERMANOVA results indicated a significant effect of sample type (sediments and macrophytes) on HM profiles ($F = 8.62$, $R^2 = 0.28$, $p = 0.001$). However, there was a shared variance in HM profiles as indicated by the overlap among the sample types (Fig. 3).

3.5 Bioaccumulation Factors in Tagwai and Old Gawu Lakes

Ludwigia erecta exhibited bioaccumulation potential for certain HMs in both studied lakes. In Old Gawu Lake, only Cd showed a bioaccumulation factor (BAF) greater than 1 (BAF = 1.53), indicating a higher concentration in plant tissue than in sediment. Other metals in this lake had BAF values below 0.5. In Tagwai Lake, *L. erecta* accumulated more Pb and Cr than in the surrounding sediments, with BAF values of 1.26 and 1.25,

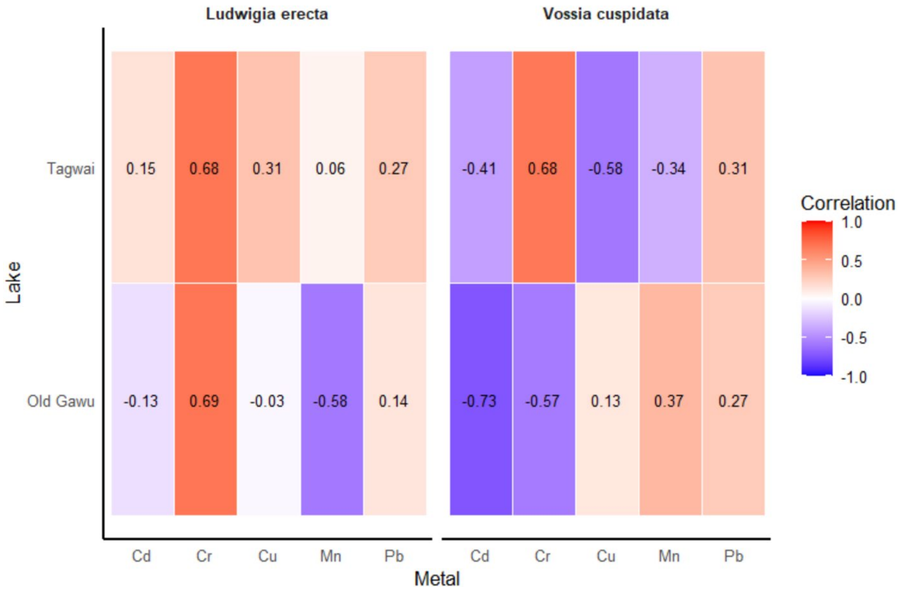

Fig. 2 Correlation of heavy concentration of heavy metals in macrophytes and sediments

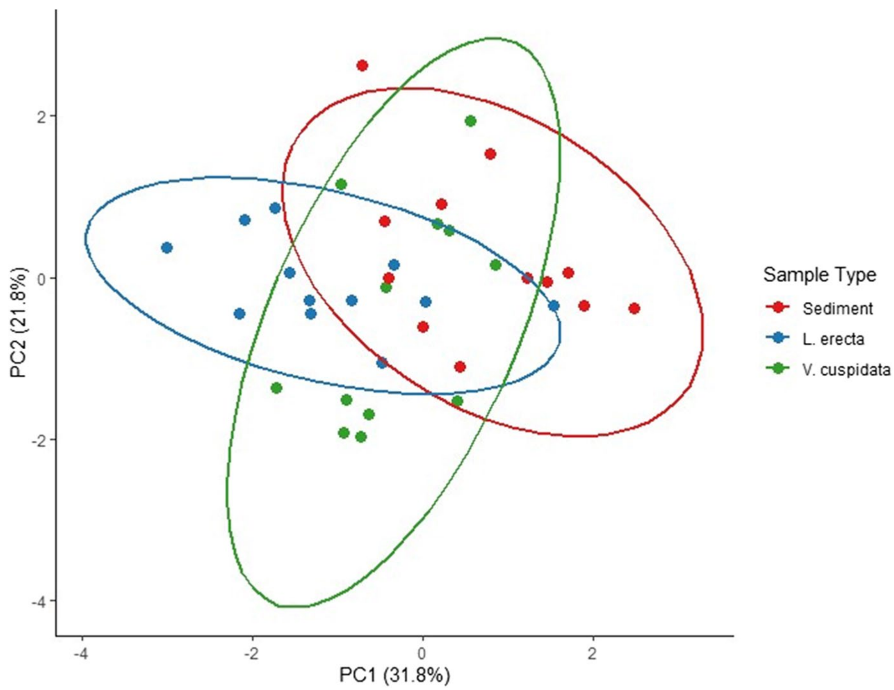

Fig. 3 Principal component analysis (PCA) of heavy metals in sediment and macrophytes of Tagwai and Old Gawu lakes

respectively (Fig. 3). Similarly, *V. cuspidata* in the same lake showed the ability to accumulate Mn, Pb, and Cr (BAF > 1), while Cu and Cd had the lowest accumulation levels (BAF > 0.5). Meanwhile, at Old Gawu Lake, *V. cuspidata* accumulated more Cd than in the sediment (BAF > 1), while other metals had BAF values below 1, following the order: Cd > Pb > Mn > Cr > Cu (Fig. 4). Although Cu showed low BAF, its concentrations in both species and their corresponding sediments were significantly different (L. erecta: V = 0, $p = 0.00049$; V. cuspidata: V = 3, $p = 0.0024$), unlike the rest, with slight differences ($p > 0.05$).

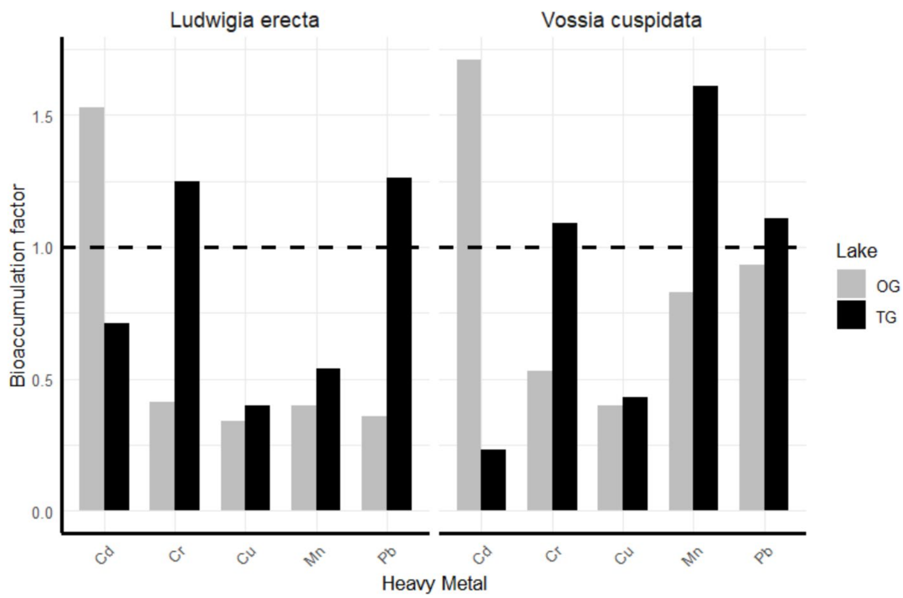

Fig. 4 Bioaccumulation factor (BAF) of heavy metals in macrophytes from Old Gawu (OG) and Tagwai (TG) Lakes

4 Discussion

4.1 Concentration of Heavy Metals in Sediments of Tagwai and Old Gawu Lakes

The results highlighted both distinct differences and notable similarities in the HM profiles of the two lakes, providing insights into potential contamination sources and underlying environmental processes. In Tagwai Lake, there was a slight variation in metal concentration, however, they were not statistically significant. This could be associated with the influence of diffuse, non-point sources from agricultural runoff, residential wastewater, and atmospheric deposition (Hu et al., 2022). The elevated Cu concentrations in Tagwai Lake are plausibly linked to agricultural inputs (e.g., copper-based pesticides), urban runoff, and corrosion of metal infrastructure, including pipes and fittings (Alengebawy et al., 2021; Pesce et al., 2024). Indeed, the lake's catchment is characterized by subsistence farming and urban residential areas, which are likely sources/contributors of the observed Cu levels (Ndatimana et al., 2023; Pandey & Dwivedi, 2009). Copper pollution in the sediment of the same lake was previously reported by Chukwuemeka et al. (2020), who attributed the high concentration to anthropogenic waste and industrial activities in the vicinity. Although Chukwuemeka et al. (2020) reported moderate HMs pollution in Lake Tagwai, Pb was not detected in the water and sediments. However, the present finding showed Pb at a detectable level in sediment, plausibly ascribed to an increase in the use of lead materials during water abstraction for irrigation and fishing activities.

On the other hand, Old Gawu Lake showed a different HM distribution where the highest median concentration of Cr was recorded at Site 4 (16.14 mg/kg), the same site with elevated levels of Cd, Mn, and Pb, plausibly indicating a localized pollution hotspot (Kapungwe, 2013). The elevated Cr concentrations could be resulting from municipal and industrial sewages, as well as natural geological sources, such as chromite-bearing rock formations (Prego et al., 2014; Yozukmaz & Yabanlı, 2023). This finding was not surprising, given the customary practice of stone and gravel washing for construction purposes around the site. These gravels comprise various metals, dislodging into the lake during the washing process (Singh et al., 2022), contributing to HM enrichment.

In both lakes, Site 4 consistently exhibited the highest concentrations of HMs, likely due to their proximity to inflow points, limited water circulation, and intensive human activities. These factors facilitate metal accumulation and limit dispersion, particularly in littoral zones where pollutant-rich runoff enters the lakes (Abotalib et al., 2023; Sanad et al., 2025a). Site-specific observations revealed common anthropogenic activities at Site 4, such as laundry, boat cleaning, swimming, and fishing gear preparation, animal watering, which may contribute directly to the elevated metal loads (Singh et al., 2022). The variation in dominant metals across sites within each lake suggests that metal input sources differ locally, reflecting the heterogeneity of land use across the catchments (Huang et al., 2022; Sanad et al., 2025b). However, catchment geology and hydrological patterns cannot be overlooked when discussing the possible sources of this pollution. These patterns influence sediment deposition and metal retention, playing a significant role in shaping the lakes' contaminant profiles (Sanad et al., 2025b; Stauch et al., 2024).

4.2 Sediment Contamination and Ecological Risk

The contamination factor for Cd were above 1.0 in all sites, reaching up to 3.5 in Tagwai Lake (Fig. 2). Based on PLI values, both lakes are considered unpolluted with respect to the studied metals ($<$PLI<1). However, Tagwai Lake exhihibited slightly higher PLI than Old Gawu Lake due to relatively higher Cd concentration. This suggests marginally elevated metal inputs, in agreement with its higher Cd levels. Meanwhie, the total risk index indicates low overall pollution, Cd contributes more than 95% of total RI. This may indicate potential anthropogenic Cd enrichment. The elevated contamination of Tagwai Lake with Cd could be rising from a combination of anthropogenic inputs such as agricultural activities, industrial process, and domestic wastes, as well as natural processes like atmospheric deposition, and weathering or erosion of Cd-bearing rocks (Chetan et al., 2025: Kubier et al., 2019). This lake is located in a region that experiences long dry seasons (up-to 6 months), and is surrounded by irrigated vegetable farms that rely heavily on fertilizers and pesticides. The use of fertilisers particularly, phosphate-based types, which are reportedly used in the region (Ederigbe et al. 2024), has been reported as an important source of Cd in the environment (Li et al., 2020; Samrane & Bouhaouss, 2022). Additionally, Cd commonly occurs in gold bearing orebodies, and can be released in the environment during mining activities (Fashola et al., 2016). Numerous artisarnal gold mines are present in the vicinity of Tagwai Lake (Odukoya et al., 2022), and these operations could be a key source of Cd in the lake.

The sediment-based indices indicated that overall metal contamination in both Old Gawu and Tagwai Lakes was low to moderate. PLI values remained below 1, suggesting the lakes are generally unpolluted relative to the PAAS, and RI values indicated low ecological risk (RI <150) (Hakanson, 1980). Among the metals studied, Cd contributed disproportionately to the ecological risk due to its high toxic-response factor, despite its low absolute concentrations in sediments. This pattern highlights the importance of considering both concentration and toxicity when evaluating ecological risk. Although Cr and Cu were present at higher concentrations than Cd in some sites, their contribution to the RI was minimal due to their lower toxic-response factors (Hakanson, 1980; Xiang et al., 2019). Mn and Pb also contributed little to overall ecological risk, reflecting their comparatively low sediment enrichment. Although the calculated potential ecological risk was low, we acknowledge that using global background values may differ from the true, site-specific geochemical background of these lakes. Therefore, to strengthen ecological inference, integrating multiple assessment approaches such as sediment-based indices together with biota-based metrics (e.g., accumulation in aquatic species) is recommended to detect risks at a finer ecological scale.

4.3 Concentration of Heavy Metals in Macrophytes of Tagwai and Old Gawu Lakes

Both species (*L. erecta* and *V. cuspidata*) accumulated detectable levels of all tested HMs, reflecting widespread contamination within the lakes (Vardanyan & Ingole, 2006; Martinez & Shu-Nyamboli, 2011, Nafea & Ali, 2019; Outa et al., 2020). This indicates that these macrophytes are capable of accumulating HMs, likely influenced by sediment-associated bioaccessible metal fractions (Zhang et al., 2014). No significant spatial differences were observed within each lake, suggesting a relatively uniform distribution of contaminants in the macrophytes. Given the small size of the lakes, pollution can easily be diffused across all sampling sites of each lake (e.g., Pan et al., 2023).

Between lakes, *V. cuspidata* exhibited significantly higher Pb concentrations in Old Gawu Lake, while Mn levels were significantly higher in Tagwai Lake. This could be attributed to the higher bioavailability of these metals compared to other HMs in the respective lakes, combined with the root absorption capacity of *V. cuspidata* (Skorbiłowicz & Sidoruk, 2025; Zhang et al., 2014). Moreover, it showed a greater capacity to accumulate relatively higher concentrations of most metals compared to *L. erecta*, indicating its potential suitability as a bioindicator and phytoremediation agent (Outa et al., 2020). Indeed, *V. cuspidata* has been used in various phytoremediation studies (Bhat et al., 2022; Farahat et al., 2021a; Galal et al., 2017). Despite slight variations, there was no significant difference in the accumulation of HMs by *L. erecta* across the lakes. This uniformity may be attributed to its relatively stable and species-specific HM uptake mechanisms (e.g., Aveiga et al., 2023), which enable it to regulate metal absorption despite minor environmental fluctuations. Such regulation is considered an avoidance strategy, whereby plants limit HM uptake and restrict their translocation into tissues (Dalvi & Bhalerao, 2013; Yan et al., 2020). This physiological regulation may contribute to the consistent levels of HMs observed in *L. erecta* across different sites. However, species within the same genus, such as *Ludwigia octovalvis*, have been reported to accumulate arsenic from sediments and have been utilized in phytoremediation efforts (Onyia et al., 2021; Titah et al., 2013). Thus, *L. erecta* might exhibit a conservative uptake strategy for certain metals, although some species of the same genus can still demonstrate significant phytoremediation potential, depending on the specific metal and environmental context.

The detection of toxic elements such as Cd and Pb in both Tagwai and Old Gawu Lakes and both tested macrophytes raises ecological and public health concerns, particularly given that these lakes support fishing, irrigation, or domestic water use (Phaenark et al., 2024). While metals concentrations in macrophytes are likely influenced by the levels in sediments, it is important to note that whole-plant analysis does not account for tissue-specific accumulation. Metals are typically concentrated in the roots, with limited translocation to stems and leaves, unless the species are hyperaccumulators (Mishra & Tripathi, 2008; Soon et al. 2012; Leitenmaier & Küpper, 2013). Despite this limitation, the presence of Cd and Pb in macrophytes indicates environmental exposure to these metals and their potential entry into the aquatic food web. Considering human exposure through ingestion of contaminated water and food, these metals may pose health risks, including neurological, cardiovascular, and renal effects, as well as carcinogenic outcomes (Ahmed et al., 2016; Benoit et al., 2019; Khan et al., 2008). These findings highlight the importance of continued ecological monitoring and, in future studies, tissue-specific analyses and further quantitative human health risk assessments.

4.4 Correlations and Multivariate Patterns of Heavy Metal Concentrations in Sediments and Macrophytes

The correlations between HM concentrations in sediment and macrophytes suggest species- and site-specific uptake patterns. *L. erecta* exhibited moderate positive correlations with Cr in both lakes. This consistent accumulation trend is aligned with the known ability of *L. erecta* to uptake trace metals from sediment-rich environments (Nafea & Ali, 2019). It also showed weak positive relationships with Pb, Cd, and Mn at Tagwai Lake, while a negative correlation with Mn at Old Gawu Lake. Similar patterns have been reported in other studies and are often linked to redox-dependent speciation or, competitive ion uptake (Heisi et al., 2023; Li et al., 2023[b]), although these factors were not directly measured in the present study. Such factors can modulate metal uptake mechanisms independently of bulk sediment concentrations, potentially explaining observed variability in correlation. Meanwhile, *V. cuspidata* exhibited a moderate overall correlation with HMs in the sediment of Tagwai Lake, indicating that its tissue metal content reflects environmental levels to a measurable extent. This indicate that the species may indicate sediment-associated HMs, supporting its potential use as a general bioindicator of aquatic metal pollution (Martinez & Shu-Nyamboli, 2011; Farahat et al., 2021b; Awad et al., 2023). However, its negative correlations with Cd and Cr at Old Gawu may indicate exclusion strategies or site-specific geochemical limitations to uptake. Indeed, some macrophytes may have developed adaptive mechanisms to prevent metal uptake or to minimize its impact on tissues (Dalvi & Bhalerao, 2013; Nayek et al., 2010). Thus, both species traits and local environmental factors govern metal accumulation dynamics in macrophytes. This is emphasized by the results of PCA, which show the contribution of the sample group to the metal profile.

This could be ascribed to the specific metal uptake ability by macrophytes, concentration of HMs in sediment, and the bioaccessibility of sediment-associated metal fractions (Oliveira et al., 2024).

4.5 Bioaccumulation Factors in Tagwai and Old Gawu Lakes

The bioaccumulation factor (BAF) values for *L. erecta* and *V. cuspidata* reveal distinct patterns of metal uptake that are both species- and site-specific. In *L. erecta*, Cd exhibited the highest BAF (1.53) in Old Gawu Lake. Since Cd is a non-essential element, it is primarily taken up passively through cell walls and non-specific transporters for essential cations such as Ca^{2+}, Zn^{2+}, Fe^{2+}, or Mn^{2+} (Zhang et al. 2024). Its uptake is largely driven by concentration gradients and competition with essential ions, and it is readily translocated from roots to above-ground tissues due to its mobility within plant transport pathways (Degryse & Smolders, 2011; Thomas, 2021). Other metals in this lake showed BAF values below 0.5, portending limited accumulation in the macrophytes. This pattern may be associated with limited metal availability at the sediment–water interface and low dissolved metal fractions in the water phase (Xiong et al., 2024; Rashid et al., 2023). Although root exudates can locally acidify the rhizosphere and increase metal solubility (Xing et al., 2023), their influence under the present conditions appears limited, as whole-plant analysis does not resolve tissue-specific accumulation pathways..

In Tagwai Lake, *L. erecta* exhibited BAF values greater than one for Pb (1.26) and Cr (1.25), indicating strong accumulation in this environment. This pattern may reflect higher bioavailability or mobility of these metals, although confirmation would require porewater or sequential extraction data. This is consistent with previous findings that rooted macrophytes preferentially absorb more mobile metals under mesotrophic conditions (Xiong et al., 2024; Oliveira et al., 2024). While *L. erecta* demonstrated efficient accumulation of metals, its BAF patterns were more selective compared to *V. cuspidata*. It exhibited broader accumulation capacity, particularly in Tagwai Lake, where BAF values for Mn, Pb, and Cr exceeded 1. Notably, Mn reached a BAF of 1.61 as the highest record, indicating an efficient translocation mechanism or high Mn bioavailability in that lake (Branković et al., 2015; Zhang et al., 2014). These results were consistent with those of Farahat et al., (2021a, 2021b), who reported significant accumulation of Fe, Mn, and Zn by *V. cuspidata* in the River Nile, further supporting this species' potential for phytoremediation in freshwater systems across Africa.

In Old Gawu Lake, although only Cd had a BAF greater than 1 in *V. cuspidata*, the observed decreasing trend (Cd > Pb > Mn > Cr > Cu) indicated a selective uptake, possibly governed by metal speciation or plant-metal interactions (Bhat et al., 2022; Galal et al., 2017). A similar pattern was reported in Nairobi River, Kenya, where native macrophytes exhibited varying metal uptake capacities, influenced by local contamination levels and hydrological dynamics (Njuguna et al., 2017). The consistently low accumulation of Cu and Cd in Tagwai Lake (BAF < 0.5) for both macrophytes could be ascribed to metal exclusion mechanisms or lower solubility under prevailing environmental conditions (Nayek et al., 2010; Yan et al., 2020).

Notably, *V. cuspidata* was able to accumulate all HMs taken up by *L. erecta*, and in some cases, exceeded it in concentration, indicatinging a higher general phytoremediation potential. Its broader metal uptake profile, combined with higher BAF values in Tagwai Lake, supports its suitability for phytoremediation of aquatic environments contaminated with multiple metals. Meanwhile, *L. erecta* may be more suited for targeted remediation of Cd, Cr, or Pb, particularly in environments with high bioavailability of these elements. The study revealed clear species-specific metal accumulation patterns: Ludwigia erecta strongly accumulated Cd, while Vossia cuspidata showed broader uptake of Mn, Pb, and Cr. These patterns highlight the potential of specific macrophytes as bioindicators or phytoremediation candidates. Such information is valuable for guiding restoration efforts and managing heavy-metal exposure risks in tropical lake ecosystems.

5 Conclusion

This study highlights the complexity of heavy metal distribution and accumulation in two municipal lakes influenced by varied anthropogenic and natural factors. Distinct differences in sediment metal concentrations between Tagwai and Old Gawu Lakes show the role of local land use, pollution inputs, and catchment characteristics in shaping contaminant profiles. Both *L. erecta* and *V. cuspidata* accumulated detectable levels of all studied metals. However, *V. cuspidata* consistently exhibited higher uptake capacity, broader bioaccumulation potential, particularly for Mn, Pb, and Cr, and stronger sediment-plant correlations in Tagwai Lake. These patterns indicate a comparatively higher bioaccumulation capacity in *V. cuspidata*, indicating its potential relevance for phytoremediation applications pending further mechanistic evaluation. In contrast, the accumulation patterns observed in L. erecta portend a tendency for selective uptake of metals like Cd and Cr. The presence of toxic metals such as Pb and Cd in plant tissues and sediments, even in shallow, moderately impacted lakes, raises ecological and human health concerns, particularly where water is used for domestic, fishing, or agricultural purposes. The combined evidence from sediment-based contamination and ecological risk indices, together with species-specific bioaccumulation patterns in macrophytes, provides a clearer picture of metal dynamics in the studied lakes. While sediment indices indicated generally low to moderate contamination, the macrophyte data revealed notable uptake of Cd, Pb, Cr, and Mn, portending their continued bioavailability within the sediment-plant system. These complementary findings indicate the value of integrating sediment and biotic indicators in lake assessment and offer practical implications for management. In particular, the identified macrophyte species may serve as effective bioindicators and warrant further investigation for phytoremediation potential, supporting targeted monitoring, early warning systems, and informed restoration planning for tropical freshwater ecosystems. Future studies would benefit from water-phase metal measurements and analyzing separate macrophyte tissues to improve understanding of metal mobility and strengthen ecological risk assessments.

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Data Availability Data is available in the manuscript.

Declarations

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