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Phytoremediation Potential of Dominant Native Weeds in Metal Contaminated Tin Mining and Non Mining Soils in Jos-North Plateau Nigeria

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Abstract Tin mining has resulted in persistent contamination of soils by potentially toxic elements (PTEs), posing significant ecological and human health risks in many mining regions of Nigeria. Native weed species that naturally colonize contaminated sites may provide a sustainable and cost-effective approach for phytoremediation. This study evaluated the phytoremediation potential of five dominant native weed species (*Cyperus bipartitus*, *Spermacoce verticillata*, *Festuca rubra*, *Tithonia diversifolia*, and *Ipomoea asarifolia*) growing on active mining, abandoned mining, and non-mining soils in Jos North, Plateau State, Nigeria. Rhizosphere soils and plant tissues were analyzed for Cd, Pb, Zn, As, and Ni using Atomic Absorption Spectrophotometry (AAS), while phytoremediation performance was assessed using biological accumulation coefficient (BAC), bioconcentration factor (BCF), and translocation factor (TF). Nickel had the highest mean soil concentration, followed by Cd, Zn, As, and Pb. Significant differences ($p < 0.05$) were observed in PTE concentrations, BAC, BCF, and TF among weed species, plant tissues, and site conditions, indicating species-specific metal uptake, accumulation, and translocation patterns. *Cyperus bipartitus* and control-site populations of *Spermacoce verticillata*, *Ipomoea asarifolia*, and *Tithonia diversifolia* exhibited notable Pb phytoextraction potential, whereas *Festuca rubra*, *Spermacoce verticillata*, and *Ipomoea asarifolia* demonstrated effective Zn phytoextraction in mining-impacted soils. In contrast, *Festuca rubra* showed Cd phytostabilization potential, while *Cyperus bipartitus*, *Ipomoea asarifolia*, and *Tithonia diversifolia* displayed metal-specific phytostabilization capacities for Zn, As, Ni, and Pb depending on site conditions. Principal component analysis revealed that mining activities predominantly influenced the spatial distribution of potentially toxic elements, with Ni and Pb emerging as the principal indicators of mining-derived contamination. These findings demonstrated that dominant native weeds employ diverse, site-dependent remediation strategies that enhance their adaptation to heterogeneous contamination. Overall, the identified native weed species represent promising candidates for metal-specific and multi-metal phytoremediation of mining-impacted landscapes. The study provides baseline evidence to support the selection of indigenous plants for ecological restoration, sustainable management of contaminated soils, and remediation planning in tin mining regions of Nigeria and similar tropical environments.

Keywords: *phytoremediation, native weed species, potentially toxic elements, tin mining, bioaccumulation, phytostabilization, phytoextraction*

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1. Introduction

Mining activities are a major source of potentially toxic elements (PTEs) in terrestrial ecosystems and remain an important environmental challenge in several mineral-producing regions worldwide. The extraction and processing of mineral resources release PTEs and metal (loid)s such as cadmium (Cd), lead (Pb), arsenic (As), zinc (Zn), and nickel (Ni) into surrounding soils, where their persistence, non-biodegradability, and potential toxicity threaten soil quality, ecosystem functions, agricultural productivity, and human health through food-chain transfer [1,2]. Consequently, sustainable management of mining-contaminated soils has become a global environmental priority.

The Jos-North in Plateau state, North-Central Nigeria is one of the country's principal tin-mining regions [3,4]. The region has experienced decades of intensive mining, leaving numerous active and abandoned mine sites with little or no ecological restoration [4,5]. Previous studies around the region have reported elevated concentrations of PTEs in soils, water bodies, vegetables, fish, and medicinal plants within mining-impacted communities, indicating continued environmental contamination and potential human exposure [6,7]. These legacy contaminants continue to impair human and soil health as well as environmental quality, highlighting the urgent need for practical and sustainable remediation strategies suitable for resource-limited settings.

Among available remediation technologies, phytoremediation has gained considerable attention because it utilizes plants to extract, stabilize, or immobilize contaminants while improving soil structure and ecological functions. Compared with conventional physicochemical remediation methods, phytoremediation is relatively inexpensive, environmentally sustainable, and particularly suitable for large contaminated areas where financial and technical resources are limited [8,9]. Native plant species are especially attractive for phytoremediation because they are naturally adapted to local environmental conditions, produce substantial biomass, tolerate environmental stress, and readily colonize degraded landscapes [2,5]. Depending on their capacity to accumulate and translocate metals to harvestable shoots or retain them within root tissues, native plants may function as phytoextractor or phytostabilizer, respectively [2,10].

Although numerous studies have evaluated metal accumulation in cultivated crops [4] and selected plant species [7], however field-based assessments of the phytoremediation potential of indigenous weed species [2] in Nigerian mining environments remain limited [5]. This knowledge gap constrains the identification of suitable native plants for ecological restoration of contaminated mine lands, particularly under the heterogeneous contamination conditions typical of the Jos Plateau.

This study hypothesized that dominant native weed species naturally growing across active mining, abandoned mining, and non-mining soils exhibit species-specific and site-dependent differences in PTE uptake, accumulation, and translocation, enabling them to function as effective phytoextractors or phytostabilizers for different metals. Therefore, this study evaluated the phytoremediation potential of five dominant native weed species by determining the concentrations of Cd, Pb, Zn, As, and Ni in rhizosphere soils and plant tissues and assessing their bioaccumulation coefficient (BAC), bioconcentration factor (BCF), and translocation factor (TF). The findings will provide baseline information for selecting indigenous species for metal-specific and multi-metal phytoremediation and contribute to evidence-based ecological restoration and sustainable management of mining-impacted soils in Jos-North Plateau and similar tropical mining landscapes.

2. Materials and Methods

2.1. Study Area

The study area covers Jos North Local Government Area, Plateau state, North-Central Nigeria. It lies on Jos Plateau at an average height of about 1,200-1,300 metres above sea level and is characterized by distinct rainy (April-October) and dry (November-March) seasons. The mean annual rainfall ranges between 1,200 and 1,500mm, while its average temperature varies between 18°C and 28°C. The area is underlain by granitic rock and is historically recognized for extensive tin and columbite mining, leading to numerous active and abandoned mines. Four sites identified by preliminary survey as major mining and farming or grazing sites except for the control site, where no mining but only farming or grazing occurs were randomly chosen for the study. As indicated in Figure 1, the study area comprised of two active mining sites, where mining activities were on going at time of sample collection, namely Bida Bidi (N09°59'05.4", E08°52'11.4") and Hwoll Zangam (N09°59'43.0", E08°53'14.0"). It also included an abandoned mining site at Farin Lamba (N10°00'25.7",E08°50'43.0"), where mining stopped more than six months prior to sampling and a non-mining control site at University of Jos Permanent Site (N09°57'47.2",E08°53'12.3"), located appropriately 7km from the mining sites, were used as the study areas [11].

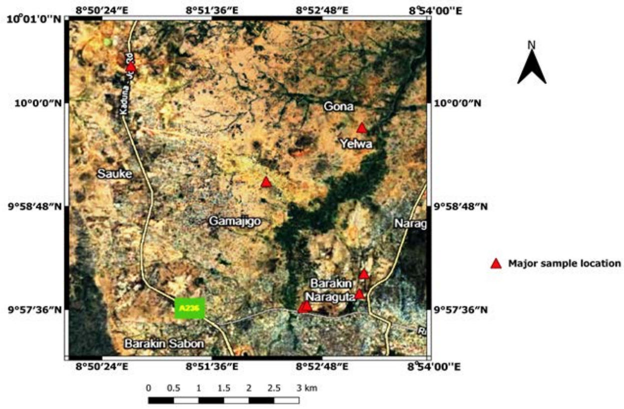

Figure 1. Map of studied sites indicated by red triangles

2.2. Sample Selection, Collection and Identification

Representative sampling across selected weed species and the study areas was achieved using factorial sampling arrangement [12], involving five dominant weed species, three biological replicates and four study sites adopted, giving a total of sixty (60) weed samples and their corresponding rhizosphere soil samples. The dominant weeds were determined using squared meter quadrat comprised of ten toss [13]. Based on the criteria of species that demonstrated higher relative density, rapid growth and substantial biomass (average size) [2], five dominant weeds namely *Cyperus bipartitus* (Slender flat sedge), *Spermacoce verticillata* (Shubby false Bottom weed), *Festuca rubra* (Red Fescues), *Tithonia diversifolia* (Mexican sunflower) and *Ipomoea asarifolia* (Morning glory) were selected, identified and their respective vouchers (JUHN23000659, JUHN23000662, JUHN23000661, JUHN23000664 and JUHN23000663) deposited at the Department of Plant Science and Biotechnology, University of Jos. Jos, Nigeria. The selected dominant weed species and corresponding rhizosphere soils of about 2000g were randomly excavated at about 20-30cm depth and carefully collected in triplicates with their intact roots using digger and big hole . Plant and rhizosphere soil samples were collected during the peak rainy season (August–September), when weed growth was at its maximum, to facilitate reliable species identification and assessment of metal accumulation under active growth conditions.

2.3. Metal Analysis

To evaluate Cd, Pb, Zn, As and Ni concentrations, collected weed samples were washed with distilled water; leaves, shoot and root were carefully separated by plucking. The weed parts and their rhizosphere soils were air-dried at room temperature for 72 hours and oven dried at 65° C for 48 hours to constant weights [2]. Dried samples were pulverized separately using clean porcelain mortar and pestle to obtain particle less than 0.2mm. A 0.5g portion of homogenized plant and soil samples were respectively wet digested in mixture of analytical grade concentrated nitric acid and perchloric acid (3:1 volume to volume ratio), on a digestion block, heated at about 120°C for 2 hours , until white fumes appeared [14]. After cooling to room temperature, the digests were diluted with deionized water to final volume of 50mL and filtered through Whatman No. 42 filter paper [15]. The concentrations of Cd, Pb, Zn, As and Ni were determined in the filtrate using flame atomic absorption spectrophotometer (Model Buck Scientific 210 VGP), following instrument calibration with appropriate standard solutions according to manufacturer's instruction.

2.4. Data Analysis

The ability of the selected weed species to absorb or immobilize the PTEs in soil was assessed using three phytoremediation indices, namely Bioconcentration Factor (BCF), Biological accumulation Coefficient (BAC) and Translocation Factor (TF) defined by the following equations (1-3)

$$BCF = \frac{PTEs\ concentration\ in\ root}{PTEs\ concentration\ in\ soil} \quad (1)$$

$$BAC = \frac{PTEs\ concentration\ in\ shoot}{PTEs\ concentration\ in\ soil} \quad (2)$$

$$TF = \frac{PTEs\ concentration\ in\ shoot}{PTEs\ concentration\ in\ root} \quad (3)$$

The PTEs concentrations represent Potentially Toxic Elements mean concentrations expressed in mg per sample kg (mg/kg).

The principal component analysis (PCA) was performed using soil and weed metal concentrations to identify key variation sources and species group patterns. Descriptive statistics of the PTEs (Cd, Pb, Zn, As and Ni) were expressed as mean ± standard error (SE). Two-way analysis of variance (ANOVA) was used to evaluate the effects of sites, weed species and tissues at $p < 0.05$, followed by post-hoc tests. Statistical analysis were performed using SPSS and Microsoft Excel.

3. Results and Discussions

3.1. Characteristics of the Selected Dominant Weeds

The floristic analysis illustrated in Table 1 revealed the selected dominant weed species belonging to five different families including four herbs and one shrub.

Table 1. Characteristics of Selected Dominant Weed Species on Mining and Non-mining Soils within Jos-North Plateau

Family	Common Names	Plant Species	Sampling Location Global Positioning System (GPS)	Source Site(Mining, Abandoned, Control)	Habit	Life Span	Mean Above ground size (cm)	Mean Under ground size (cm)	References
Cyperaceae	Slender flat sedge	*Cyperus bipartitus*	N09°59'05.3'' E08°52'11.4''	Mining	Herb	Annual	28.00	17.00	[16]
Rubiaceae	Shubby false Bottom weed	*Spermacoce verticillata*	N09°59'05.4'' E08°52'11.4'' N09°57'47.2'' E08°53'12.3''	Mining Control	Semi-woody herb	Perennial	30.60	45.00	[17]
Asteraceae	Mexican sunflower	*Tithonia diversifolia*	N10°00'25.9'' E08°50'42.9'' N09°57'47.2'' E08°53'12.3''	Abandoned Control	Shrub	Perennial	200.00	125.00	[18]
Convolvulaceae	Morning glory	*Ipomoea asarifolia*	N09°59'43.0'' E08°53'14.0'' N09°58'01.3'' E08°53'15.4''	Mining Control	Herb	Perennial	63.00	75.00	[19]
Poaceae	Red Fescues	*Festuca rubra*	N09°59'43.0'' E08°53'14.0''	Mining	Herb	Perennial	45.00	40.00	[20]

The studied sites showed some limited and uneven weed species diversity in the mining sites compared to the non-mining area. As shown in Table 1, the *Cyperus bipartitus* and *Festuca rubra* were present only in the studied active mining soil but absent in the abandoned mine and non-mining soils at the time of the study. Species with preferential abundant growth on contaminated sites but limited occurrence in uncontaminated soil, suggest they possess adaptive advantages and potentials for successful colonization and remediation in contaminated soil [2]. *Tithonia diversifolia* was absent in the active mines but present at both the abandoned mine and non-mining soils. The observed limited vegetation diversities could be due to disturbance arising from mining activities [13]. Additionally, limited natural weed colonization may be attributed to the differences in soil nature and contamination influenced by age and orientations of the sites, as well as the extreme soil characteristics that hinder the establishment of adapted species elsewhere [21]. Hence, the identified dominant weed species persisted in the studied areas, due to adaptations that allowed them thrive in the disturbed and unmined sites.

3.1.1. Cyperus bipartitus Torr

Cyperus bipartitus is an annual sedge characterized with V-shaped leaves, short lifecycle and dense fibrous roots. Although phytoremediation studies on *C. bipartitus* remain limited, a closely related *Cyperus rotundus* of the genus *Cyperus*, was previously reported to promote phytostabilization, through rhizosphere microbe mediated immobilization of heavy metals [22], thus supporting contaminated soil remediation potential of the genus *Cyperus* .

3.1.2. Spermacoce verticillata L

Spermacoce verticillata is a perennial semi-woody herb, with leaves arranged in opposite pattern and flowers occuring in small terminal clusters. Its ability to readily colonize nutrient deficient, disturbed and open habitats, suggests good ecological adaptation for early stage soil stabilization and degraded land re-vegetation, during initial stages of mine land restoration [23].

3.1.3. Tithonia diversifolia (Hemsl.) A. Gray

Tithonia diversifolia is a perennial shrub, having large leaves and conspicuous orange inflorescences that readily colonize degraded soils, roadsides and mining spoils. Its high biomass, tolerance to elevated concentrations of potentially toxic elements and ability to accumulate as well as translocate selected metals vary with soil properties, metal type and its developmental stage [24].

3.1.4. Ipomoea asarifolia (Desr.) Roem. & Schult

Ipomoea asarifolia is a perennial creeping herb, with ovate leaves and funnel shaped flowers, and it commonly colonizes nutrient deficient, compacted and disturbed lands. Previously, *I. asarifolia* demonstrated potentials of accumulating significant amount of Pb and others heavy metals, but may also exhibit limited shoot translocation depending on soil properties and metal content [25]. Hence, its phytoremediation capacity may vary between phytoextraction and phytostabilization under some conditions.

3.1.5. Festuca rubra L

Festuca rubra is a perennial grass possessing persistent fibrous root, tolerance for nutrient deficient soil, acidic and compacted soils. It establishes a dense root mat that reduces erosion and dust emission on spoil heaps as well as previously demonstrated reasonable tolerance to some heavy metals and suitable for phytostabilization of contaminated soil [26].

The morphological and ecological characteristics as well as the reported metal tolerance of these selected dominant weeds further provided the basis for subsequent evaluation of their bioaccumulation activities for Cd, Pb, Zn, As and Ni in this study.

3.2. Metal Specific Behaviour

3.2.1. Cadmium (Cd)

The Cd content in rhizosphere soils ranged from 8.50mg/kg to 55.00mg/kg and were significantly higher than all parts of weeds growing on them, except *Festuca rubra* associated rhizosphere soil with Cd (8.50mg/kg) significantly lower than Cd accumulation in its root (28.00mg/kg) and shoot (19.47mg/kg). Both active and abandoned mining (ranged 8.50-36.16mg/kg) as well as non-mining (28.70-55.00mg/kg) rhizosphere soils were significantly contaminated with Cd, as seen in Table 2.

Table 2. Cadmium (Cd) Distribution in Rhizosphere Soil and Parts of Selected Weeds from Mining and Non-mining sites in Jos-North Plateau

		Cd(mg/kg)			
Sites	**Weeds**	**Soil**	**Root**	**Shoot**	**Leaves**
Active mine	*Cyperus bipartitus*	28.31 ± 1.67[a]	17.93 ± 3.77[a]	24.48 ± 1.20[b]	NA
Active mine	*Spermacoce verticillata*	36.16 ± 1.48[b]	18.68 ± 2.92[a]	14.41 ± 4.58[a]	5.22 ± 1.47[c]
Active mine	*Festuca rubra*	8.50 ± 2.97[c]	28.00 ± 2.07[a]	19.47 ± 1.09[d]	NA
Active mine	*Ipomoea asarifolia*	29.33 ± 14.07[a]	7.69 ± 4.63[c]	14.72 ± 1.39[a]	13.25 ± 1.07[d]
Abandon mine	*Tithonia diversifolia*	33.00 ± 2.31[b]	26.46 ± 2.38[b]	20.43 ±1.59[d]	16.21 ± 1.87[e]
Non-mine	*Spermacoce verticillata*	55.00 ± 2.89[c]	22.77 ± 1.52[a]	9.05 ± 1.32[c]	19.16 ± 2.44[d]
Non-mine	*Ipomoea asarifolia*	55.00 ± 2.89[c]	23.75 ± 3.70[a]	4.56 ± 1.33[c]	13.38 ± 1.45[d]
Non-mine	*Tithonia diversifolia*	28.70 ± 8.54[a]	18.17 ± 6.07[a]	14.82 ± 3.60[a]	16.75 ± 1.31[e]

NA represent not applicable due to no distinct leave analyzed. Values are expressed in mean ± standard error. Values with different letters are significantly different at P<0.05.

Further comparison of the observed rhizosphere soil Cd concentrations across the active and abandoned mining soils as well as the non-mining control soil, with the Cd global soil limits shown in Table 3, indicated that the studied rhizosphere soil Cd exceeded the global standard soil Cd threshold (1.00mg/kg) and are within the threshold of highly contaminated soil (>6.00mg/kg) [10].

Therefore, Cd pollution was widespread throughout the rhizosphere soils across both mining and non-mining areas and not limited to the mining areas only. Higher Cd content of non-mining rhizosphere soil compared to the mining soil may also indicates possible site specific geochemical Cd enrichment, likely from natural weathering of Cd rich underlying parent materials, agricultural activities, soil organic matter and speciation as well as long-range atmospheric deposition [27,28].

Additionally, Cd accumulation significantly varied (P<0.05) across studied weed species parts as shown on Table 2. *Cyperus bipartitus* and *Ipomoea asarifolia* growing at mining soil sites respectively exhibited significantly higher Cd shoot accumulation (24.48 mg/kg and 14.72mg/kg) than their roots (17.93mg/kg and 7.69mg/kg). Although both weed species exhibit efficient metal translocation (TF >1), their BCF and BAC values below unity (<1) as seen in Figure 2, indicate restricted Cd uptake from the mining soil and poor phytoextraction potential on the studied mining soil.

Table 3. Metal Contents of Soil Compared to Global Standard Limits

	Cd	Pb	Zn	As	Ni	References
Average concentration range in non-mining rhizosphere soil	28.70-55.00	16.47-17.00	11.08-22.38	4.67-33.80	10.78-38.30	
Average concentration range in mining rhizosphere soil	8.50-36.16	11.62-31.50	8.75-35.98	3.68-31.11	10.62-151.04	
Average in studied Jos-North rhizosphere soil	34.25	19.11	20.93	19.41	47.87	
Average in most natural soils	0.01–2.00	15–30.00	50–100.00	0.1–15.00	20-50	[32-33]
Threshold for most natural soil	1.00	100.00	200.00	15.00	35	[34-35]
Threshold for uncontaminated soil	0.11-5.20	<40.00	<90.00	<3.00	<50	[36-38]
Threshold for contaminated soil	*	40–60.00	90-200.00	3–8.00	75-150	[8,39]
Threshold for highly contaminated soil	>6.00	>60.00	>90.00	>8.00	>150	[39-40]

Values represents mean (mg/kg). * represent unavailable threshold value

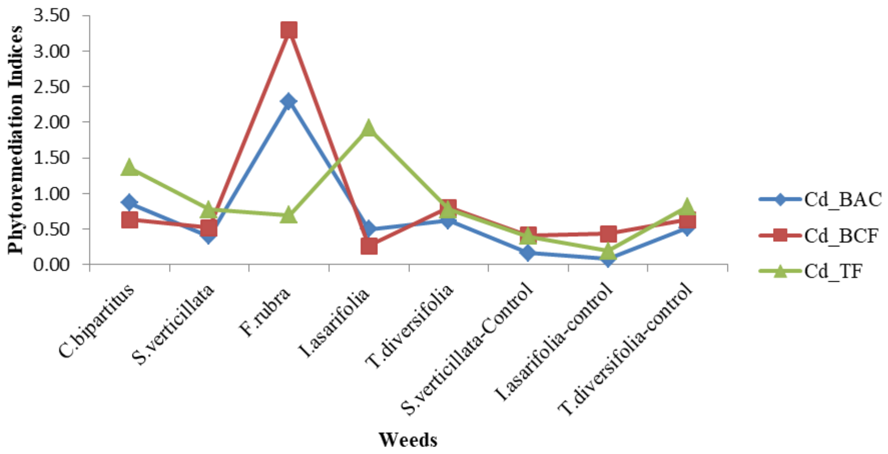

Figure 2. Graphical illustration of Phytoremediation Indices of Selected Weeds for Cadmium (Cd)

Festuca rubra demonstrated significant higher root Cd accumulation (28.00mg/kg) than in its rhizosphere soil (8.50mg/kg), suggesting an efficient Cd root uptake. Thus, Figure 2 also shows *F. rubra* exhibited notable biological accumulation coefficient (BAC) and bioconcentration factors (BCF) >1 but limited translocation (TF<1). Therefore, *F. rubra* is potentially a phytostabilizer candidate, suitable for stabilizing or immobilizing Cd in the rhizosphere soil, minimizing contamination of shoot biomass and desirable for reducing environmental risk of Cd mobility [29]. Similar Cd root-retention strategies of *F.rubra* was previously associated with species-specific detoxification and root sequestration mechanisms, thereby reducing metal mobility and protecting photosynthesis active organs [26,30]. Also the perennial growth pattern, extensive root system and preferential Cd sequestration in the root of *F.rubra* support its suitability as phytostabilizer species, making it desirable for long term reduction of Cd bioavailability in contaminated soils [26,31].

3.2.2. Lead (Pb)

Across the studied samples, lead (Pb) distributions demonstrated uptake and translocation patterns that are species dependent. The rhizosphere soils Pb level ranged from 11.62mg/kg to 31.50mg/kg across the mined and non-mine soils as seen in Table 4 and was within the global standard threshold (<40.00mg/Kg) for Pb uncontaminated soil shown in Table 3. However, given that soil Pb levels within regulatory permissible threshold, may still be bioavailable, negatively impact soil organisms and accumulate in plant tissues, as well as contaminate food chains [41,42]. There is the need to assess plant-based remediation strategies with potentials of mitigating the subtle Pb contamination ecological risks.

Table 4. Lead (Pb) Distribution in Rhizosphere Soil and Parts of Selected Weeds from Mining and Non-mining Sites in Jos-North Plateau

		Pb(mg/kg)			
Site	Weeds	Soil	Root	Shoot	Leaves
Active	*Cyperus bipartitus*	13.61 ± 1.34^{a}	18.21 ± 31.85^{ab}	21.25 ± 1.25^{b}	NA
Active	*Spermacoce verticillata*	23.22 ± 1.25^{c}	13.82 ± 0.95^{a}	15.56 ± 1.05^{a}	24.12 ± 0.69^{c}
Active	*Festuca rubra*	31.50 ± 4.16^{d}	22.47 ± 2.15^{b}	25.09 ± 1.78^{b}	NA
Active	*Ipomoea asarifolia*	11.62 ± 0.94^{a}	19.86 ± 3.59^{ab}	14.35 ± 0.84^{a}	22.16 ± 0.59^{c}
Abandon	*Tithonia diversifolia*	22.50 ± 1.47^{c}	12.95 ± 2.93^{a}	19.99 ± 0.69^{b}	23.90 ± 4.99^{c}
Non-mine	*Spermacoce verticillata*	17.00 ± 1.15^{b}	21.86 ± 0.85^{c}	29.04 ± 3.69^{d}	29.90 ± 0.82^{d}
Non-mine	*Ipomoea asarifolia*	17 .00± 1.15^{b}	22.10 ± 0.98^{c}	24.51 ± 2.66^{c}	15.13 ± 0.79^{b}
Non-mine	*Tithonia diversifolia*	16.47 ± 0.85^{b}	21.14 ± 1.39^{c}	22.84 ± 1.26^{c}	24.55 ± 1.41^{c}

NA represent not applicable due to no distinct leave analyzed. Values are expressed in mean ± standard error. Values with different letters are significantly different at P<0.05

Table 4 indicates *Cyperus bipartitus*, control soil growing *Spermacoce verticillata* and *Tithonia diversifolia* respectively demonstrated progressive Pb increase up take from soil (13.61,17.00, 16.46) mg/kg to root (18.21, 21.86, 21.14) mg/kg and shoot (21.25, 29.04, 22.84) mg/kg. Also, as seen in Table 4, the dominant Pb accumulation in leaves of *S. verticillata* and *T. diversifolia* on control soil , respectively showed a pattern of Pb in their leaves (29.90 and 24.55) mg/kg > shoots (29.04 and 22.84)mg/kg > roots (21.86 and 21.14) mg/kg. Additionally, *C. bipartitus*, control soil growing *S. verticillata*, *I. asarifolia* and *T. diversifolia* demonstrated effective Pb uptake (BAC and BCF>1), and efficient translocation (TF>1) as seen in Figure 3, thereby showing potential for phytoextraction.

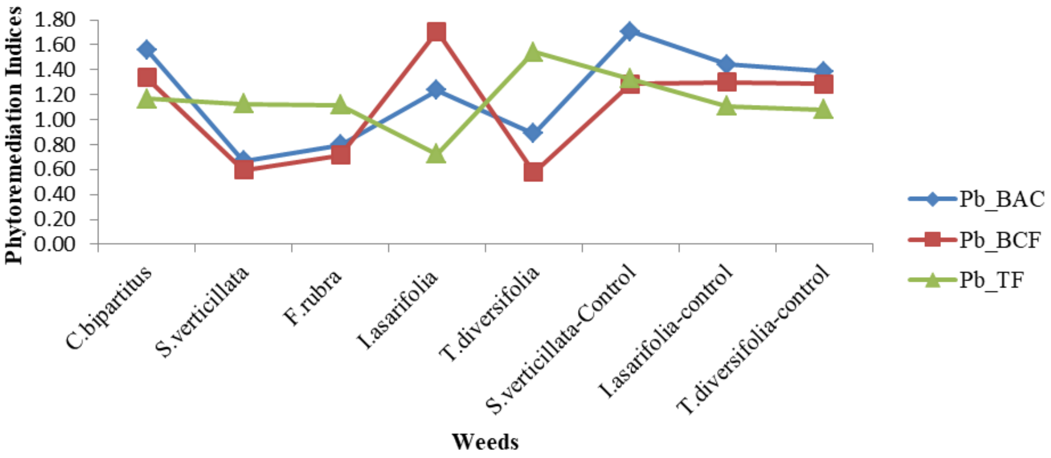

Figure 3. Graphical illustration of phytoremediation indices for lead (Pb)

Although a closely related *Cyperus rotundus* in the same genus as *C. bipartitus* , was primarily reported as a phytostabilizer through rhizosphere-mediated metal immobilization [22]. The Pb accumulation pattern observed in *C. bipartitus* suggest that phytoremediation strategies may differ among species within the genus. The relatively inconspicuous leaf structures observed in *C. bipartitus* may partly explain its comparatively limited vegetative growth, as reflected in its respective mean above-ground (28.00cm) and below-ground (17.00cm) sizes as shown in Table 1. However, plant sizes may also be influenced by species specific growth characteristics and site conditions. Notably, *I. asarifolia* on active mining soil, exhibited Pb root accumulation (19.86 mg/kg) that exceeded shoot levels (14.35mg/kg), but higher leaf concentration (22.16mg/kg), demonstrating effective root Pb uptake (BCF and BAC >1) but limited shoot translocation (TF<1) as illustrated in Figure 3, thus exhibiting potentials for phytostabilization. The observed Pb accumulation patterns have been reported in metal-tolerant plants, where Pb is largely immobilized through root cell wall adsorption, complexation with phytochelatins and organic ligands, as well as sequestration into root vacuoles, thereby restricting translocation to shoots and minimizing metal-induced toxicity [43,44]. Similarly, [25] identified *I. asarifolia* as a metal-tolerant species with phytostabilization potential in gold mine wastes, supporting the view that this species preferentially retains potentially toxic elements within the root system under mining conditions rather than facilitating extensive translocation to aerial tissue. Although Pb was reported to commonly exhibit poor mobility and largely retained in plant roots [45], however Figure 3 shows efficient Pb redistribution (TF>1) in the tissues of *C. bipartitus*, *S. verticillata*, *T. diversifolia* and control *I. asarifolia* , reflecting their potentials for Pb phytoextraction and consistent with previous reports, suggesting, some accumulator weeds can under favourable physiological conditions, translocate and accumulate Pb in their above ground tissues [29,43,46]. However, due to some of these weed species especially *T. diversifolia*, being grazed to varying degrees by livestock and commonly utilized as fodder, their use for phytoremediation should be accompanied by strict biomass management such as controlled incineration, measures, ensure safe handling and disposal of contaminated biomass to prevent livestock access to it and forestall transfer of accumulated metals into the food chain [47,48].

3.2.3. Zinc (Zn)

Table 5. Zinc (Zn) Distribution in Rhizosphere Soil and Parts of Selected Weeds from Mining and Non-mining Sites in Jos-North Plateau

		Zn(mg/kg)			
Site	Weeds	Soil	Root	Shoot	Leaves
Active	*Cyperus bipartitus*	14.88 ± 3.16^{c}	30.27 ± 3.81^{b}	25.94 ± 2.03^{b}	NA
Active	*Spermacoce verticillata*	26.01 ± 3.45^{b}	27.14 ± 3.05^{b}	27.43 ±5.62^{b}	25.48 ± 3.60^{b}
Active	*Festuca rubra*	26.01 ± 2.47^{b}	28.57 ± 5.48^{b}	37.87 ± 5.62^{a}	NA
Active	*Ipomoea asarifolia*	8.75 ± 2.22^{d}	27.89 ± 4.90^{b}	41.59 ± 2.69^{a}	22.05 ± 4.36^{c}
Abandon	*Tithonia diversifolia*	35.98 ± 3.97^{a}	25.65 ± 3.30^{b}	7.79 ± 3.30^{e}	28.76 ± 2.24^{b}
Non-mine	*Spermacoce verticillata*	22.38 ± 3.45^{b}	35.93 ± 4.29^{a}	30.97 ± 0.63^{b}	28.55 ±4.77^{b}
Non-mine	*Ipomoea asarifolia*	22.38 ± 3.45^{b}	38.66 ± 15.64^{a}	28.44 ± 2.48^{b}	31.61 ± 4.04^{a}
Non-mine	*Tithonia diversifolia*	11.08 ± 2.52^{d}	31.82 ± 4.17^{b}	23.31 ± 3.36^{c}	36.82 ± 4.16^{a}

NA represent not applicable due to no distinct leave analyzed. Values are expressed in mean ± Standard error. Values with different letters are significantly different at P<0.05.

Table 5 shows Zn concentrations in rhizosphere soils ranged from 11.08-22.38mg/kg at non-mining control soil and 8.75-35.98mg/kg at mining soil sites respectively. Given that the ranges were within global soil Zn threshold (<90mg/kg) as seen in Table 2, rhizosphere soil Zn were moderately distribution across the studied sites. However, notable tissue-specific Zn variation was shown, with maximum Zn accumulations pattern follows, roots of *I. asarifolia* (38.66 mg/kg) > shoots of *F. rubra* (37.87 mg/kg) > leaves of *T. diversifolia* (36.82 mg/kg). Leaf Zn content was not assessed in *C.bipartitus* and *F. rubra* due to distinct leaf absence.

Further assessment of Zn bioaccumulation, showed *S. verticillata*, *F. rubra* and *I. asarifolia* on mining soil , exhibited BAC, BCF and TF values >1, illustrated in Figure 4, indicating efficient Zn uptake and translocation tendency as Zn phytoextraction capable plants.

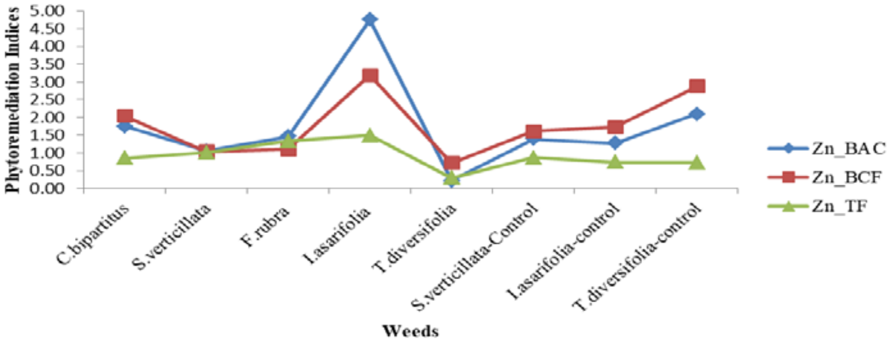

Figure 4. Graphical Illustration of Phytoremediation indices of Selected Weeds for Zinc (Zn)

Similar Zn accumulation patterns to the findings of this study have been reported for weeds and grasses colonizing mining sites, which was suggested to be likely due to their high biomass, nutrient demand and rapid growth rates [49,50]. In contrast, Figure 4 indicates *C.bipartitus* from mining soil as well as *S. verticillata*, *I. asarifolia*, and *T. diversifolia* on non-mining soils showed BAC and BCF > 1 but TF < 1. Indicating these species showed Zn substantial accumulation at their roots with limited translocation to above ground tissues of the weeds and have potential Zn phytostabilization, restricting Zn mobility and bioavailability. Phytostabilization of Zn often result from its sequestration in plant roots, restricted xylem uptake, or adaptive exclusion mechanisms under metal stress [49,51]. The observed Zn accumulation patterns of this study indicate that the dominant weeds possess complementary phytoremediation strategies, with some species favoring phytoextraction through efficient uptake and translocation, whereas others promote phytostabilization by restricting Zn movement to the shoots. These contrasting strategies enhance the potential application of native vegetation for sustainable management of Zn in mining-affected ecosystems. It also emphasizes the importance of species selection according to site-specific remediation objectives. Since Zn is an essential element required by living organisms, efficient Zn accumulation may also reflects normal nutrient acquisition and homeostasis. Although the studied rhizosphere soil Zn were below the global Zn standard threshold, they currently may not require active Zn remediation but the identified weed species may serve as sentinel plants for biomonitoring Zn bioavailability or as candidate species for remediation should future anthropogenic activities cause increased Zn contamination. These findings align with studies from other mining-impacted ecosystems in Africa and Asia, where native grasses often display selective accumulation of essential metals such as Zn [52,53]. Therefore the elevated Zn in above ground biomass of weeds reinforces the potential application of studied native weeds in site-specific Zn remediation strategies.

3.2.4. Nickel (Ni)

Nickel (Ni) is also essential micronutrients in plants and animals, but become toxic at elevated concentrations. Table 6 shows in addition to Ni accumulation in the selected weed parts varying remarkably, Ni at the rhizosphere soils of *F. rubra* (151.04mg/kg) and *C.bipartitus* (66.88mg/kg) growing naturally on active mining sites, notably exceeds Ni averages for global soils (20.00-50.00mg/kg) and common agricultural soils (18.00-21.00mg/kg) as well as surpasses regulatory threshold of 50.00mg/kg for uncontaminated soil as illustrated in Table 3. Suggesting the Ni contamination in rhizosphere soil of active mining site growing *F.rubra* and *C. bipartitus* may pose likely ecological and health risks, warranting further risk and remediation assessments [54].

Table 6. Nickel (Ni) Distribution in Rhizosphere Soil and Parts of Selected Weeds from Mining and Non-mining Sites in Jos-North Plateau

		Ni (mg/kg)			
Site	**Weeds**	**Soil**	**Root**	**Shoot**	**Leaves**
Active	*Cyperus bipartitus*	66.88 ± 6.77^{b}	29.03 ± 0.75^{c}	28.73 ± 0.62^{c}	NA
Active	*Spermacoce verticillata*	46.73 ± 25.33^{b}	20.96 ± 0.52^{c}	15.23 ± 0.35^{d}	33.16 ± 0.44^{c}
Active	*Festuca rubra*	151.04 ± 33.83^{a}	30.79 ± 0.38^{c}	34.68 ± 0.47^{c}	NA
Active	*Ipomoea asarifolia*	10.62 ± 0.25^{e}	33.07 ± 0.42^{c}	11.07 ± 0.50^{e}	29.96 ± 0.61^{c}
Abandon	*Tithonia diversifolia*	20.35 ± 12.11^{d}	18.05 ± 0.32^{c}	27.00 ± 0.34^{c}	17.66 ± 0.64^{c}
Non-mine	*Spermacoce verticillata*	38.30 ± 0.00^{c}	21.68 ± 0.19^{c}	14.83 ± 0.46^{d}	12.06 ± 0.20^{d}
Non-mine	*Ipomoea asarifolia*	38.30 ± 0.00^{c}	20.17 ± 0.45^{c}	28.53 ± 0.68^{c}	17.51 ± 0.64^{c}
Non-mine	*Tithonia diversifolia*	10.78 ± 0.28^{e}	18.35 ± 0.79^{c}	17.34 ± 0.69^{c}	16.11 ± 0.28^{c}

NA represent not applicable due to no distinct leave analyzed. Values are expressed in mean ± Standard error. Values with different letters are significantly different at P<0.05.

Also despite the relatively low rhizosphere Ni concentration (10.62 mg /kg) at the mining site as seen in Table 6 *I. asarifolia* showed efficient Ni uptake into its root (BAC=1.04, BCF= 3.11) ,but restricted translocation to its aerial tissues (TF=0.33) as illustrated in Figure 6, indicating preferential root sequestration and phytostabilization potential.

In contrast, at the non-mining soil, despite growing in soil with higher Ni concentration (38.30 mg /kg), Figure 5 indicates rhizosphere soil Ni uptake by *I. asarifolia* was reduced (BAC=0.74, BCF= 0.53) but shoot translocation was enhanced (TF= 1.14), suggesting altered internal metal partitioning rather than increased uptake. This pattern shows *I.asarifolia* demonstrate environment dependent remediation approach, consistent with its phytostabilization potentials indicated by BCF>1 with TF <1 , while phytoextraction potential is shown by TF>1. Figure 6 further shows *T. diversifolia* from the abandoned mines exhibited moderate root accumulation (BCF= 0.89) but efficient shoot enrichment (BAC= 1.33 and TF= 1.50), indicating good phytoextraction potential. In contrast, the *T. diversifolia* from non-mining soils accumulated more Ni in roots (BCF=1.70, BAC= 1.61), but showed limited shoot translocation (TF = 0.95) as seen in Figure 6, suggesting greater suitability for phytostabilization. Hence *T. diversifolia* adapts its Ni uptake and distribution based on environmental conditions. The observed contrasting behaviours may reflect possible differences in Ni bioavailability, rhizosphere chemistry, and physiological regulation between sites. Increased Ni shoot transport (TF>1) observed in abandoned mine plants may arise from enhanced xylem transport of absorbed Ni to harvestable shoots [43]. While greater root retention in non-mining weeds may result from increased sequestration of Ni within root cell walls and vacuoles, likely serving as a tolerance mechanism that minimizes metal toxicity [55].

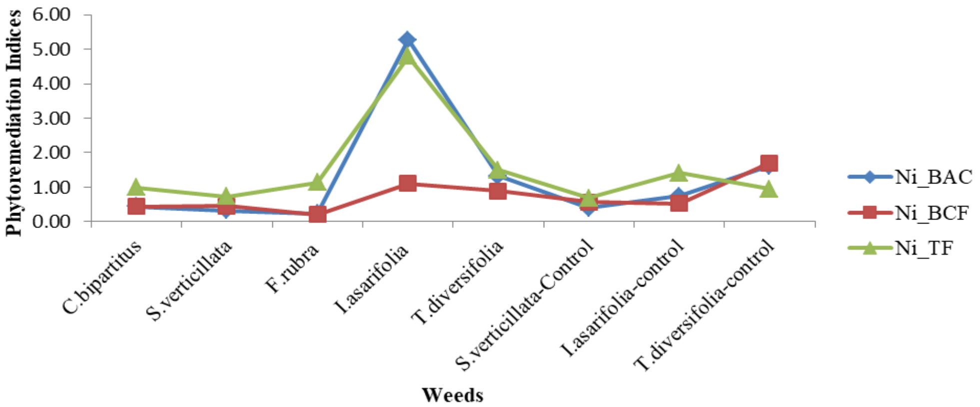

Figure 5. Graphical illustration of phytoremediation indices for Nickel (Ni)

3.2.5. Arsenic (As)

Table 7 indicates arsenic (As) contamination varied significantly(P<0.05) across studied rhizosphere soils of active and abandoned mining and control soils, ranging from 4.67–33.80 mg/kg and mostly beyond widely reported global As contaminated soil threshold (3.00 to 8.00mg/kg) [10].

The unexpectedly high As levels in non-mining rhizosphere soils of *S. verticillata* (33.80mg/kg), *I. asarifolia* (33.80mg/kg) and *T. diversifolia* (4.67mg/kg), suggest likely natural presence, plant mediated concentration as well as stabilization of As in the studied control rhizosphere soils, rather than from mining or anthropogenic contamination [56]. The observed significantly elevated As concentration in active mining rhizosphere soil compared to those of abandoned sites indicate on-going or active mining may alter soil As exposure, due to increase As mobilization by oxygen addition and soil disturbance processes [57]. Furthermore, significantly high (P<0.05) accumulation of As was observed mainly in roots of active mine *C. bipartitus* (27.04 mg/kg), *I.asarifolia* (28.91mg/kg) and non-mining soil growing *T. diversifolia* (16.30mg/kg) as seen in Table 7. The active mine *C. bipartitus* , *I.asarifolia* and non-mining soil growing *T. diversifolia* also demonstrated enhanced As root accumulation (BCF and BAC >1), but showed restricted shoot translocation (TF <1) as seen in Figure 6, suggesting their respective suitability for site-specific phytostabilization remediation strategy.

Table 7. Arsenic (As) Distribution in Rhizosphere Soil and Selected Weeds from Mining and Non-mining Sites in Jos-North Plateau

Site	Weeds	As (mg/kg)			
		Soil	Root	Shoot	Leaves
Active	*Cyperus bipartitus*	16.69 ± 4.41^{b}	27.04 ± 3.83^{a}	14.88 ± 2.45^{b}	NA
Active	*Spermacoce verticillata*	18.57 ± 2.49^{b}	19.85 ± 1.03^{b}	8.68 ± 3.99^{c}	26.57 ± 0.61^{a}
Active	*Festuca rubra*	31.11 ± 1.43^{a}	24.40 ± 2.07^{a}	18.34 ± 3.34^{b}	NA
Active	*Ipomoea asarifolia*	3.68 ± 1.17^{d}	28.91 ± 1.60^{a}	6.04 ± 1.15^{c}	20.14 ± 1.30^{b}
Abandon	*Tithonia diversifolia*	12.97 ± 2.44^{c}	12.45 ± 2.81^{c}	22.51± 3.01^{b}	19.75 ± 5.49^{b}
Non-mine	*Spermacoce verticillata*	33.80 ± 1.57^{a}	25.60 ± 11.24^{a}	3.35 ± 1.76^{d}	8.96 ± 2.06^{c}
Non-mine	*Ipomoea asarifolia*	33.80 ± 1.57^{a}	18.10 ± 3.60^{b}	19.62 ± 2.64^{b}	11.82 ± 5.25^{c}
Non-mine	*Tithonia diversifolia*	4.67 ± 1.32^{d}	16.30 ± 1.80^{b}	15.05 ± 2.32^{b}	10.97 ± 3.30^{c}

NA represent not applicable due to no distinct leave analyzed. Values are expressed in mean ± standard error. Values with different letters are significantly different at P<0.05.

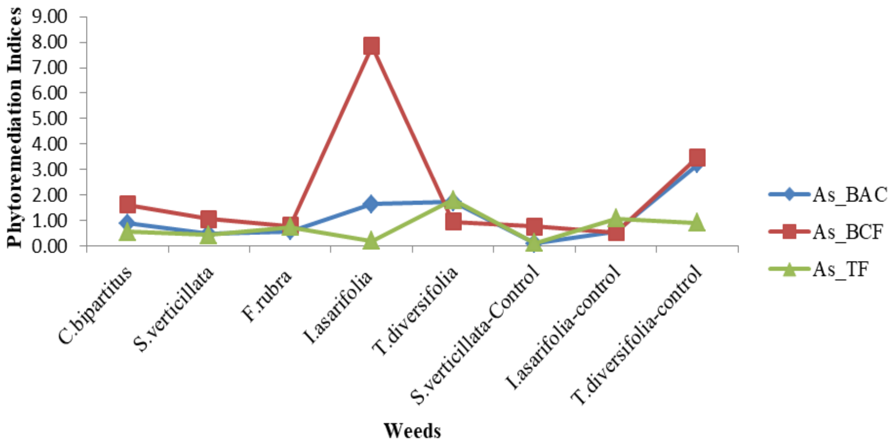

Figure 6. Graphical Illustration of Phytoremediation Indices of Selected Weeds for Arsenic (As)

Similar phytostabilization pattern was reported in *I. asarifolia* grown on As containing substrates, where root As levels exceed shoot concentrations up to twenty fold, supported by microbial processes that alter As mobility and speciation [25].

Furthermore, Figure 6 shows notable contrast in As bioaccumulation pattern in *T. diversifolia* on abandoned mining soil (BAC>1, TF>1), indicating efficient translocation of absorbed As to above-ground tissues despite relatively low root enrichment, suggests that the species functions predominantly as a potential phytoextractor of arsenic under mining conditions. Whereas under non-mining conditions it functioned primarily as a phytostabilizer through enhanced root accumulation (BAC and BCF > 1) and restricted shoot translocation (TF < 1). Such functional adaptability may improve its suitability for soil arsenic remediation across heterogeneous contaminated landscapes. These findings are consistent with previous reports on arsenic tolerant plant species, which demonstrates that tolerant plant species can shift between phytoextraction and phytostabilization depending on arsenic bioavailability, soil properties, and physiological regulation [58]. Specifically, the present findings agree with the report of [59], showing the phytoremediation behaviour of *T. diversifolia* is not fixed but varies with environmental conditions, contaminant type, and soil characteristics. The observed enhanced As root uptake and restricted shoot translocation may arise from phosphate transporter mediated As (V) uptake and subsequent root vascular sequestration, a common detoxification strategy that limits shoot translocation and results to As retention in root tissues [57]. Additionally, plant species differ in arsenic uptake, translocation and detoxification depending on species-specific transporters, reduction to arsenite (As [III]), complexation with thiol ligands (glutathione and phytochelatins), vacuolar sequestration, and root-to-shoot partitioning [60]. Also, remediation performance of *T. diversifolia* is supported by its robustness, rapid biomass production, and tolerance to contaminated soils [61], making it a strong candidate for large-scale remediation in tropical environments. It also implies the As enriched biomass must be properly managed to prevent secondary contamination.

3.3. Principal Component Analysis

To determine possible relationships of the studied potentially toxic elements (PTEs) and their spatial distribution, the Principal Component Analysis (PCA) was performed. Figure 7 illustrated the Principal Component 1 (PC1) accounted for 98.6% of the total variance, suggesting that spatial variation in concentrations of PTE was predominantly associated with mining-related activities [62].

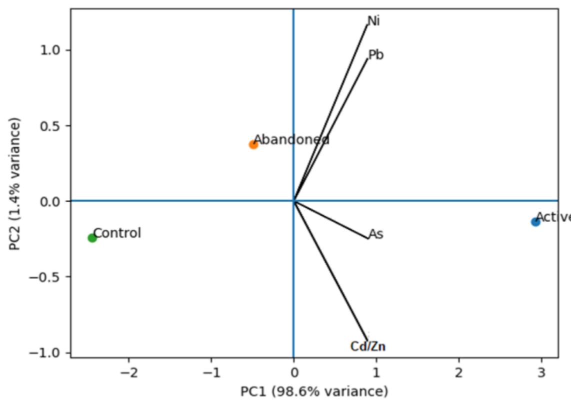

Figure 7. Principal Component Analysis (PCA) Biplot of Cd, Pb, Zn, As and Ni Across Studied Rhizosphere Soils in Jos-North Plateau

Also Figure 7 showed the close clustering of Ni and Pb suggests a common source and similar geochemical behaviour, consistent with their co-occurrence in tin mining environments [63]. In contrast, the separation of Zn, Cd and As from Ni and Pb along Principal Component 2 (PC2) shows differences in their distribution patterns, environmental behaviour and controlling geochemical processes [64]. The intermediate position of the abandoned mine between the active mining and non-mining sites indicates partial ecological recovery following mining cessation, although residual contamination remains evident [52]. Likewise, the clear distinction of mining and non-mining sites along PC1 agrees with previous findings that PCA effectively distinguishes active, abandoned and uncontaminated tin-mining soils based on heavy metal composition [5]. Ni exhibited the strongest contamination gradient, followed by Pb, suggesting that these metals contributed most to the spatial variability associated with active mining and may serve as useful indicators of mining-derived contamination in the study area [65]. Their positive association further suggests a common mining-related source, consistent with previous studies reporting that PCA groups metals originating from similar mining activities and mineral assemblages [66]. In contrast, Zn and Cd displayed negative loadings on PC1, indicating their distinct distribution patterns may reflect relatively greater environmental mobility and bioavailability than Ni and Pb [29]. Arsenic showed moderate association with the active mining sites, suggesting that its distribution was influenced by both geogenic processes and mining activities [60]. These PCA results are consistent with previous reports [62,63] on mining-impacted soils, where Ni and Pb exhibited strong association with mining-related contamination, while Zn, Cd and As showed distinct loading patterns reflecting differences in geochemical behaviour and environmental mobility.

4. Conclusion

This study evaluated the phytoremediation potential of dominant native weed species growing in active mining, abandoned mining, and non-mining soils in Jos North, Plateau State, Nigeria. The findings demonstrated that both legacy mining activities and natural geogenic enrichment have significantly influenced the distribution and accumulation of potentially toxic elements (PTEs) in rhizosphere soils and associated vegetation. The investigated weed species exhibited distinct, site-dependent remediation strategies, reflecting their physiological adaptability to varying contamination levels and environmental conditions. Among the studied species, *Festuca rubra* showed promising potential for Cd phytostabilization and Zn phytoextraction, while *Cyperus bipartitus* was identified as a potential Pb phytoextractor and Zn as well as As phytostabilizer. *Spermacoce verticillata*, *Ipomoea asarifolia*, and *Tithonia diversifolia* displayed considerable flexibility in metal uptake and translocation, functioning either as phytoextractors or phytostabilizers depending on the metal species and site conditions. This site-specific behaviour highlights their suitability for application in remediation of heterogeneous multi-metal contaminated environments. Overall, the results indicate that *Festuca rubra*, *Cyperus bipartitus*, *Spermacoce verticillata*, *Ipomoea asarifolia*, and *Tithonia diversifolia* are promising indigenous candidates for phytoremediation of mining-impacted soils. However, the generally limited Cd accumulation observed across most species suggests that phytoremediation of Cd-contaminated sites may require integration with complementary remediation technologies to enhance remediation efficiency. Multivariate analysis confirmed that mining activities primarily controlled the distribution of potentially toxic elements, with Ni and Pb emerging as the dominant indicators of mining-derived contamination across the study sites. This study provides new evidence on the adaptive accumulation strategies of native weed species under contrasting environmental conditions and offers a scientific basis for selecting appropriate species for site-specific phytoremediation of multi-metal contaminated mining landscapes. Future studies to evaluate the long-term field performance, metal removal efficiency, biomass productivity, as well as underlying physiological and molecular mechanisms governing metal tolerance and accumulation will be beneficial in facilitating large-scale phytoremediation applications.

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Conflicts of Interest

Authors declare that they have no conflicts of interest.

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