

Assessment of potentially harmful elements in mine spoils of Jos and environs, central Nigeria

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Abstract

One of the main human activities that has greatly deteriorated the environment and people's health is mining. This study aimed to determine the level of potential harmful element contamination in mine spoils collected from Jos, Central Nigeria. Forty-five samples were collected, air-dried, pulverized, and sieved to collect fine particles and analyzed for As, Ba, Co, Cr, Cu, Mo, Mn, Ni, Pb, Sb, Th, U, V, and Zn using Inductively Coupled Plasma Mass Spectroscopy (ICP-MS). The average concentrations of the potentially harmful elements in the spoils were; As: 5.70 ppm; Ba: 97.31 ppm; Be: 3.02 ppm; Co: 7.48 ppm; Cr: 124.64 ppm; Cu: 19.16 ppm; Mo: 6.19 ppm; Mn: 165 ppm; Ni: 28.84 ppm; Pb: 38.72 ppm; Sb: 0.51 ppm; Th: 36.17 ppm; U: 10.94 ppm; V: 119.84; Zn: 19.15 ppm. Pollution indices such as contamination factor (CF), pollution load index (PLI) and index of geo-accumulation (Igeo) were used to determine the level of contamination in the samples. The CF values show that the soils are considerably contaminated with As, Ba, Be, Co, Cr, Cu, Mo, Mn, Ni, Pb, Sb, V, and Zn while it is highly contaminated with Th and U. Conversely, the PLI of 0.439 shows that the site is unpolluted. Based on the index of geo-accumulation, the mine spoils are moderately- uncontaminated with As, Ba, Be, Co, Cr, Cu, Mo, Mn, Ni, Pb, Sb, Th, U, V, and Zn. Most of these elements are sourced from natural or geogenic sources, and some are remobilized from mining activities.

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1. Introduction

Mining has detrimental effects both on human and animal lives, although it offers numerous economic, social, and infrastructure benefits [1]. These effects result from processing minerals that can occasionally be dangerous or possibly toxic, thereby degrading the environment including humans, crops, animals, vegetation, and surrounding water bodies resulting in erosion, loss of biodiversity, soil contamination, and ground and surface-water contamination through the discharge of heavy metals [2]. The situation is considerably worse in sub-Saharan Africa where poverty has aggravated the use of crude and non-scientific methods of mining [3]. Trace elements with weight density greater than or equal to 5 gram per cubic centimeter are collectively referred to as heavy metals and these metals are potentially toxic or harmful [4]. The concentrations of these elements in soils and other geological media in Jos and Environs have increased significantly over the years and this can be attributed to reactivation of tin mining and other associated minerals [5].

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Geochemical analyses of soils near cassiterite mining sites, playgrounds, and some vegetables as studied in Refs. [5, 6] revealed higher heavy metals content. Potentially hazardous heavy metals can transform from non-bioavailable to highly toxic bioavailable forms. Phase association, temperature, adsorption, sequestration, and other physical variables all affect the bioavailability of heavy metals. Complexation kinetics, lipid solubility, octanol/water partition coefficients, and other chemical variables that affect speciation at thermodynamic equilibrium also have an effect [7]. Additionally, Trophic interactions, biochemical/physiological adaptability, and species traits are examples of biological factors that are crucial to bioavailability of elements [8]. Heavy metals are potentially harmful because they have shown to have an impact on cellular organelles and components in biological systems, including the nucleus, mitochondria, lysosome, endoplasmic reticulum, and some enzymes that are involved in metabolism, detoxification, and damage repair [9].

Potentially harmful elements can also accumulate in some organisms and become more concentrated down the food chain [10–12], thereby endangering the health of the ecosystem. The immediate community and the mine workers mostly suffer this hazard. Therefore, the evaluation of these heavy metals in geological media such as soil and water is particularly important as it reveals the level of environmental toxicity because these metals are transported through soils and have the potency to reach groundwater and are subsequently absorbed by plants [13]. Heavy metals, some of which are classified as potentially harmful elements (PHEs), are introduced into the environment through both geogenic and anthropogenic pathways. Geogenic sources include natural processes such as the weathering of minerals, erosion, volcanic activity, forest fires, and other biogenic mechanisms. On the other hand, anthropogenic inputs arise mainly from industrial and agricultural activities, including the application of pesticides, large-scale mining operations, and the manufacture of various commodities such as paints and pigments, plastics, fertilizers, steel, and automobile batteries, which collectively contribute to heavy metal emissions into the environment [14–16]. A growing body of research [17–20] has shown that human activities, particularly mining and mineral exploration, are central to the mobilization of heavy metals from their natural geological reservoirs beneath the earth's crust and rocks to the surface environment. Although these activities have historically served as important drivers of economic growth and industrial development across many nations, they have also resulted in widespread ecological disturbances. The accumulation of heavy metals in soils, water bodies, and the atmosphere has, in turn, created significant environmental threats and posed considerable risks to human health, underscoring the dual role of these elements as both economic resources and environmental contaminants.

Chen *et al.* [21] reported high levels of contamination by potentially harmful elements (PHEs), including Cd, Cu, Zn, and As, in areas surrounding copper mining sites worldwide, highlighting their potential ecological risks. Several other studies [22–24] have also documented elevated concentrations of Cd, Cu, Pb, and Zn in soils exceeding natural background values, thereby contributing to environmental pollution. In Nigeria, Umeobi *et al.* [25] observed severe contamination by As, Cu, Pb, and Zn in soils from the Ameka mining site in the southeast. Similarly, Obasi and Akudunobi [26] reported significant Cd, Cu, Pb, and Zn enrichment in croplands adjacent to a Pb–Zn mining site. Furthermore, gold mining activities in southwestern Nigeria have been shown to increase the accumulation of PHEs in surrounding soils, posing considerable threats to both environmental quality and human health.

According to Mafuyai *et al.* [27] irrigation soils in Bokokos, near Jos, are contaminated with Cd and Cr. As a result, frequent soil monitoring is necessary to prevent an excessive build-up of toxic heavy metals, which could eventually be transferred to crops and vegetables. Similarly, Kwaghe *et al.* [28] assessed the impact of tin mining on the accumulation of heavy metals in soils around Jos and environs and concluded that the soils are contaminated with $\text{Fe} > \text{Mn} > \text{Cr} > \text{Zn} > \text{Cu} > \text{Ni}$ in decreasing order. The Jos Plateau is richly endowed with mineral resources that are distributed in varying proportions, the principal of which is tin and its associated minerals. Mining of tin on the Jos Plateau has led to chemical contamination of the environment leading to pollution of surface and groundwater, causing damage to the ecosystem and resulting in socio-economic effects that have impacted human health and safety [29]. A lot of mine spoils have been dumped in the Jos- Bukuru area; some have been there since pre-colonial times and are now occasionally processed for tin while some are used for construction purposes, thereby further remobilizing some of these elements into the environment. While some of these metals such as Zn and Cu are necessary for human survival and well-being, only little amounts are needed, and larger concentrations may be harmful [30]. Heavy metals, especially those considered potentially harmful, may enter the bodies of mine employees, construction workers, and members of the host community through inhalation, ingestion, dermal contact or through the food chain [31] and cause significant health issues to their body system. environment. Thus, the present study aims to (1) evaluate the distribution and concentration of PHEs, in the mine spoils and (2) evaluate the pollution level of the potentially harmful elements (PHEs) in the mine spoils. These will provide a comprehensive analysis of the mine spoils, inform sustainable development practices and minimize the impact of mining activities on the environment.

1.1. Geology of the study area

The study area is part of the Jos-Bukuru complex which is the focal point of the younger granite magmatic activity in Nigeria. The younger granites occur in the study area as chains of highlands of variable heights with textures ranging from fine, medium, coarse grained and porphyritic textures. The granite porphyry is usually composed of quartz, feldspar, and biotite in a fine-grained granular matrix of the same constituents [32]. The study area is characterized by diverse rock types including Hornblende fayalite granite, Biotite Microgranite, Rayfield Gona Biotite granite, Dilimi Biotite granite, Bukuru Biotite granite, Sabon Gida South Biotite granite, Sabon Gida North Biotite granite, N'geil biotite granite, Kuru stock Biotite granite, Foron Biotite granite, Shen Hornblende fayalite granite, Vom Hornblende Biotite granite, Neils Valley granite porphyry, Porphyritic Biotite granite, granite gneiss, and

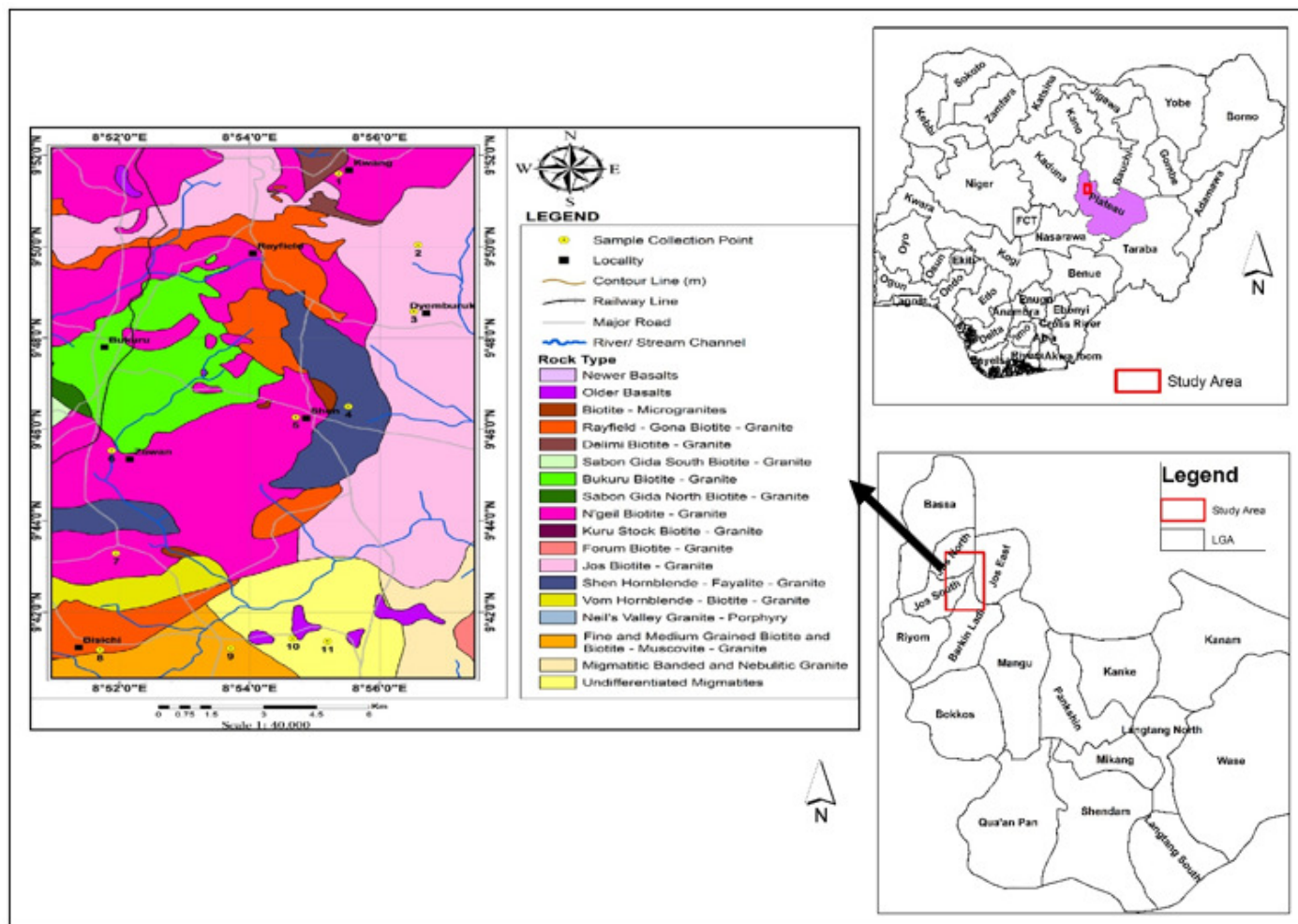


Figure 1. Regional geologic map of the study area after MacLeod [33].

undifferentiated migmatite (Figure 1). Consequently, the region is known as the major source of tin and the one of the world's largest deposits of columbite hosted by the unusually enriched alkali Younger Granite Complex of Jos. Tin mining in the area dates to the 20th century, with British colonialists commencing large-scale operations in 1904 [34]. As mentioned earlier, mining activities have caused severe environmental damage and health issues to the local population. Artisanal mining is still prevalent in the study area with many miners extracting cassiterite and associated minerals manually, both from the mine spoils and other alluvial sources (Figure 2).

2. Materials and methods

2.1. Sampling and sample preparation

The mine spoils numbering 45 were sampled from different locations within the Jos- Bukuru area where tin mining was prevalent. This was done using a shovel and digger with samples taken at the top, middle, and bottom of the spoil to obtain a composite sample due to the heterogeneous nature of the spoils. The samples were placed in polythene bags and transported to the laboratory and air-dried for one week at ambient temperature.

2.2. Analytical methods

All the samples for the geochemical analysis were powdered in an agate mortar. The acid digestion method was applied for the extraction of heavy metals using HCl-HNO₃-HF-HClO₄. Fractions of approximately 100 mg of powdered sediments were digested into a mixture of 10 mL of HCl ($\rho = 1.19$ g/mL), 10 mL of HNO₃ ($\rho = 1.42$ g/mL), 10 mL of HF ($\rho = 1.49$ g/mL), and 10 mL of HClO₄ ($\rho = 1.68$ g/mL) digested at 180 °C in a microwave oven (ETHOS TOUCH CONTROL, Milestone Inc., Via Fatebenefratelli, 1/5 24010 Sorisole (BG), Italy). The obtained suspension liquid was then filtered using a membrane filter. The concentrations of



Figure 2. (a) Artisanal mining of tin from mine spoils in Du district of Jos south, Plateau state. (b) Mining and washing of tin from mine spoils into a water body at Rayfield.

Table 1. Classes of CF (after Hakanson) [35].

CF	Contamination degree
$CF_i < 1$	Low
$1 \leq CF_i < 3$	Moderate
$3 \leq CF_i < 6$	Considerable
$CF_i \geq 6$	High

the potentially harmful elements in spoil were analyzed using inductively coupled plasma mass spectroscopy (ICP-MS, Element) at the Bureau Veritas (ACME) Laboratory IN Vancouver, Canada. To guarantee the accuracy of the results, quality assurance/control (QA/QC) was adopted in all aspects of laboratory analysis [36]. Reagent blanks, duplicate samples, and verified geochemical reference materials with a variance of less than 5% were used to control the laboratory analysis correctness.

2.3. Heavy metal concentration and contamination assessment

2.3.1. Contamination factor

Hakanson [35] identified CF as an easy-to-use and reliable method for monitoring heavy metal contamination and proposed Eq. (1) for computing CF:

$$CF_i = \frac{C_i}{B_i}, \quad (1)$$

where C_i and B_i are measured in concentration and the background value of metal i , respectively. CF_i is a CF of heavy metal in the soil. As seen in Table 1, the CF divides sediments into four quality classes.

2.3.2. Pollution load index

As a means of evaluating the overall level of contamination of mine spoils, the PLI Eq. (2) was computed as the n th root of the total number of multiplied CF values [37]. $PLI < 1$ indicates unpolluted, while $PLI > 1$ indicates polluted.

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)^{1/n}. \quad (2)$$

2.3.3. Index of Geo-accumulation

The Index of geo-accumulation (I_{geo}) Eq. (3) as formulated by Muller [38] has been used widely to ascertain the degree of contamination of heavy metals in different environments. It is expressed as:

$$I_{geo} = \log_2 \left(\frac{C_M}{1.5 B_M} \right), \quad (3)$$

where C_M is the Measured Concentration and B_M is the Background concentration of metal. Based on the indices of geo-accumulation, the contamination level of soils or sediments can be divided into seven classes as shown in Table 2.

Table 2. Index of geo-accumulation (Igeo) classification after Muller [38].

Igeo Value	Igeo Class	Description
> 5	6	Extremely contaminated
4 – 5	5	Strongly to extremely contaminated
3 – 4	4	Strongly contaminated
2 – 3	3	Moderately to strongly contaminated
1 – 2	2	Moderately contaminated
0 – 1	1	Uncontaminated to moderately contaminated
< 0	0	Uncontaminated

Table 3. Descriptive statistics of heavy metal concentrations (ppm) in the study area

	As	Ba	Be	Co	Cr	Cu	Mo	Mn	Ni	Pb	Sb	Th	U	V	Zn
Average	5.60	97.31	3.02	7.48	124.64	19.16	6.20	165.16	28.84	38.72	0.52	36.18	10.95	119.84	19.16
Standard Deviation	3.09	73.90	1.14	4.28	91.53	8.34	3.80	80.71	10.14	10.21	0.19	17.01	7.95	54.59	8.34
Variance	9.52	5460.86	1.29	18.29	8378.19	69.59	14.42	6514.32	102.81	104.27	0.03	289.43	63.19	2980.27	69.59
Minimum	1.00	22.00	1.00	1.40	25.00	5.00	1.60	53.00	8.80	23.30	0.20	21.40	3.90	35.00	5.00
Maximum	14.00	477.00	7.00	20.70	454.00	44.90	21.50	395.00	48.70	76.00	0.90	129.50	57.30	292.00	44.90

2.3.4. Multivariate analysis

Principal Component Analysis (PCA) is used to extract highly correlated heavy metals components into independent factors and minimize the dimension of the data, while Pearson's Correlation Analysis is used to assess the relativity between heavy metal elements. This was done using the SPSS Statistical package 25.0.

3. Results and discussion

3.1. Potentially harmful elements concentration

The descriptive statistical summary (Table 3) provides key information about the concentration of various elements in mine spoils of the study area. The average concentration of Chromium (Cr) is 124.64 ppm with a high standard deviation of 91.53 ppm, indicating that the concentration values of Cr vary significantly across the samples and a very high variance of 8378.19, further confirming the high variability of Cr concentrations in the dataset. Also, Chromium with minimum concentration of 25 ppm and maximum concentration of 454.00 ppm, indicates a large variation in the samples. Similar variability is seen in other elements as shown in Table 3. Notable Observations by Element show that Outliers and High Variability Elements such as Chromium (Cr) and Barium (Ba) show large ranges and high variability, indicating that these elements are enriched in specific areas or geological units. Also, Manganese (Mn) shows substantial variation, which could be related to differences in rock types or the geochemical environment of the area. However, elements with Relatively Low Variability like Beryllium (Be), Arsenic (As), and Antimony (Sb) show lower variability, indicating more consistent concentrations across samples and are less likely to show significant anomalies or enrichments in specific locations. Therefore, the variability in element concentrations could be influenced by the underlying geology. Typically, high concentrations of elements like Chromium (Cr), Manganese (Mn), and Barium (Ba) may indicate the presence of specific rock types or mineral deposits.

Consequently, comparative analysis of element concentrations with background values derived from other granitic sources after Rose *et al.* [39], showed that high concentrations of Chromium in certain samples (up to 454.00 ppm) could raise environmental concerns as it exceeds safe limits for soil or water. Lead is another element with potential toxicity, and concentrations up to 76.00 ppm could also be of concern. The concentrations of the potentially harmful elements (PHEs) in the mine spoils were also compared with other mine tailings in other regions of the world (Table 4). The result suggests that the mine spoils have a higher concentration of As, Mo, Pb, Th, and U than other places of the world where a higher concentration of elements like As, Pb, Cd, Hg, Sb, and Zn have been reported. The geology of the region, where granites predominate, is consistent with this, and it is known that Th and U have large ionic radii, which may cause these elements to crystallize in granites.

Table 4. Comparison of PHEs in mine spoils of Jos and other regions of the world.

Place/Country	PHEs	Reference
Jos, Nigeria	As, Mo, Pb, Th and U	This Study
Kabwe, Zambia	Pb	[40]
Isa, Australia	Cd, Cu, Pb and Zn	[41]
Rio Tinto, Spain	Cu, Zn and Pb	[42]
Ghana	As, Cd, Fe, Ti	[43]
Longnan, China	As, Hg and Sb	[44]

Table 5. Pearson's correlation matrix of PHEs in mine spoils.

PHEs	As	Ba	Be	Co	Cr	Cu	Mo	Mn	Ni	Pb	Sb	Th	U	V	Zn
As	1														
Ba	-0.124	1													
Be	0.075	.334*	1												
Co	0.165	.550**	.476**	1											
Cr	.679**	-0.161	-0.094	0.139	1										
Cu	.501**	0.158	.308*	.567**	.615**	1									
Mo	.512**	-.335*	-0.049	-0.138	.371*	0.089	1								
Mn	0.288	.362*	.511**	.862**	0.296	.614**	0.083	1							
Ni	.400**	0.283	0.114	.496**	.485**	.732**	-0.012	.397**	1						
Pb	0.269	-0.077	.333*	0.168	0.181	0.293	0.254	.329*	0.153	1					
Sb	.898**	-0.221	-0.063	0.011	.671**	.344*	.545**	0.143	.369*	0.204	1				
Th	0.05	-0.209	-0.032	-0.127	-0.011	-0.158	0.252	-0.05	-0.204	.559**	0.054	1			
U	0.143	-0.183	-0.014	-0.105	0.009	-0.124	0.22	-0.041	-0.116	.554**	0.157	.902**	1		
V	.676**	-0.058	0.035	.355*	.900**	.820**	0.271	.454**	.625**	0.258	.602**	-0.114	-0.074	1	
Zn	.501**	0.158	.308*	.567**	.615**	1.000**	0.089	.614**	.732**	0.293	.344*	-0.158	-0.124	.820**	1

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

Table 6. Factor Loadings of PHEs in mine spoils of Jos.

Parameter	Factor loadings		
	1	2	3
V	0.949	0.143	
Cr	0.907		
Cu	0.802	0.488	
Zn	0.802	0.488	
As	0.801		0.201
Ni	0.659	0.426	-0.156
Mo	0.471	-0.305	0.390
Co	0.274	0.865	
Mn	0.405	0.767	
Ba	-0.146	0.729	-0.230
Be		0.726	0.160
U			0.909
Th	-0.137	-0.122	0.909
Pb	0.241	0.276	0.766
Eigenvalues	5.613	2.768	2.089
% of Variance	40.090	19.772	14.923
Cumulative %	40.090	59.862	74.785

3.2. Potentially harmful elements assessment

To understand the contamination level of potentially harmful elements in the mine spoils, CF, PLI and the index of geo-accumulation were applied. The average CF values in mine spoils for As, Ba, Be, Co, Cr, Cu, and Mo are 3.16, 0.19, 1.14, 0.33, 1.24, 0.37, and 3.98 while the average CF for Mn, Ni, Pb, Sb, Th, U, V, and Zn are 0.16, 0.37, 3.09, 2.57, 6.02, 6.07, 1.08 and 0.74 respectively. Based on the CF values, the sampling sites showed considerable contamination with As, Ba, Be, Co, Cr, Cu, Mo, Mn, Ni, Pb, Sb, V, and Zn. However, the site is highly contaminated with Th and U (Figure 3). On the other hand, as a means

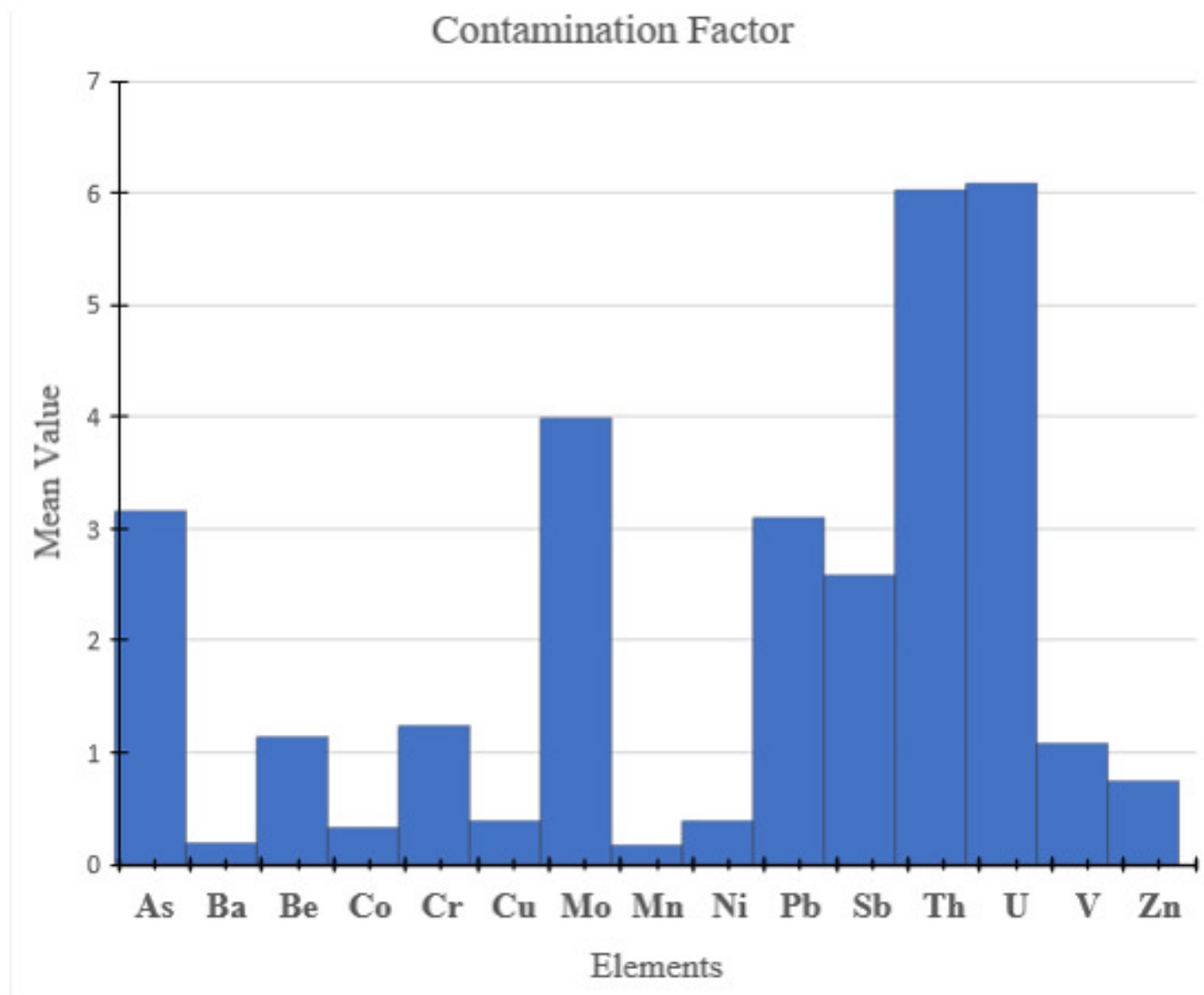


Figure 3. Bar graph of CF of some PHEs in mine spoils of the study area.

of evaluating the overall level of contamination of the environment by the mine spoils, the PLI was computed. The PLI of 0.439 for this study shows that the site is unpolluted [45]. As, Ba, Be, Co, Cr, Cu, Mo, Mn, Ni, Pb, Sb, Th, U, V, and Zn were selected and their respective indices of geo-accumulation (Igeo) determined because of their potentially harmful nature, especially at elevated concentrations [4, 6, 45]. The Igeo for As ranged from -1.43 to 2.27 with an average of 0.85, Ba ranged from -5.10 to -0.65 with an average of -3.23, Be ranged from -2.12 to 0.73 with an average of -0.57, Co ranged from -4.35 to 1.82 with an average of -2.28, Cr ranged from -2.58 to 1.59 with an average of -0.54, Cu ranged from -3.32 to 2.15 with an average of -1.39, Mo ranged from -0.32 to 3.25 with an average of 1.23, Mn ranged from -4.83 to 4.46 with an average of -2.78, Ni ranged from -3.68 to 1.20 with an average of 1.00, Pb ranged from 0.31 to 2.01 with an average of 1.00, Sb ranged from -0.59 to 1.58 with an average of 0.69, Th ranged from 1.24 to 3.83 with an average of 1.90, U ranged from 0.52 to 4.40 with an average of 1.81, V ranged from -2.23 to 0.83 with an average of -0.54 while Zn ranged from 2.32 to 0.60 with an average of -1.06. The mean Igeo concentration in the spoils is presented in Figure 4. The implication of this, according to Muller [38] is that the mine spoils are mostly moderately - uncontaminated with As, Ba, Be, Co, Cr, Cu, Mo, Mn, Ni, Pb, Sb, Th, U, V and Zn. This is influenced by the geology of the area which consists chiefly of granites which are formed in the late stage of magma crystallization. Atafar *et al.* [13] attributed elevated As and Pb concentrations to the application of inorganic fertilizers. These results as summarized in Figures 3 and 4 agreed with contamination levels in similar mining areas as reported in Refs. [46–48] in Nigeria, Africa and around the world.

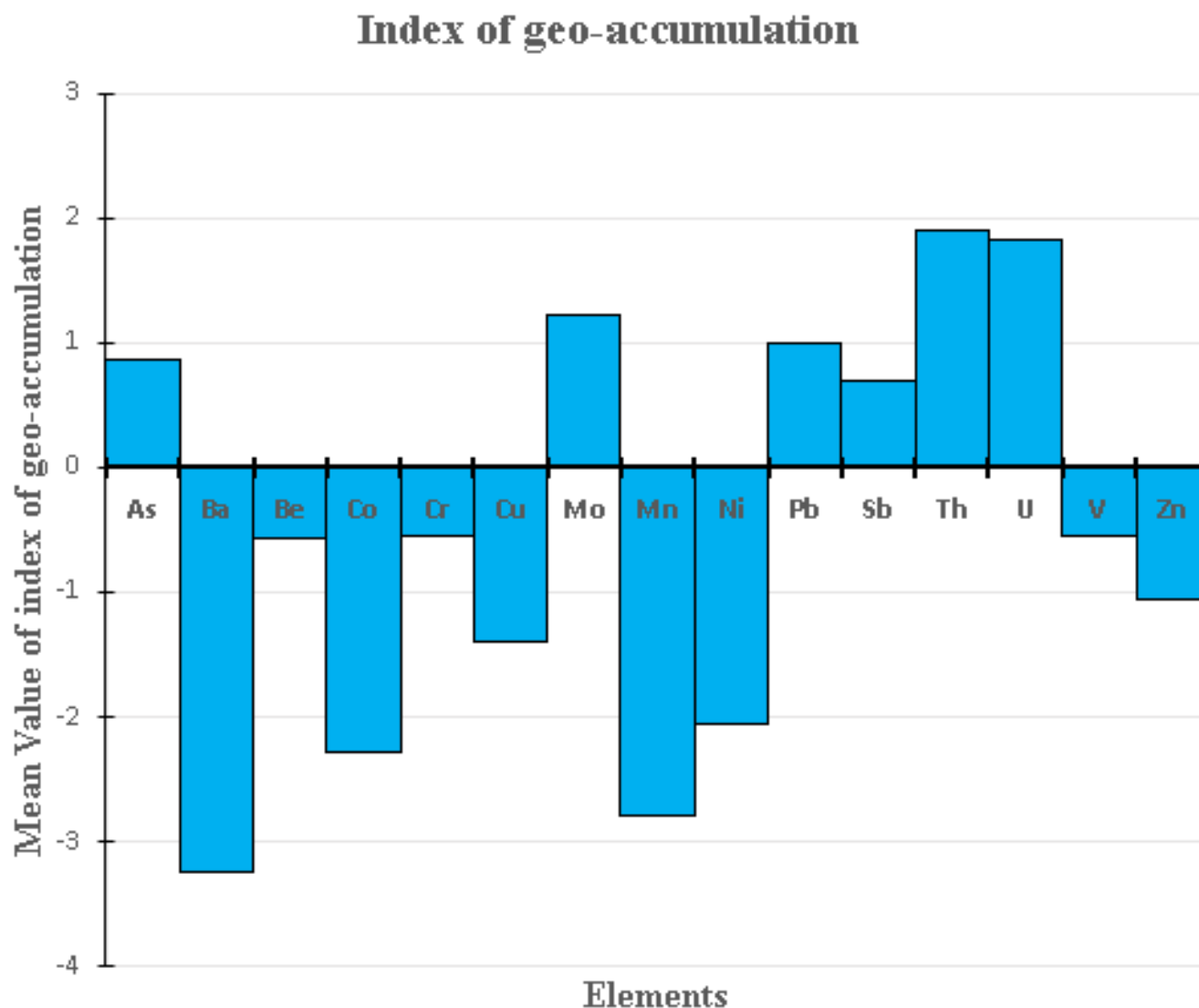


Figure 4. Bar graph of index of geo-accumulation of some PHEs in mine spoils in the study area.

3.3. Pollution source identification

When heavy metals have a relationship with one another, Pearson's analysis, principal component analysis (PCA), and cluster analysis (CA) could be used to find shared origins or geochemical traits [49, 50]. Pearson's correlation analysis (Table 5) was used to determine how closely the heavy metals (As, Ba, Be, Co, Cr, Cu, Mo, Mn, Ni, Pb, Sb, Th, U, V, and Zn) are related to one another. The Pearson's correlation coefficients of the elemental pairs As-Cr (0.679), As-Sb (0.898), As-V (0.676), Co-Mn (0.862), Cr-Cu (0.615), Cr-Sb (0.671), Cr-V (0.900), Cr-Zn (0.615), Cu-Mn (0.614), Cu-Ni (0.732), Cu-V (0.820), Cu-Zn (1.00), Mn-Zn (0.614), Ni-V (0.625), Ni-Zn (0.732), Th-U (0.902), and V-Zn (0.820) implied that a significant correlation at $p < 0.01$ was found among As, Co, Cr, Cu, Ni, V and Zn. A significant positive correlation at $p < 0.01$ can be observed between Cu and Zn and between Th and U. The principal component analysis showed that three principal components with an eigenvalue > 1 explained appropriately 74.79% of the total variance as can be seen in Table 6. Principal Component 1 (PC1) shows a strong positive loading among Vanadium (V), Chromium (Cr), Copper (Cu), Zinc (Zn), Arsenic (As), and Nickel (Ni) which represent a cluster of elements with similar geochemical behaviour or a common source resulting from either a mineralization event or geochemical process that affects these elements together and reflect mineralization associated with base metals, such as sulfides or oxides. In principal component 2 (PC2), Strong positive loadings exist among Cobalt (Co), Manganese (Mn), Beryllium (Be), and moderate loadings between Vanadium (V) and Zinc (Zn) which represent a different geochemical process or mineral association, perhaps linked to Co-Mn-bearing minerals or specific environmental conditions. The presence of Co, Mn, and Be suggests association with certain oxidized environments or perhaps skarn-type mineralization. While in principal component 3 (PC3), there is strong positive

loadings among Uranium (U), Thorium (Th), and Lead (Pb), and a moderate loading for Arsenic (As) which likely represents a radioactive component, particularly associated with uranium and thorium-bearing minerals, often linked with granitic or pegmatitic environments. Uranium and thorium associations indicate the presence of radioactive minerals, possibly linked to granitic rocks or pegmatites.

Geogenic, industrial, agricultural, pharmaceutical, household effluents, and atmospheric sources are among the documented sources of heavy metal contamination in the environment [51]. Mining, foundries, smelters, and other metal-based industrial processes are point sources of significant environmental pollution [52, 53]. On the other hand, industrial sources include metal processing in refineries, coal burning in power plants, petroleum combustion, nuclear power stations and high-tension lines, plastics, textiles, microelectronics, wood preservation and paper processing plants [54, 55]. A careful look at the above possible sources of heavy metal pollution which can be potentially harmful compared with the environment where these spoils were sampled, one can infer that these potentially harmful elements were sourced possibly from natural sources (geogenic) or were introduced during mining operations. The possibility of these elements been sourced from industries is not tenable because there is no documented history of industries ever sited in the area.

4. Conclusion

This study assessed the concentrations, contamination levels, and potential sources of PHEs in mine spoils from the Jos–Bukuru tin field. The mean concentrations of As, Mo, Pb, Th, and U exceeded background threshold values, while the CF revealed considerable enrichment of As, Ba, Be, Co, Cr, Cu, Mo, Mn, Ni, Pb, Sb, V, and Zn, as well as contamination with Th and U. Geo-accumulation indices indicated that the spoils range from uncontaminated to moderately contaminated with these elements. In contrast, the PLI suggested that the site remains unpolluted. Multivariate statistical analyses, including Pearson's correlation, principal component analysis, and cluster analysis, revealed that while a significant portion of these elements originates from natural geogenic sources, mining activities also contribute to their presence.

Data availability

The datasets generated and analyzed during the present study are available from the corresponding author upon reasonable request.

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