FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 1, January, 2026, pp 101 – 110
DOI: https://doi.org/10.33003/fjs-2026-1001-4512

MULTI-MEDIA ASSESSMENT OF POTENTIALLY HARMFUL ELEMENTS AND ASSOCIATED HEALTH RISKS IN SOILS, WATER, AND FOOD CROPS FROM DERELICT MINING LANDS IN JOS AND BARKIN-LADI, NORTH CENTRAL NIGERIA

***[1]Abubakar Ridwan Muhammad, [1]Hyeladi Usman Dibal, [1]Raymond I. Daspan and [2]Auwalu Dalha**

[1]Department of Geology, University of Jos, Nigeria.
[2]Department of Geology, Gombe State University Gombe State, Nigeria.

*Corresponding authors’ email: abubakarridwanm@yahoo.com

ABSTRACT

Abandoned tin-columbite mining on the Jos Plateau has left extensive mine dumps and water-filled pits that continue to contaminate surrounding soils, surfa9ce waters, and food crops with potentially harmful elements (PHEs). This study integrates concentration analysis, pollution indices, chemical speciation, and human health risk assessment across dump soils, farm soils, mine pond waters, and edible vegetables from Jos and Barkin-Ladi, North-Central Nigeria. A total of seventy-one soil samples, thirty-seven water samples, and representative vegetable samples were analyzed using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS). Pollution indices, including the geo-accumulation index (Igeo) and contamination factor (CF), were applied, while human health risks were evaluated using United States Environmental Protection Agency (USEPA) exposure models for adults and children. Metal speciation was assessed using thermodynamic equilibrium modeling (WATEQ4F). Results indicate elevated concentrations of Mn, Ba, Ag, Zn, Pb, As, and Cr across all environmental media, with pollution indices revealing moderate to extreme contamination factors linked to legacy tin mining, particularly for Ag and Ba. Speciation modeling indicates that many metals occur predominantly as free ionic species under prevailing pond-water chemistry, enhancing mobility and transfer into agricultural soils and crops irrigated with mine water. Non-carcinogenic risks (HI > 1) are substantial, particularly for Mn and Zn, with children facing disproportionately higher risks. Arsenic carcinogenic risk exceeds acceptable limits for both age groups. These findings highlight an active soil-water-plant contamination continuum and underscore urgent needs for restricting mine-pond irrigation, targeted soil remediation, and routine monitoring of food crops in mining-impacted communities.

Keywords: Potentially harmful elements, Mining contamination, Health risk assessment, Metal speciation, Jos Plateau; Nigeria

INTRODUCTION

Environmental contamination by potentially harmful elements (PHEs) is a persistent global concern because of their toxicity, non-biodegradability, and capacity for bioaccumulation within ecological and human systems (Alloway, 2013; Tchounwou et al., 2012). Among anthropogenic activities, mining remains one of the most significant sources of PHE release, particularly in abandoned or poorly rehabilitated mining landscapes where tailings, waste rock, and mine ponds continue to act as long-term secondary pollution sources (Obiora et al., 2016; Li et al., 2020).

The Jos Plateau of north-central Nigeria represents one of the most extensive legacy tin–columbite mining districts in West Africa. Intensive mining activities that peaked between the 1940s and 1980s generated large volumes of mine dumps and water-filled pits that now dominate the landscape (Macleod et al., 1971; Nganje et al., 2010). In the absence of systematic reclamation, these features have become chronic sources of metal-rich dust, leachates, and contaminated surface waters of particular concern is the widespread reuse of abandoned mine ponds for dry-season irrigation, which creates a direct pathway for contaminant transfer from mining wastes into agricultural soils and food crops (Momoh et al., 2014).

Several studies have documented elevated concentrations of heavy metals in soils, waters, and crops across the Jos Plateau (Jibiri et al., 2007; Shibdawa et al., 2019; Emeribe et al., 2022). However, most previous investigations have focused on single environmental compartments or relied solely on total metal concentrations, providing limited insight into contaminant mobility, bioavailability, and cross-media transfer. Consequently, the mechanisms linking mine dumps, irrigation water, cultivated soils, food crops, and human exposure remain poorly constrained. Metal speciation is particularly critical in this setting because hydrogeochemical conditions typical of mine ponds on the Jos Plateau-generally circumneutral pH, variable redox states, and elevated dissolved ions can strongly influence the chemical form, mobility, and reactivity of metals. Under such conditions, metals occurring as free or weakly complexed ionic species are more readily transported and potentially available for plant uptake than those bound in stable mineral phases. Despite this, speciation-based assessments remain scarce for the Jos Plateau, and their implications for food-chain contamination have not been adequately explored.

Human health risk assessment has become a standard extension of contamination studies, yet few works in the region explicitly link exposure pathways to site-specific land-use practices. Children are expected to be particularly vulnerable in mining-impacted communities due to lower body weight, higher soil ingestion rates, and greater dependence on locally grown vegetables irrigated with mine water. Explicitly testing these expectations requires an integrated, multi-media framework.

This study addresses these gaps by integrating (i) concentration and pollution assessment of PHEs in mine dump soils, farm soils, mine pond waters, and edible vegetables, (ii) thermodynamic metal speciation modelling to evaluate chemical availability under local hydrogeochemical conditions, and (iii) multi-pathway human health risk assessment for adults and children. By explicitly tracing contaminant transfer across environmental media, this work advances understanding of the soil-water-plant-human continuum in legacy mining landscapes of the Jos Plateau and provides a stronger scientific basis for risk management and land-use regulation.

Literature Review

Extensive studies have demonstrated that mining activities are major contributors to the accumulation of potentially harmful elements (PHEs) in soils, particularly in abandoned and artisanal mining environments. On the Jos Plateau, prolonged tin and columbite mining has resulted in significant soil degradation and enrichment of metals such as Cd, Pb, Zn, Cu, Ni, Mn, As, and Ba (Nganje et al., 2010; Awuchi et al., 2020; Nimyel & Chundusu, 2021). The extent of contamination varies with distance from mine dumps, land-use practices, and depth of sampling.

Analytical approaches including Atomic Absorption Spectrometry (AAS), ICP-OES, ICP-MS, and selective extraction techniques (e.g., DTPA, sequential extraction) have been widely employed to assess both total metal concentrations and their environmentally available fractions. While some studies reported metal concentrations within regulatory limits (Jibiri et al., 2007; Mokhtari et al., 2015; Sundaray et al., 2011), others revealed exceedances of FAO/WHO and FEPA guidelines, particularly for Cd and Ni, highlighting spatial heterogeneity and localized contamination hotspots (Nimyel & Chundusu, 2021). Importantly, metal speciation studies indicate that metals occurring in exchangeable and carbonate-bound fractions pose greater ecological and health risks than those in residual forms due to their enhanced mobility and bioavailability (Mokhtari et al., 2015; Sundaray et al., 2011).

Mine pond waters associated with abandoned mining sites act as long-term reservoirs of dissolved and particulate metals. Studies from Jos and Barkin-Ladi show elevated concentrations of As, Pb, Cd, Zn, Mn, Hg, and Cr in mine ponds used for irrigation and domestic activities, often exceeding WHO permissible limits (Jibiri et al., 2007; Momoh et al., 2014; Emeribe et al., 2022). Water chemistry, particularly pH and redox conditions, plays a critical role in metal solubility and transport. Acidic to slightly alkaline waters enhance the mobility of metals such as Cd and Pb, increasing their potential to enter agricultural soils and the food chain. Sequential extraction studies reveal that Cd and Pb are commonly associated with exchangeable and carbonate fractions, indicating high environmental risk (Sunday, 2020; Obasi & Akudinobi, 2020). Seasonal variations further influence contamination levels, with higher concentrations often recorded during the dry season due to evaporation and reduced dilution (Emeribe et al., 2022).

Numerous studies confirm that crops cultivated on contaminated soils or irrigated with polluted mine pond water accumulate PHEs in edible tissues. Vegetables such as garden egg, pepper, jute mallow, and cassava grown around Jos Plateau mining areas have been reported to contain elevated levels of Zn, Cd, Pb, Ni, and As (Makanjuola et al., 2019; Mafuyai et al., 2020).

Plant uptake of metals is influenced by soil pH, metal speciation, root physiology, and the presence of chelating agents. While some metals are essential micronutrients, excessive concentrations result in phytotoxicity and increased dietary exposure risks. Children are particularly vulnerable due to higher consumption rates relative to body weight and developing physiological systems (Mahmood & Malik, 2014; Wei et al., 2018).

Metal speciation is increasingly recognized as a critical factor controlling toxicity and environmental behavior. Studies from Nigeria and other mining regions globally demonstrate that metals such as Cd, Zn, Mn, Ni, and Pb commonly occur as free ions or weakly bound complexes, which are readily available for plant uptake and human exposure (Liu et al., 2013).

Environmental factors including pH, organic matter content, redox potential, and microbial activity strongly influence metal partitioning between solid and aqueous phases. Metals in residual fractions represent long-term contamination sources, while those in labile forms pose immediate ecological and health threats.

Health risk assessments across mining-impacted regions consistently indicate that ingestion of contaminated food and water constitutes the dominant exposure pathway. Elevated Hazard Index (HI) values for Mn, Zn, Pb, and V have been reported, with children experiencing significantly higher risks than adults (Nganje et al., 2010; Tepanosyan et al., 2017).

Carcinogenic risk assessments highlight arsenic as the most critical element, frequently exceeding acceptable risk thresholds (1×10^{-4}), thereby posing long-term cancer risks to exposed populations (Smith et al., 2002; USEPA, 2011).

Despite numerous studies, gaps remain in integrated multi-media assessments linking soil, water, and food pathways. Limited attention has been given to metal speciation-based risk assessment, seasonal variability, atmospheric exposure routes, and long-term epidemiological data in mining communities. These gaps necessitate comprehensive studies that combine geochemical characterization, speciation analysis, and population-specific health risk evaluation.

MATERIALS AND METHODS

Study Area and Site Selection

The study was conducted in Jos North, Jos South, and Barkin-Ladi Local Government Areas of Plateau State, North-Central Nigeria (Figure 1). Sampling sites were selected to represent major legacy mining zones characterized by abandoned mine dumps, water-filled pits, and adjacent farmlands actively cultivated using mine pond water for irrigation. Soil samples were collected from locations outside the influence of mining activities. Site selection was guided by field reconnaissance, historical mining records, and accessibility.

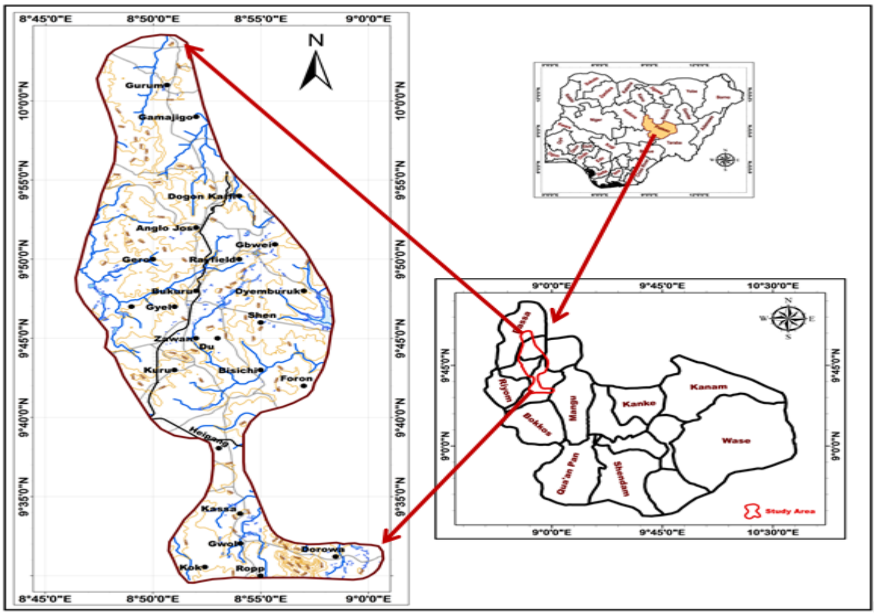


Figure 1: Location Map of the Study Area (Map of Plateau State with Jos and Barkin-Ladi)

Sample Collection, Preparation and Analysis

Sampling was carried out during the dry season, when mine ponds are intensively used for irrigation and dilution from rainfall is minimal. A total of 71 soil samples (dump soils and farm soils), 37 mine pond water samples, and representative edible vegetable samples were collected. Geographic coordinates were recorded using a handheld GPS. Dump and farm soils were collected using a hand auger at depths of 0-20 cm. Composite samples were prepared from subsamples collected at the top, middle, and base of mine dumps. Water samples were collected in acid-washed polyethylene bottles, filtered on-site, and acidified with ultrapure nitric acid. Edible vegetables commonly consumed locally were harvested directly from farms. Soil samples were air-dried, oven-dried at 40 °C, disaggregated using an agate mortar, and sieved prior to analysis. Vegetable samples were oven-dried at 35 °C and pulverized. All samples were analyzed for trace elements using Inductively Coupled Plasma–Mass Spectrometry (ICP–MS) at Bureau Veritas Mineral Laboratory, Vancouver, Canada, following standard digestion protocols. Quality assurance and quality control procedures included procedural blanks, duplicate samples, and certified reference materials. Analytical recoveries ranged between 90-110%, and detection limits were element-specific and within internationally accepted ranges.

Pollution Indices Metal Speciation Modelling

The degree of contamination was evaluated using the geo-accumulation index (Igeo) and contamination factor (CF). Background concentrations were derived from soils and published regional crustal averages. Igeo was calculated following Müller (1969): $Igeo = \log_2 (Cn / 1.5Bn)$, where Cn is the measured concentration and Bn is the background value. The contamination factor was calculated as $CF = Cn/Bn$.

Chemical speciation of dissolved metals in water samples was modelled using WATEQ4F within the Geochemist's Workbench platform. Input parameters included measured pH, temperature, major ions, and trace metal concentrations. Saturation indices were used to evaluate mineral stability. Speciation results are interpreted as indicators of chemical availability under modelled equilibrium conditions, acknowledging uncertainties related to thermodynamic assumptions.

Human Health Risk Assessment

Non-carcinogenic and carcinogenic risks were assessed using USEPA exposure models for ingestion pathways. Average daily doses were calculated for adults and children using standard exposure parameters, which were contextualized to local dietary habits and land-use practices. Hazard quotient (HQ), hazard index (HI), and carcinogenic risk (CR) were computed following USEPA guidelines.

RESULTS AND DISCUSSION

Trace Element Concentrations in Mine Dump Soils

Table 1 summarizes the descriptive statistics of trace element concentrations in mine dump soils from the study area. The results show wide variability in elemental concentrations, reflecting heterogeneous contamination associated with abandoned mining activities. Manganese (Mn) recorded the highest mean concentration (276.22 mg/kg), with values ranging from 147.00 to 722.00 mg/kg, indicating substantial enrichment likely linked to mineralized host rocks and mining residues. Barium (Ba) also exhibited elevated concentrations, with a mean value of 193.89 mg/kg and a maximum of 496.00 mg/kg, suggesting strong geogenic and mining-related inputs. Silver (Ag) concentrations were notably high, with a mean of 46.83 mg/kg and a maximum of 143.00 mg/kg, far exceeding typical background levels and pointing to significant anthropogenic enrichment from tin mining wastes. Chromium (Cr) showed a wide concentration range (38.00–428.00 mg/kg) and a relatively high mean value of 128.17 mg/kg, indicating variable but potentially hazardous contamination. Zinc (Zn) and lead (Pb) recorded mean concentrations of 66.54 mg/kg and 44.26 mg/kg, respectively, reflecting moderate to high enrichment levels (Table 1).

Arsenic (As) concentrations ranged from 1.00 to 10.00 mg/kg, with a mean of 5.99 mg/kg, while cadmium (Cd) occurred at comparatively low concentrations (mean = 0.04 mg/kg) (Table 1). Rare and trace elements such as cerium (Ce), strontium (Sr), antimony (Sb), beryllium (Be), and molybdenum (Mo) were present at variable but generally elevated levels, further confirming the influence of mining-derived materials on dump soil chemistry.

Table 1: Trace Element Concentration in Dump Soil

S/N	ELEMENTS	MIN	MAX	MEAN	MEDIAN	MODE	S. D
1.	Cu	14.30	61.10	31.77	29.00	29.80	10.83
2.	Pb	29.70	74.24	44.26	41.78	NA	10.21
3.	As	1.00	10.00	5.99	5.95	5.60	1.93
4.	Cr	38.00	428.00	128.17	85.00	83.00	86.90
5.	Cd	0.02	0.12	0.04	0.04	0.04	0.019
6.	Ni	16.50	68.50	41.52	39.80	30.50	12.26
7.	Mo	1.72	16.02	4.61	3.88	4.14	2.82
8.	Zn	29.80	133.00	66.54	63.00	63.00	25.21
9.	Mn	147,00	722.00	276.22	260.50	199.00	114.81
10.	Sr	16.00	88.00	46.00	44.50	26.00	18.33
11.	Ce	92.99	340.37	169.75	157.15	NA	61.58
12.	Ag	22.00	143.00	46.83	34.00	NA	32.90
13.	Ba	47.00	496.00	193.89	151.50	86.00	123.78
14.	Sb	0.13	0.77	0.42	0.43	0.26	0.13
15.	Be	1.00	10.00	3.50	3.00	3.00	1.86

Trace Element Concentrations in Farm Soils

Trace element concentrations in farm soils cultivated around abandoned mining sites are presented in Table 2. Overall, the soils display elevated levels of several potentially harmful elements, indicating the transfer of contaminants from mine dumps and irrigation sources into adjacent agricultural lands. Barium (Ba) shows the highest mean concentration (251.27 mg/kg), with maximum values of up to 444.00 mg/kg, highlighting its strong persistence and accumulation in cultivated soils.

Silver (Ag) showed remarkably high and consistent concentrations, with a narrow range (114.00–119.00 mg/kg) and a mean value of 116.50 mg/kg, suggesting uniform contamination across farm plots. Manganese (Mn) concentrations were also elevated, with a mean of 230.20 mg/kg, while zinc (Zn) displayed substantial variability (31.60–185.30 mg/kg), reflecting differences in soil properties and contamination intensity (Table 2).

Lead (Pb) concentrations ranged from 18.92 to 167.42 mg/kg, with a mean of 38.66 mg/kg, indicating localized hotspots of contamination. Chromium (Cr) and nickel (Ni) recorded mean values of 91.40 mg/kg and 28.16 mg/kg, respectively (Table 2), which may pose ecological and health concerns. Arsenic (As) and cadmium (Cd) occurred at lower mean concentrations (2.78 mg/kg and 0.07 mg/kg, respectively) but remain environmentally significant due to their toxicity.

The presence of elevated cerium (Ce), strontium (Sr), and antimony (Sb) further reflects the influence of mining activities and irrigation with contaminated mine pond water on farm soil quality.

Table 2: Trace Element Concentration in Farm Soil

S/N	ELEMENTS	MIN	MAX	MEAN	MEDIAN	MODE	S. D
1.	Cu	8.80	34.30	17.86	17.00	14.20	5.04
2.	Pb	18.92	167.42	38.66	31.56	NA	26.21
3.	As	1.20	8.70	2.78	2.40	1.70	1.48
4.	Cr	39.00	240.00	91.40	68.00	58.00	58.84
5.	Cd	0.02	0.29	0.07	0.04	0.03	0.07
6.	Ni	10.30	54.70	28.16	25.50	17.20	10.61
7.	Mo	0.93	5.61	2.61	2.28	NA	1.26
8.	Zn	31.60	185.30	69.56	40.24	NA	40.24
9.	Mn	152.00	561.00	230.20	201.50	NA	83.09
10.	Sr	18.00	66,00	42.63	42.50	36.00	11.96
11.	Ce	64.44	178.25	129.52	125.81	NA	30.55
12.	Ag	114.00	119.00	116.50	116.50	NA	3.54
13.	Ba	87.00	444.00	251.27	244.50	NA	99.22
14.	Sb	0.17	2.24	0.44	0.33	0.44	0.37
15.	Be	1.00	9.00	2.80	3.00	3.00	1.47

Trace Element Concentrations in Mine Pond Water

The concentrations of trace elements in mine pond water samples, expressed in µg/L, are presented in Table 3. The data reveal substantial enrichment of several elements, accompanied by considerable spatial variability across the sampling locations. Notably, zinc (Zn) records exceptionally high levels, with a mean concentration of 962.40 µg/L and peak values reaching 10,000 µg/L points to severe contamination and a strong potential for bioaccumulation.

Manganese (Mn) concentrations ranged from 9.49 to 681.95 µg/L, with a mean of 103.02 µg/L, exceeding typical background and guideline values. Barium (Ba) also showed elevated levels, with a mean concentration of 59.17 µg/L. Lead (Pb), nickel (Ni), and chromium (Cr) recorded mean concentrations of 3.06 µg/L, 4.33 µg/L, and 1.28 µg/L, respectively (Table 3), reflecting moderate contamination.

Arsenic (As) concentrations ranged from 0.50 to 1.10 µg/L, while cadmium (Cd) occurred at relatively low but consistent levels (mean = 0.057 µg/L). Cerium (Ce) displayed high variability, with concentrations reaching up to 100.30 µg/L, suggesting localized geochemical controls. Silver (Ag) was not detected in water samples, indicating limited solubility or rapid sedimentation under prevailing physicochemical conditions.

Overall, the mine pond waters represent a significant pathway for metal transport into surrounding soils and crops, especially given their widespread use for irrigation.

Table 3: Trace element concentration in Mine Pond Water (ug/l)

S/N	ELEMENTS	MIN	MAX	MEAN	MEDIAN	MODE	S. D
1.	Cu	0.50	10.50	2.94	2.30	1.60	2.40
2.	Pb	0.30	11.20	3.06	2.00	2.90	2.88
3.	As	0.50	1.10	0.72	0.60	0.50	0.26
4.	Cr	0.50	3.60	1.28	1.00	0.70	0.85
5.	Cd	0.05	0.06	0.057	0.06	0.06	0.01
6.	Ni	0.90	16.00	4.33	3.20	1.30	3.77
7.	Mo	0.10	0.10	0.10	0.10	0.00	0.00
8.	Zn	4.10	10000	962.40	250.3	0.00	1850
9.	Mn	9.49	681.95	103.02	52.54	0.00	148.40
10.	Sr	3.18	152.82	44.40	39.79	0.00	30.68
11.	Ce	0.78	100.30	14.96	8.87	0.00	20.56
12.	Ag	0.00	0.00	0.00	0.00	0.00	0.00
13.	Ba	12.28	180.77	59.17	53.11	0.00	39.11
14.	Sb	0.05	0.12	0.075	0.06	0.06	0.03
15.	Be	0.05	2.93	0.44	0.2	0.06	0.71

Trace Element Concentrations in Edible Vegetables

Trace element concentrations in edible vegetables from the study area (Table 4) indicate notable accumulation of potentially harmful elements, reflecting their bioavailability in soils and irrigation water. Manganese (Mn) shows the highest mean concentration (50.65 mg/kg), followed by zinc (Zn; 28.72 mg/kg), highlighting the efficient uptake of these metals by plants.

Lead (Pb) concentrations ranged from 0.12 to 14.45 mg/kg, with a mean of 1.19 mg/kg, suggesting potential dietary exposure risks. Arsenic (As) recorded a mean concentration of 1.27 mg/kg, while cadmium (Cd) showed a mean of 0.08 mg/kg, both of which are of concern due to their toxicity even at low levels. Chromium (Cr) exhibited a wide range of values, reaching up to 40.20 mg/kg, indicating variable accumulation among vegetable species.

Silver (Ag) was detected at notable concentrations (mean = 6.00 mg/kg), highlighting its bioavailability despite being absent in water samples. Barium (Ba) and beryllium (Be) were not detected in vegetable tissues, suggesting limited plant uptake or exclusion mechanisms. The overall pattern indicates that vegetables grown in the study area act as effective vectors for transferring mining-derived contaminants into the human food chain.

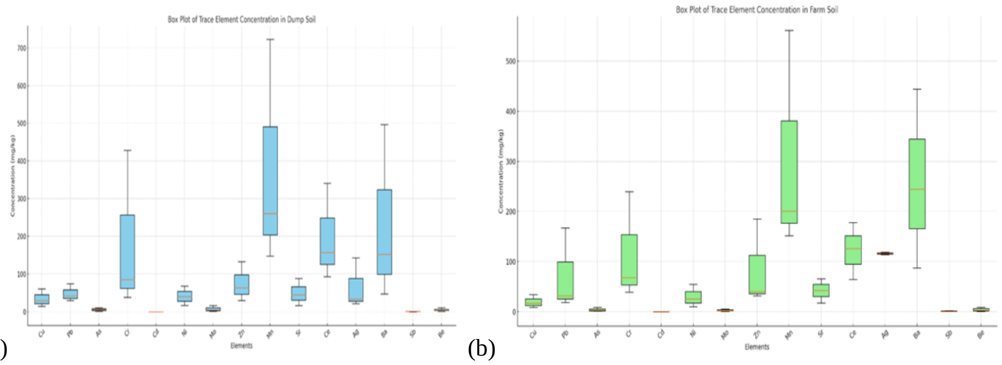
Table4: Trace Element Concentration in edible Vegetables.

S/N	ELEMENT	MIN	MAX	MEAN	MEDIAN	MODE	S. D
1.	Cu	2.69	15.52	9.11	9.56	NA	3.18
2.	Pb	0.12	14.45	1.19	0.315	0.18	2.88
3.	As	0.40	2.90	1.27	0.50	NA	1.42
4.	Cr	0.70	40.20	2.99	1.10	0.9	7.68
5.	Cd	0.02	0.20	0.08	0.07	0.07	0.05
6.	Ni	0.70	10.70	2.75	1.65	0.8	2.77
7.	Mo	0.03	2.56	0.41	0.155	0.05	0.63
8.	Zn	11.1	102.80	28.72	27.25	0	18.45
9.	Mn	18.00	126.00	50.65	39.50	30	29.86
10.	Sr	3.20	151.80	29.65	15.4	0.00	37.73
11.	Ce	0.20	81.00	5.23	0.90	0.3	15.97
12.	Ag	2.00	15.00	6.00	5.00	3.00	3.66
13.	Ba	ND	ND	ND	ND	ND	ND
14.	Sb	0.10	0.40	0.21	0.2	0.20	0.08
15.	Be	ND	ND	ND	ND	ND	ND

Discussion

Concentration and Distribution of PHEs

Elevated concentrations of Mn, Ag, Ba, Zn, Pb, As, and Cr across soils, waters, and vegetables reflect the strong influence of legacy tin mining. Extremely high CF and Igeo values for Ag and Ba indicate a dominant geogenic–anthropogenic signature linked to ore mineralization and processing residues. Spatial variability and skewed distributions suggest localized hotspots associated with specific dump sites and irrigation practices (Figure 2 a & b).



(a) (b)

Figure 2: Box-and-Whisker Plots of PHE Concentrations in (a) Dump Soils and (b) Farm Soils

Cross-Media Contaminant Transfer

The multi-media assessment reveals a clear contaminant transfer pathway from mine dumps to pond water, farm soils, and ultimately vegetables (Figure 2). Although Ag was largely absent in water samples, its elevated concentrations in soils and crops suggest indirect transfer through contaminated soils and particulate matter rather than direct aqueous uptake, highlighting the dominance of soil-mediated pathways in irrigated mining landscapes.

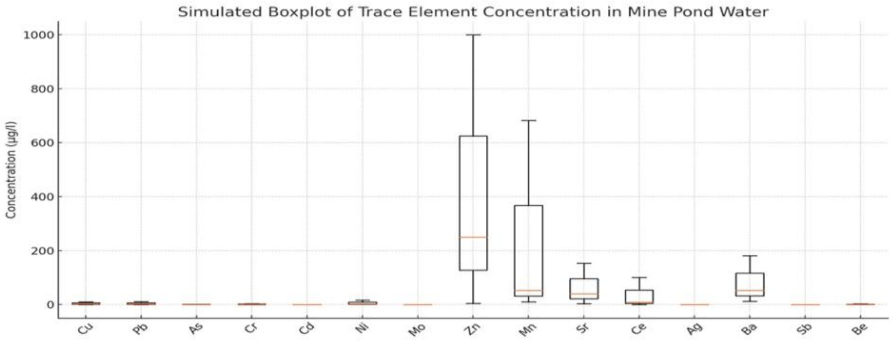


Figure 2: Box-and-whisker Plots of PHE Concentrations in Mine Pond Water

Metal Speciation

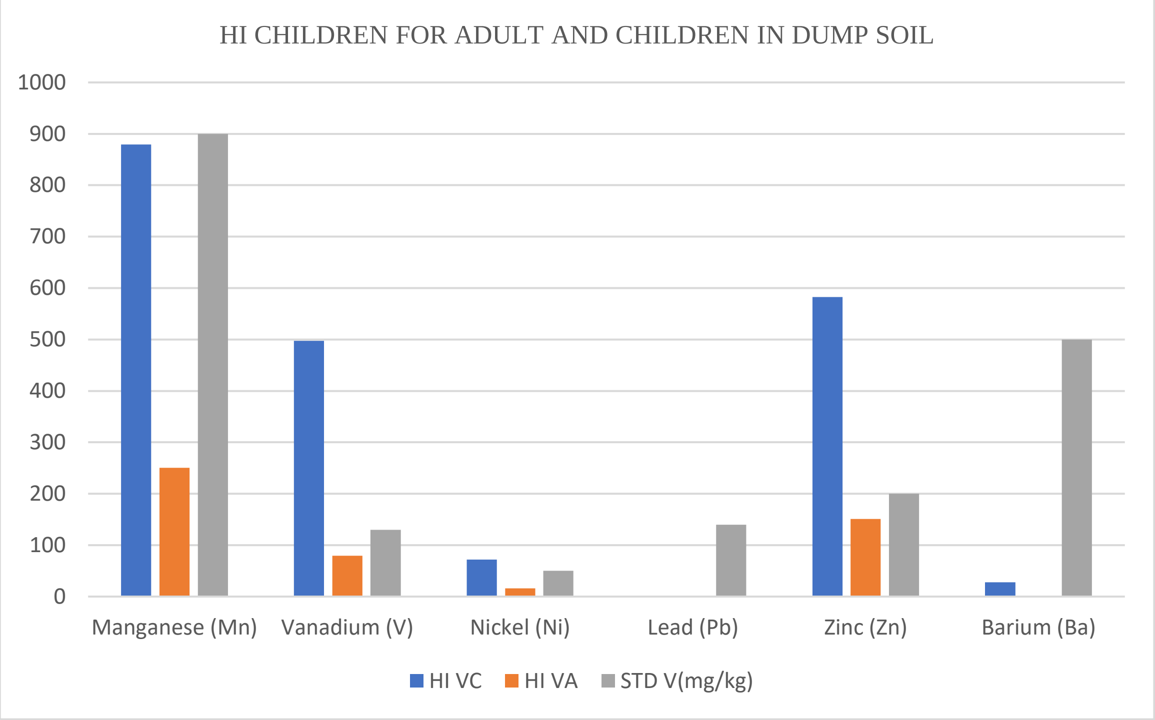
The WATEQ4F speciation modelling results (Table 1) indicate that metals such as Mn, Zn, Ba, Cd, Ni, and Ag predominantly occur as free ionic species (e.g., Mn^{2+}, Zn^{2+}), suggesting enhanced chemical mobility under prevailing hydrogeochemical conditions. (Stumm & Morgan, 1996; Alloway, 2013). These results represent equilibrium chemical availability rather than direct biological uptake, as thermodynamic models do not explicitly account for biological or kinetic controls (USEPA, 1989). Actual bioaccessibility may be further influenced by plant physiological regulation, adsorption onto soil mineral phases, and rhizosphere-mediated processes that govern metal solubility and uptake (Kabata-Pendias, 2011; Alloway, 2013). Nevertheless, the dominance of labile ionic species under local hydrogeochemical conditions supports a high potential for metal transfer within the soil–water–plant system, particularly in irrigated mining-impacted environments such as the Jos Plateau (Nganje et al., 2010; Momoh et al., 2014).

Table 1: WATEQ4F Forms of Trace Elements in Dump, Farm Soils, Vegetable and Water

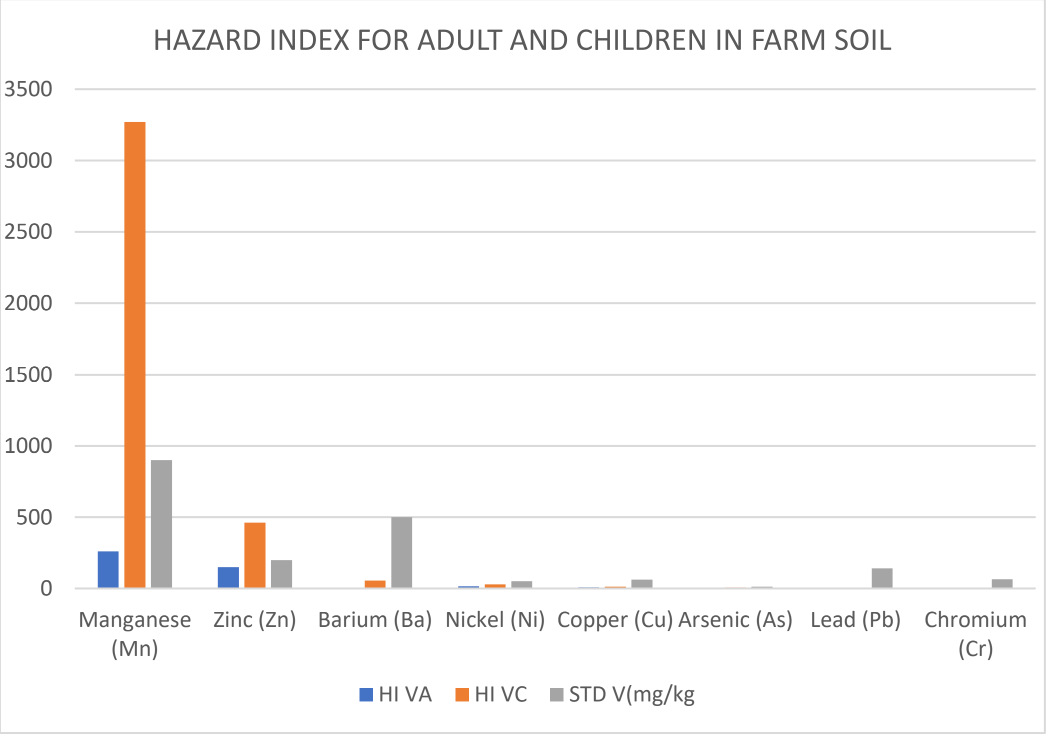
METALS	DUMP SOIL	FARM SOIL	WATER	VEGETABLE	Most toxic metals after Logan and Tarima 1993	Most Toxic Metals	% Dump Soil	%Farm Soil	%Water	%Vegetable
Ag		Ag^+	Ag^+	Ag^+	Ag^+	Ag+		100	18.05-95.02	100
As	$As0_3^{-1}$	$As0_3^-$		$As0_3$	to check for the most toxic for As					
	$As0_3$	$As0_3$								
Ba	Ba^{+2}	Ba^{+2}	Ba^{+2}	Ba^{+2}	Ba^{+2}	Ba^{+2}	100	100	100	
Cd	Cd^{+2}	Cd^{+2}	Cd^{+2}	Cd^{+2}	Cd^{+2}	Cd^{+2}	100	100	100	
			$CdBr^+$							
Cr	Cr_3^{+3}	Cr_3^{+3}	Cr_3^{+3}	Cr_3^{+3}	CrO_4^{-2}	Cr_3^{+3}	1- 5.32	0.1-29.88	99.38	
			CrF^{+2}							
	$CrOH^{+2}$	$CrOH^{+2}$					8.16-81.95	31.11-70.03		
	$CrOH^+$	$CrOH^+$					0.08-28.36			
	$CrOH_3$	$CrOH_3$					1.45-17.05			
	$Cr_2OH_2^{+4}$	$Cr_2OH_2^{+4}$					0.43-10.99			
	$Cr_3OH_4^{+5}$	$Cr_3OH_4^{+5}$								
Cu	Cu^+	Cu^+	Cu^+Cu^{+2}	Cu^+Cu^{+2}	Cu^{+2}	Cu^{+2}	99.59-99.65	99.59-99.65	99.43	99.43
	Cu^{+2}	Cu^{+2}					0.31-0.44	0.35-0.41	0.34-0.57	0.57
	$Cu(OH)_2$	$Cu(OH)_2$					0.03	0.02	0	0
Se			Hse^-							
Mn	Mn^{+2}	Mn^{+2}	Mn^{+2}	Mn^{+2}	Mn^{+2}	Mn^{+2}	100	100	100	100
Ni	Ni^{+2}	Ni^{+2}		Ni^{+2}	Ni^{+2}		100	100	0	100
Pb	Pb^{+2}	Pb^{+2}	Pb^{+2}	Pb^{+2}	Pb^{+2}	Pb^{+2}	99.3-99.89	99.25-99.99	91.71-100	100
	$PbOH^+$	$PbOH^+$					0.11-66	0.01-0.74		
		$Pb_2(OH)$						0.01-0.03		
			$PbBr^+$						0.15-0.29	
Zn	Zn^{+2}	Zn^{+2}	Zn^{+2}	Zn^{+2}	Zn^{+2}	Zn^{+2}	100	100	100	100

Health Risk Assessment

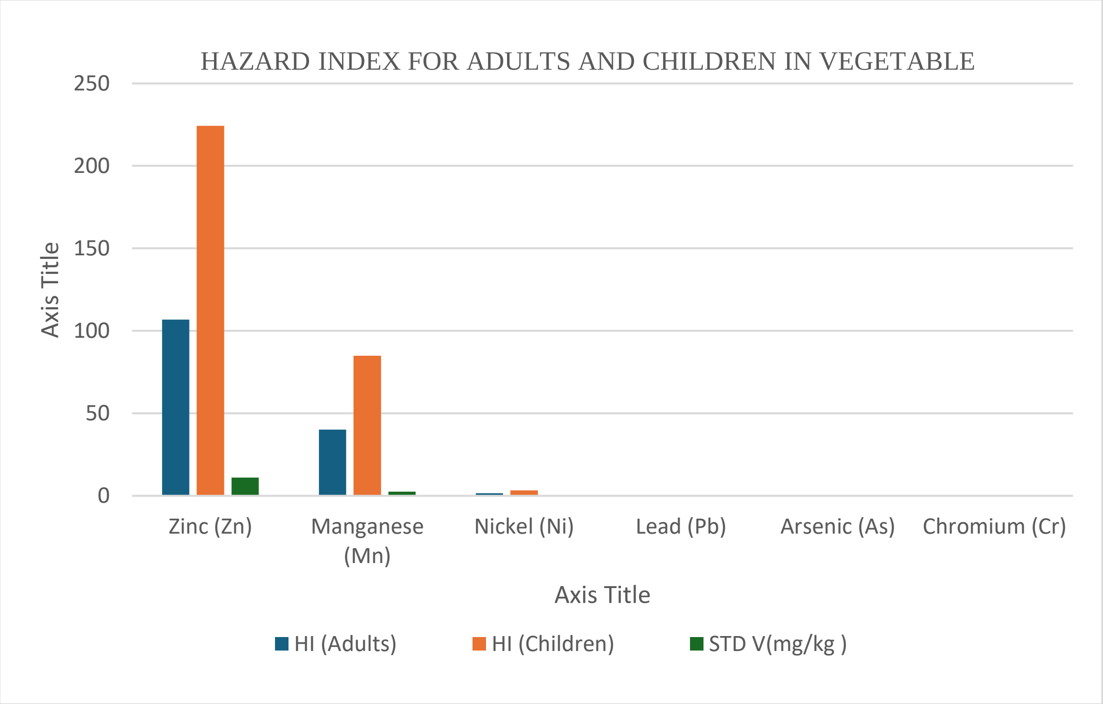
Hazard index (HI) values exceeding unity (HI > 1) indicate significant non-carcinogenic health risks, with children exhibiting substantially higher vulnerability due to lower body weight and higher exposure relative to intake (USEPA, 1989; Tepanosyan et al., 2017). Carcinogenic risk values for arsenic exceed the acceptable threshold of 1 × 10^{-4}, suggesting a potential long-term cancer risk. These findings are comparable to reports from other mining-impacted regions of Nigeria, including the Jos Plateau and Barkin-Ladi tin-mining districts (Jibiri et al., 2007; Shibdawa et al., 2019; Emeribe et al., 2022), as well as similar legacy mining environments globally (Tepanosyan et al., 2016; Li et al., 2020). Although uncertainties associated with spatial heterogeneity, seasonal sampling constraints, and exposure-model assumptions are recognized (USEPA, 1989), the consistently elevated risk indices across environmental media indicate a robust and persistent public health concern.



(a)



(b)



(c)

Figure 3: Hazard Index Comparison Between Adults and Children (a) in Dump (b) in Farm Soil (c) in Vegetables

CONCLUSION

This study demonstrates that derelict tin-mining landscapes in Jos and Barkin-Ladi remain active sources of potentially harmful elements across soils, waters, and food crops. The predominance of free ionic metal species reflects site-specific pond-water chemistry and tailings mineralogy, facilitating contaminant mobility and transfer into irrigated agricultural systems. Vegetable consumption represents the dominant exposure pathway, with children facing disproportionately higher health risks. Despite uncertainties inherent in modelling and sampling, the findings clearly indicate an urgent need for restricting mine pond water use for irrigation, targeted remediation of highly contaminated soils, and routine monitoring of food crops to safeguard public health in mining-impacted communities.

REFERENCES

Alloway, B. J. (2013). Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability (3rd ed.). Springer.

Awuchi, C. G., Twinomuhwezi, H., & Amagwula, I. O. (2020). Heavy metal contamination of agricultural soils and food crops: A review of sources, impacts and remediation strategies. *Environmental Analysis & Health Toxicology*, 35(2), e2020005.

Emeribe, C. N., Onyekachi, A. M., & Uche, O. M. (2022). Seasonal variation and health risk assessment of heavy metals in surface water around mining areas in Nigeria. *Environmental Monitoring and Assessment*, 194, 1–18.

Jibiri, N. N., Farai, I. P., & Alausa, S. K. (2007). Estimation of annual effective dose due to ingestion of food crops from tin mining areas in Jos Plateau, Nigeria. *Journal of Environmental Radioactivity*, 94(1), 31–40. Kabata-Pendias, A. (2011). *Trace Elements in Soils and Plants.* CRC Press.

Li, Z., Ma, Z., van der Kuijp, T. J., Yuan, Z., & Huang, L. (2020). A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment. *Science of the Total Environment*, 468, 843–853.

Liu, H., Probst, A., & Liao, B. (2013). Metal contamination of soils and crops affected by the Chenzhou lead–zinc mining area, China. *Science of the Total Environment*, 447, 373–380.

Macleod, W. N., Turner, D. C., & Wright, E. P. (1971). *The geology of the Jos Plateau*. Geological Survey of Nigeria Bulletin No. 32.

Mafuyai, G. M., Kamoh, N. M., Kangpe, N. S., Ayuba, S. M., & Eneji, I. S. (2020). Heavy metals contamination in vegetables grown around mining areas in Jos South, Plateau State, Nigeria. *African Journal of Environmental Science and Technology*, 14(3), 70–81.

Mahmood, A., & Malik, R. N. (2014). Human health risk assessment of heavy metals via consumption of contaminated vegetables collected from different irrigation sources in Pakistan. *Arabian Journal of Chemistry*, 7(1), 91–99.

Makanjuola, O. O., Adejumo, J. A., & Ajayi, O. O. (2019). Heavy metal accumulation in vegetables grown around mining areas and associated health risks. *Environmental Geochemistry and Health*, 41, 173–186.

Mokhtari, M., Mirzaei, R., & Ghasemi, M. (2015). Speciation and mobility of heavy metals in contaminated soils: Implications for environmental risk assessment. *Journal of Environmental Science and Health, Part A*, 50(13), 1316–1326.

Momoh, A., Olorunfemi, M. O., & Ojo, J. S. (2014). Trace element concentrations in food crops from tin mining areas of

Plateau State, Nigeria. *African Journal of Environmental Science and Technology*, 8(1), 20–27.

Nganje, T. N., Edet, A. E., & Ekwere, S. J. (2010). Hydrogeochemical evaluation of water resources in the lead–zinc mining area of Ishiagu, southeastern Nigeria. *Environmental Earth Sciences*, 61(6), 1235–1245.

Nimyel, D. N., & Chundusu, S. D. (2021). Assessment of heavy metal contamination in mine dump soils used for farming in Jos South, Nigeria. *Environmental Monitoring and Assessment*, 193, 1–15.

Obasi, P. N., & Akudinobi, B. B. (2020). Potential health risk and levels of heavy metals in water sources around mining communities. *Environmental Nanotechnology, Monitoring & Management*, 14, 100346.

Obiora, S. C., Chukwu, A., & Davies, T. C. (2016). Heavy metals and health risk assessment of arable soils and food crops around Pb–Zn mining localities in southeastern Nigeria. *Journal of African Earth Sciences*, 116, 182–189.

Reeder, R. J., Schoonen, M. A. A., & Lanzirotti, A. (2006). Metal speciation and its role in bioaccessibility and bioavailability. *Reviews in Mineralogy and Geochemistry*, 64(1), 59–113.

Shibdawa, A. M., Lubis, S., Adamu, H., & Ibejekwe, S. J. (2019). Determination of heavy metals concentration in soils used for cultivation of vegetables in Dorowa mining areas of Barkin Ladi, Plateau State, Nigeria. *ATBU Journal of Science, Technology & Education*, 7(1), 1–8.

Smith, A. H., Lopipero, P. A., Bates, M. N., & Steinmaus, C. M. (2002). Public health implications of arsenic in drinking water. *Environmental Health Perspectives*, 110(1), 45–53.

Stumm, W., & Morgan, J. J. (1996). *Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters.* Wiley.

Sundaray, S. K., Nayak, B. B., Lin, S., & Bhatta, D. (2011). Geochemical speciation and risk assessment of heavy metals in contaminated soils. *Journal of Hazardous Materials*, 186(2–3), 1837–1846.

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *Experientia Supplementum*, 101, 133–164.USEPA (United States Environmental Protection Agency). (2011). *Exposure Factors Handbook* (EPA/600/R-09/052F). Washington, DC.

Tepanosyan, G., Sahakyan, L., Belyaeva, O., et al. (2016). Origin identification and potential ecological risk assessment of potentially toxic inorganic elements in urban soils. *Journal of Geochemical Exploration*, 167, 1–11.

Tepanosyan, G., Sahakyan, L., Maghakyan, N., et al. (2017). Heavy metal pollution levels and children health risk assessment. *Ecotoxicology and Environmental Safety*, 142, 257–265.

United States Environmental Protection Agency (USEPA). (1989). *Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part A).*

Wei, B., Yang, L., & Li, H. (2018). Heavy metal contamination in soils and vegetables from mining areas: A global meta-analysis. *Environmental Pollution*, 242, 1029–1038.