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Assessment of Potentially Harmful Elements (PHEs) in Farm Soils Near Abandoned Tin–Columbite Mine Sites, Jos, Barkin Ladi, North-Central Nigeria

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ABSTRACT

An assessment of potentially harmful elements (PHEs) in farm soils around abandoned tin–columbite mine sites in Jos and Barkin Ladi, north-central Nigeria, was conducted to evaluate contamination levels and potential environmental risks. Thirty-three composite soil samples and four control samples were collected from cultivated farmlands and analyzed using Inductively Coupled Plasma–Mass Spectrometry (ICP–MS). Pollution assessment was conducted using the Index of Geo-accumulation (Igeo) and Contamination Factor (CF). The results indicate elevated concentrations of several trace elements, particularly Pb, Ba, Ce, Zn, and Mn, reflecting both lithological influence and anthropogenic contamination associated with historical mining activities. Lead concentrations exceeded background levels in all sampled soils, while silver showed localized anomalous enrichment. Geo-accumulation and contamination factor analyses revealed that most elements were in the unpolluted to moderately contaminated range, whereas Ag and Ba showed very high contamination levels. Chromium and nickel largely reflected geogenic contributions from the parent rocks. The study demonstrates that abandoned mining activities continue to influence the geochemical quality of agricultural soils within the study area. The enrichment of toxic elements such as Pb, Ba, As, and Ag raises concerns regarding long-term soil quality, crop contamination, and human exposure through the food chain. Continuous environmental monitoring, improved irrigation management, and remediation of contaminated mine sites are therefore recommended to support sustainable agriculture and protect public health.

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INTRODUCTION

Potentially harmful elements (PHEs) in soils have become a major environmental concern because of their persistence, toxicity, and ability to accumulate within ecological systems and food chains (Manta et al.,2002; Alloway, 2013). Mining and mineral processing activities are among the most significant anthropogenic sources of soil contamination, particularly in abandoned mining environments where waste dumps, tailings, and mine ponds remain exposed to weathering processes (Baloyi et al., 2024). These contaminants may subsequently migrate into surrounding agricultural soils, surface water, groundwater, and crops.

The Jos–Barkin Ladi area of north-central Nigeria has experienced extensive tin and columbite mining since the colonial period. Although mining contributed significantly to economic development, abandoned mine sites have left widespread environmental degradation characterized by mine tailings, contaminated ponds, and disturbed landscapes (MacLeod et al., 1971; Olarinoye et al., 2021). In many locations, irrigation farming is currently practiced around abandoned mine ponds, increasing the possibility of trace element transfer into agricultural soils and food crops.

Soils contaminated with PHEs may adversely affect agricultural productivity, soil microbial activity, and crop quality. Long-term exposure to toxic elements such as Pb, As, Cd, and Cr may also pose serious human health risks through ingestion, inhalation, and food-chain transfer (Tchounwou et al., 2012). Assessing the concentration and contamination levels of trace elements in cultivated soils is therefore important for environmental management and sustainable agriculture in mining-impacted areas.

Although several studies have examined mining-related contamination in parts of the Jos Plateau, limited information exists regarding contamination status and enrichment patterns of cultivated farm soils near abandoned mine sites in Jos and Barkin Ladi (Abraham et al.,2025; Ayeni, J. K., 2025; Nganje et al.,2010; Olarinoye et al.,2021; Nwankwoala, H. O., et al., 2022; Odewumi, S.C., 2024, 2025). This study, therefore, evaluates the concentrations, distributions, and contamination status of potentially harmful elements in agricultural soils using ICP–MS analysis, the geo-accumulation index (Igeo), and the contamination factor (CF).

METHODOLOGY

The Study Area

The study area covers parts of Jos North, Jos South, and Barkin Ladi Local Government Areas in Plateau State, north-central Nigeria. The study area is approximately bounded by Latitudes 8°55′N – 9°40′N and Longitudes 8°45′E – 9°00′E. It lies within the Naraguta (Sheet 168) and Kura (Sheet 124), connected by primary and secondary roads and footpaths, making it easily accessible (Fig. 1)

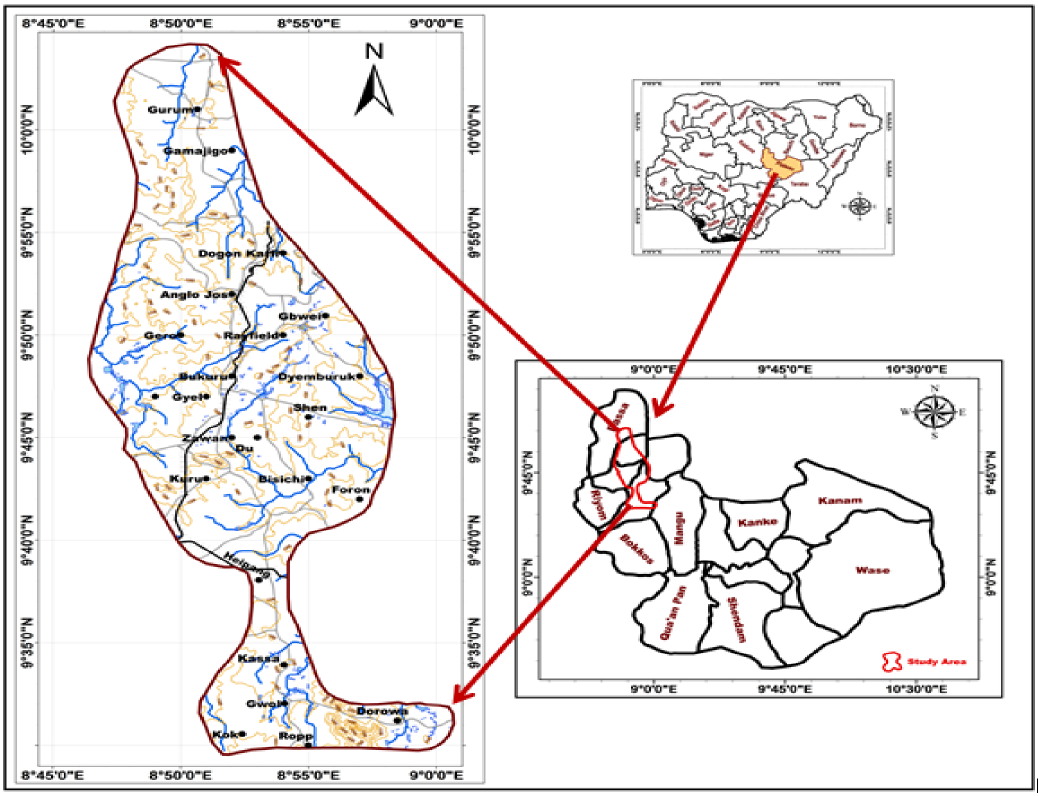

Figure 1: Location Map of the Study Area

The general geology of the Jos Plateau was described and elaborated by Macleod (1971), et al. (2022), Odewumi (2025, 2024, and Abraham et al (2025) as an isolated upland area with an elevation of 1,219 m, covering an area of 8600 km^2; and in some places up to 1500 m above sea level. The Jos Plateau is part of the Precambrian to Mid-Cambrian and Jurassic northern Nigerian crystalline basement, with patches of Cenozoic and Quaternary volcanic rocks.

The Jos-Bukuru complex occupies the central portion of the Jos Plateau and comprises almost all rock types in the province. Igneous activity in this complex is represented by two cycles: Fayalite-bearing granite and porphyry-hosted biotite granite. Five other phases of biotite granite constitute the first igneous cycle. The second igneous cycle, whose rocks crosscut the earlier one, is made up of fayalite, hastingstite, granite porphyry, hastingstite biotite granite, and four phases of biotite. The boundary between them is gradational. In most cases, they are indistinguishable.
Jos Biotite Granite is the most significant individual intrusion recognized in the Younger Granite Province, covering an area of 285 km². Based on similarities in age, structural relations, and petrology, the Jos Biotite Granite appears to be closely related to the early hornblende-biotite granite and granite porphyry. Macroscopic observation reveals that the rock sample is coarse-grained, porphyritic in texture, and generally gray in colour.

Field Sampling of Farm Soil
Field sampling of farm soil was done during the dry season, when irrigation farming is at its peak. Moreover, the ponds are not recharged from external sources, minimizing dilution, and the water is extensively used. Also, this period makes it easier to access these abandoned mine sites, which are mostly difficult to reach during the rainy season.

Farm soil samples were collected from farms near mine dumps and ponds where crops were cultivated using water from the mine ponds. A total of thirty-three (33) farm soil samples were collected, along with four (4) control samples obtained from locations distant from mining activities to serve as background references. The thirty-three composite soil samples were considered adequate to provide representative spatial coverage of cultivated farmlands surrounding abandoned mine ponds and mine dumps across the study area.

To obtain a composite sample, farm soils were collected from the four corners and the centers of the farms and homogenized. This is to ensure that every portion within the farm's vicinity is sampled. Sampling at this site was also conducted using a hand auger. Soil samples were collected at a depth of 10 – 15 cm in line with the Commonwealth Scientific and Industrial Research Organization (CSIRO guidelines of 2021. Soil sampling at a depth of 10–15 cm provides a scientifically reliable, standardized, and practical approach for assessing soil quality, contamination levels, and environmental risk. It ensures that the data obtained are both representative of active soil processes and relevant for ecological and human health evaluations.

Sample Preparation for Soil
Oven Drying of Farm Soils: The farm soil samples were oven-dried at a temperature of 34 °C to free them from moisture before they were disaggregated and sieved at the Laboratory Department of Geology, University of Jos

Disaggregation of Soil Samples
The soil samples were disaggregated with a mortar and pestle before sieving (Plate 24). This is to increase the surface area of the soil samples before analysis. The samples were then packaged in a polyethylene Ziploc bag and transported to the Bureau Veritas Mineral Laboratory in Vancouver, Canada, for analysis.

Laboratory Analysis of Trace Elements
Trace elements in soils were analysed using an Inductively Coupled Plasma Mass Spectrometer at the Bureau Veritas Mineral Laboratory in Vancouver, Canada. Approximately 0.5 g of pulverized soil sample was digested using a multi-acid procedure involving HNO_3–HCl–HF before ICP–MS analysis at the Bureau Veritas Mineral Laboratory in Vancouver, Canada.

ICP–MS analysis was conducted under standard laboratory operating conditions with appropriate instrument calibration, internal standards, procedural blanks, and certified reference materials to ensure analytical precision and accuracy (Table 1)

Table 1: Quality Control/ Quality Assurance Data

	Analyte	Mo	Cu	Pb	Zn	Ag	Ni	Mn	As	Sr	Cd	Sb	Cr	Ba	Ce
	Unit	PPM	PPM	PPM	PPM	PPB	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM
	MDL	0.05	0.1	0.02	0.2	20	0.1	1	0.2	1	0.02	0.02	1	1	0.02
Pulp Duplicates															
FSRID2	Soil Pulp	2.49	14.20	30.36	42.80	<20	34.30	180.00	1.70	39.00	<0.02	0.30	240.00	237.00	107.08
FSRID2	Soil Pulp	2.52	14.40	30.24	44.20	<20	34.40	181.00	2.10	39.00	0.03	0.29	236.00	239.00	105.80
Reference Materials	Soil Pulp														
STD OREAS45H	Soil Pulp	1.50	793.90	12.28	41.50	134.00	462.90	433.00	17.00	29.00	0.03	0.59	704.00	350.00	24.92
STD OREAS501D	Soil Pulp	93.80	2675.80	25.81	87.80	661.00	21.80	378.00	13.80	214.00	0.33	2.21	41.00	1029.00	66.94
STD OREAS45H	Soil Pulp	1.39	771.10	11.71	37.50	91.00	441.00	419.00	15.50	27.00	<0.02	0.54	667.00	324.00	23.86
STD OREAS25A-4A	Soil Pulp	2.32	30.70	23.79	42.10	<20	45.10	485.00	9.40	46.00	0.03	0.54	116.00	150.00	46.27
BLK	Soil Pulp	<0.05	<0.1	0.06	<0.2	<20	<0.1	1.00	<0.2	<1	<0.02	<0.02	<1	<1	<0.02
BLK	Soil Pulp	<0.05	<0.1	0.03	<0.2	<20	<0.1	<1	<0.2	<1	<0.02	<0.02	<1	<1	<0.02

Statistical Analysis

Descriptive statistical analyses, including minimum, maximum, mean, median, standard deviation, and frequency distribution, were performed using Microsoft Excel and SPSS software. The geo-accumulation index (Igeo) and contamination factor (CF) were computed to assess the intensity of contamination relative to background concentrations.

Calculation of the Index of Geo Accumulation (Igeo)

Background concentrations used for Igeo and CF calculations were derived from average crustal abundance values after Taylor and McLennan (1995) and supplemented with control soil concentrations collected outside mining influence zones.

The igeo provides a numerical value indicating the level of contamination relative to background concentrations, given by Muller (1969) as:

$$Igeo = Log_2(Cn/1.5XBn)$$

Where:
C = the measured concentration of the element in the sample
Bn = the geochemical background concentration of the element
1.5 = the correction factor to account for natural variations in the element concentration.

Contamination Factor (CF)

RESULT AND DISCUSSION

Trace Element Concentration in Farm Soils

Table 2 shows the minimum, maximum, mean, median, mode, and standard deviation of trace elements in the study area. The details are presented in Table 2, including the detection limits for each element. The concentrations of these elements have also been compared with the average crust, mean soil, average in granites, diabase (dolerite), and some controls (Figs. 1–11). The following trace elements, manganese, silver, barium, and cerium, have the highest concentration in the farm soil, with values ranging from 152.00 ppm to 561.00 ppm, 114.00 ppm to 119.00 ppm, and 87.00 ppm to 440.00 ppm, respectively. While antimony, molybdenum, and arsenic have concentrations of 0.17 ppm, 0.93 ppm, and 1.20 ppm, respectively, cadmium has the lowest at 0.02 ppm.

Lead (Pb)

Although individual farm soils show varying Pb concentrations, 100% of the lead concentration across all farm soils is above the crustal abundance, the mean soil, and the average in dolerite. About 8% of the sample's concentration is above the average concentration in granite. 37% of the samples' concentrations exceeded the control levels (Fig. 1). Sample 16 had the highest concentration.

Copper (Cu)

Copper in the samples is 100% below the crustal abundance and the average dolerite concentration. Only 5% of the samples exceeded the mean soil concentration, while about 37% exceeded the control levels (Figure 2). The highest concentration of copper is obtained in sample 23

Arsenic (As)

Arsenic (Fig 3) has about 51% of its concentration in the samples above the crustal abundance and the average concentration in dolerite, while 100% of the samples' concentration is above the average concentration in granite and the control, and only 3% of the samples are above the concentration of the mean soil. Control soil sample 3, however, is above all concentration across all farm soils.

Cadmium (Cd)

Cadmium concentration in the farm soil of the study area showed that only 5% of the samples exceeded crustal abundance. 100% of the samples are below the mean soil. 29% of the sample's concentration is above the average value in granite, and only 5% is above the average value in dolerite. 18% of the concentrations are above control (Fig 5).

Chromium (Cr)

23% of the Cr concentration (Fig 4) in the sample is above the crustal abundance, mean soil, average in granite, and the control 1, while only 30% are above the average in dolerite. Controls 3 and 4 are all above the Cr concentrations in the samples, while 13% of the Cr concentrations are above control 2.

Nickel (Ni)

(100). % of the samples are below the crustal abundance and the average Nickel value in dolerite, while 67% are above the mean soil value. While 100% of the sample exceeds the average value in granite, 29% exceed the control value (Fig 6).

Molybdenum (Mo)

56% of the samples are above the crustal abundance, while only 2% of the samples' concentration is below the mean soil (Fig 7). 100% of the samples are below the average Mo concentration in granite, 100% are above the dolerite concentration, and 57% are above control.

Zinc (Zn)

27% of the Zn concentrations in the samples exceed the crustal abundance, while 35% exceeds the mean soil concentration. While 48% of the samples have Zinc concentrations above the average for granite, only 16% exceed the average for dolerite. While 100% of the samples are above the first control, only 10% and 18% are above the second and third controls, respectively (Fig 8).

Manganese (Mn)

(100). % of the Manganese sample's concentration is below the crustal abundance, mean soil, and average concentration in dolerite (Fig 9). 46% of the Mn concentration is above the average in granite and control 1. At the same time, only 6% are above control 2. Controls 3 and 4 are below 10% of the Mn concentration in the Mn samples.

Strontium (Sr)

The Sr concentration in the samples is 100% below the Crustal abundance, the mean soil, the average in granite, and the average in dolerite. Only 17% of the sample concentrations are above the 1st and 4th controls, while 50% are above the 2nd and 3rd controls (Fig 10).

Table 3: Composition of some Trace Elements in Farm Soils in the Study Area

	Analyte	Mo	Cu	Pb	Zn	Ag	Ni	Mn	As	Sr	Cd	Sb	Cr	Ba	Ce
	Unit	PPM	PPM	PPM	PPM	PPB	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM
	MDL	0.05	0.1	0.02	0.2	20	0.1	1	0.2	1	0.02	0.02	1	1	0.02
FSRID1	Soil Pulp	1.72	15.10	30.08	29.80	<20	30.50	199.00	1.00	70.00	0.04	0.13	83.00	414.00	103.53
FSRID2	Soil Pulp	4.08	61.10	47.21	67.40	<20	66.40	395.00	5.60	26.00	0.05	0.51	184.00	83.00	111.31
FSRID3	Soil Pulp	3.95	28.60	47.60	60.70	<20	44.50	233.00	7.90	31.00	0.05	0.51	60.00	105.00	145.77
FSRID4	Soil Pulp	16.02	14.30	44.30	69.00	<20	16.50	159.00	3.80	16.00	0.04	0.33	38.00	47.00	174.73
FSRID5	Soil Pulp	4.09	24.30	63.67	87.50	*	33.40	195.00	4.70	34.00	0.06	0.46	58.00	148.00	241.20
FSRID6	Soil Pulp	5.37	28.10	54.60	83.60	<20	35.20	147.00	4.10	24.00	0.06	0.38	65.00	94.00	235.44
FSRID7	Soil Pulp	4.01	29.80	54.87	44.80	<20	51.70	182.00	8.10	86.00	0.04	0.47	157.00	128.00	211.67
FSRID8	Soil Pulp	3.92	28.40	29.70	41.50	<20	38.20	191.00	7.00	26.00	0.04	0.45	215.00	58.00	96.91
FSRID9	Soil Pulp	3.84	44.40	54.46	63.00	52.00	40.30	305.00	5.20	67.00	0.04	0.26	83.00	156.00	137.64
FSRID10	Soil Pulp	6.12	20.90	59.62	40.90	*	22.60	158.00	6.70	21.00	0.04	0.44	195.00	53.00	170.10
FSRID11	Soil Pulp	4.14	31.80	44.48	55.20	29.00	51.90	303.00	8.70	32.00	0.03	0.52	70.00	123.00	197.20
FSRID12	Soil Pulp	3.20	25.60	38.71	68.10	<20	38.50	322.00	5.60	33.00	0.04	0.39	59.00	136.00	259.58
FSRID13	Soil Pulp	11.84	51.00	74.24	70.20	<20	41.30	415.00	6.90	88.00	0.07	0.44	119.00	195.00	340.37
FSRID14	Soil Pulp	4.34	39.70	39.69	46.60	38.00	46.90	211.00	7.10	29.00	0.03	0.54	180.00	97.00	97.55
FSRID15	Soil Pulp	2.98	26.30	39.95	42.50	<20	36.20	196.00	4.80	42.00	0.04	0.48	172.00	77.00	92.99
FSRID16	Soil Pulp	3.21	27.50	50.65	57.30	<20	29.00	244.00	5.60	48.00	0.04	0.56	240.00	86.00	148.09
FSRID17	Soil Pulp	7.04	43.70	35.45	58.40	143.00	58.80	223.00	10.00	69.00	0.04	0.77	428.00	86.00	118.68
FSRID18	Soil Pulp	3.49	22.20	56.64	133.00	<20	37.70	199.00	6.70	34.00	0.07	0.42	77.00	179.00	157.81
FSRID19	Soil Pulp	3.08	29.20	34.74	42.00	22.00	50.40	326.00	8.50	44.00	0.03	0.49	193.00	253.00	113.78
FSRID20	Soil Pulp	3.19	17.30	42.49	87.40	*	26.20	245.00	4.10	51.00	0.06	0.27	48.00	351.00	171.95
FSRID21	Soil Pulp	2.09	54.80	53.59	109.40	*	30.50	722.00	3.00	65.00	0.12	0.24	54.00	496.00	224.56
FSRID22	Soil Pulp	2.88	21.50	41.00	127.10	*	39.90	298.00	3.80	65.00	0.10	0.32	108.00	357.00	156.49
FSRID23	Soil Pulp	2.62	23.30	31.99	88.20	*	53.60	341.00	4.10	56.00	0.04	0.26	64.00	254.00	160.29
FSRID24	Soil Pulp	3.52	21.00	38.78	121.40	<20	32.30	259.00	4.70	61.00	0.06	0.27	57.00	405.00	145.46
FSRID25	Soil Pulp	4.66	34.40	38.96	66.70	65.00	49.00	279.00	8.10	28.00	0.04	0.53	86.00	104.00	138.24

FSRID27	Soil Pulp	6.55	49.20	43.70	66.50	30.00	59.60	469.00	8.00	52.00	0.04	0.39	103.00	220.00	207.51
FSRID28	Soil Pulp	5.24	34.90	34.36	43.10	<20	48.10	267.00	6.80	40.00	0.04	0.45	96.00	228.00	114.16
FSRID31	Soil Pulp	3.78	39.00	33.16	41.30	<20	55.20	265.00	7.40	31.00	0.03	0.42	93.00	155.00	123.78
FSRID32	Soil Pulp	3.80	29.80	37.28	71.80	<20	41.10	162.00	5.90	45.00	0.04	0.74	236.00	74.00	106.89
FSRID33	Soil Pulp	3.34	33.90	36.08	77.90	33.00	33.40	244.00	6.60	53.00	0.03	0.38	59.00	309.00	141.56

Table 2: Summary of Trace Element Concentration in Farm Soils of the Study Area (in ppm)

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

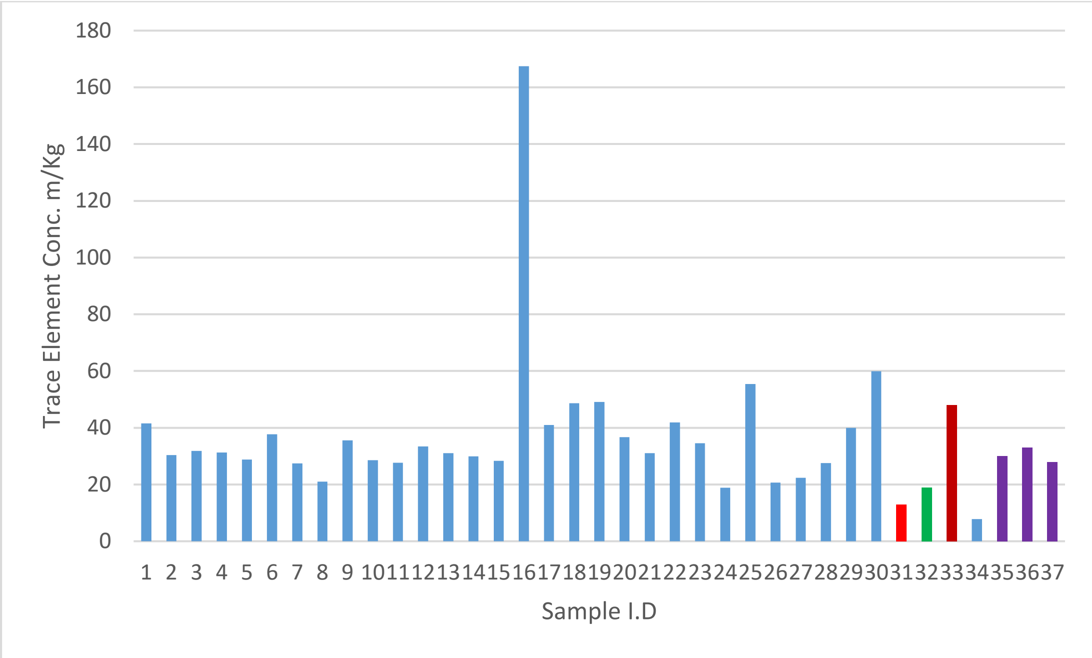

Figure. 1: Concentration of lead in the farm soil of the study Area.

Conc. CA MS AVG AVD CTR 1,2 and 3

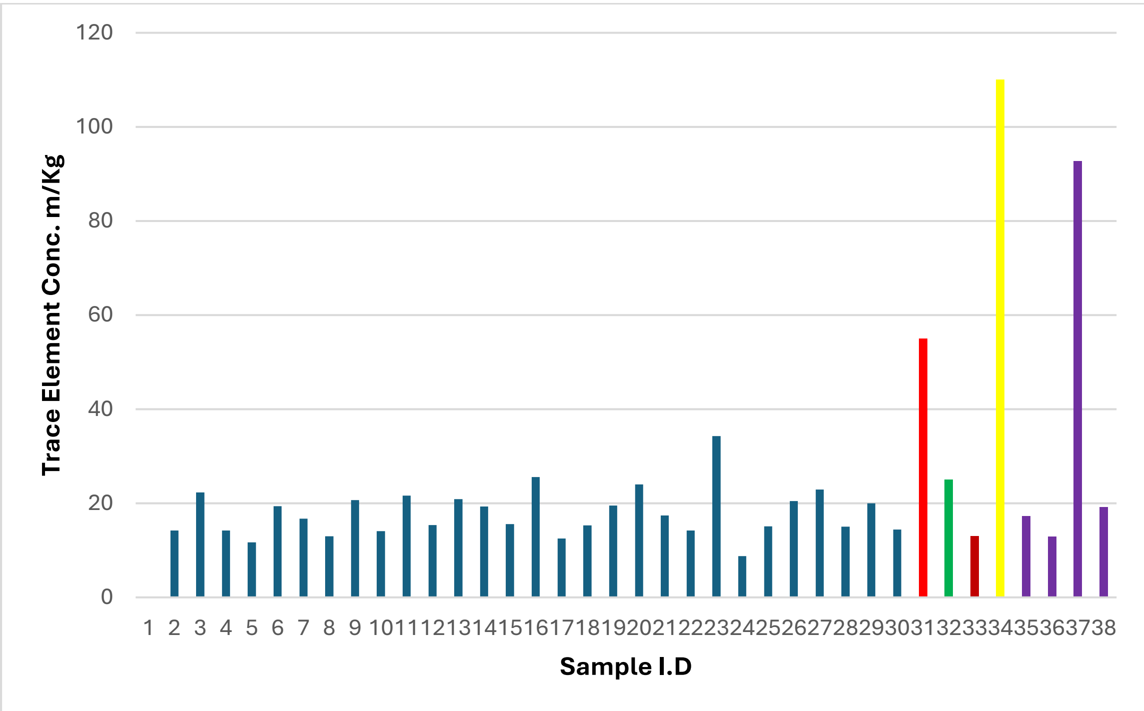

Figure 2: Concentration of Copper in Farm Soil of the Study Area.

Conc. CA MS AVG AVD CTR 1,2,3, and 4

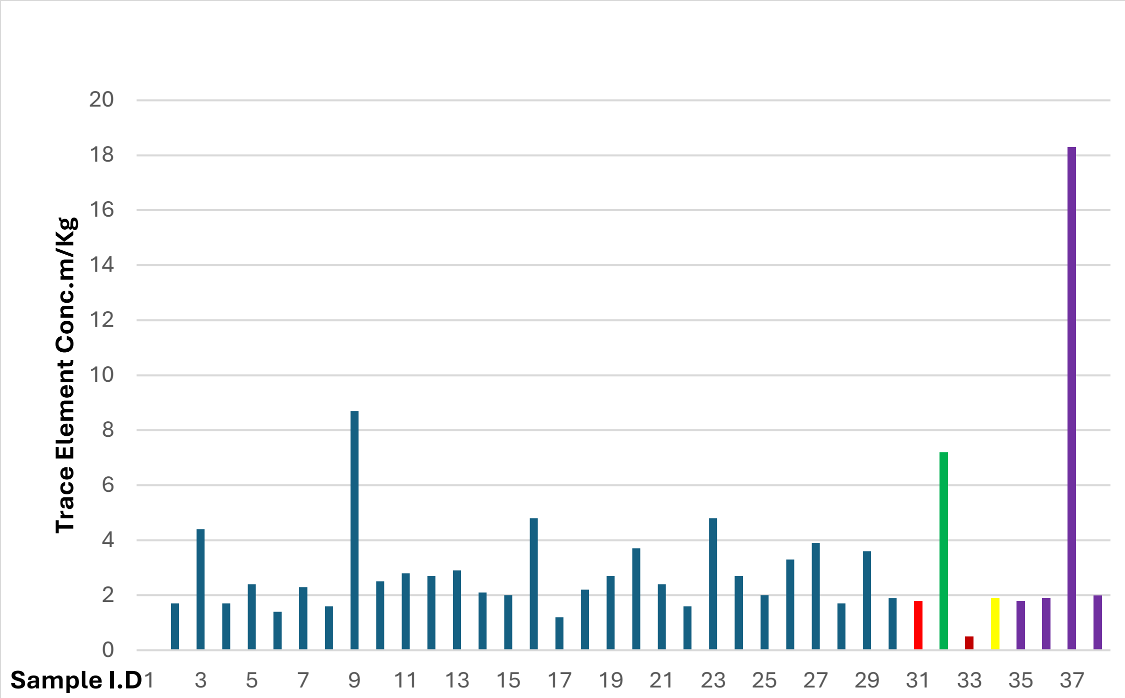

Figure. 3: Concentration of Arsenic in Farm Soil of the Study Area.

Conc. CA MS AVG AVD CTR 1,2,3, and 4

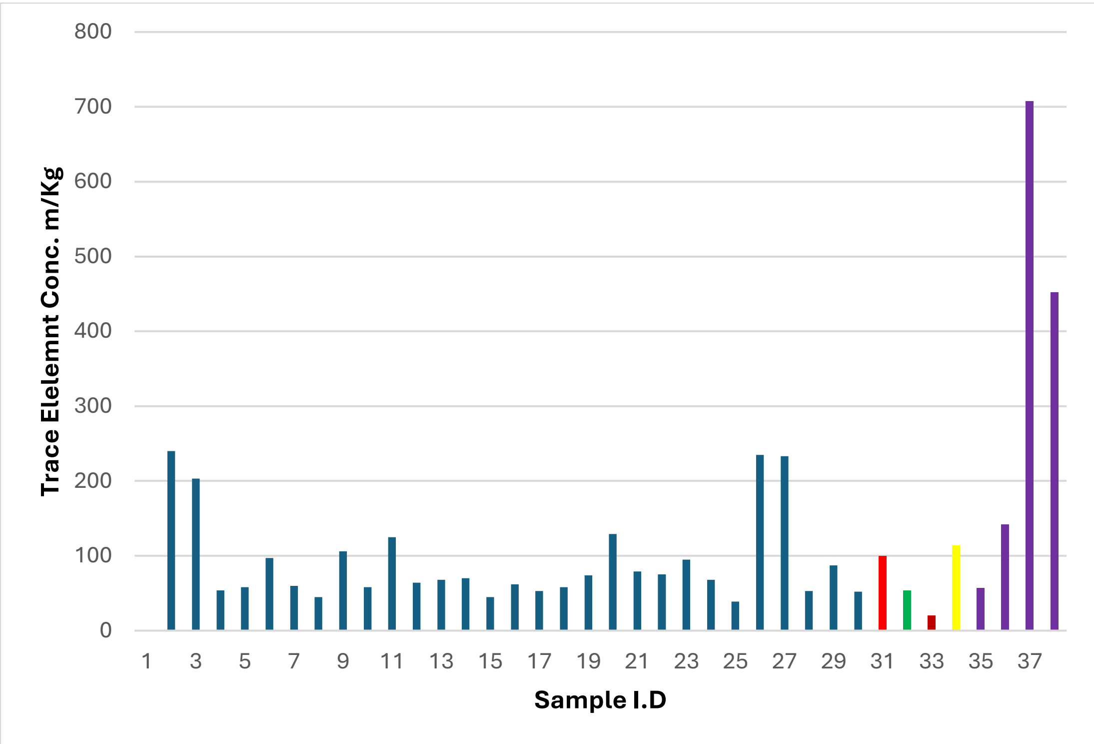

Figure 4: Concentration of Chromium in Farm Soil of the Study Area.

Conc. CA MS AVG AVD CTR 1,2,3, and 4

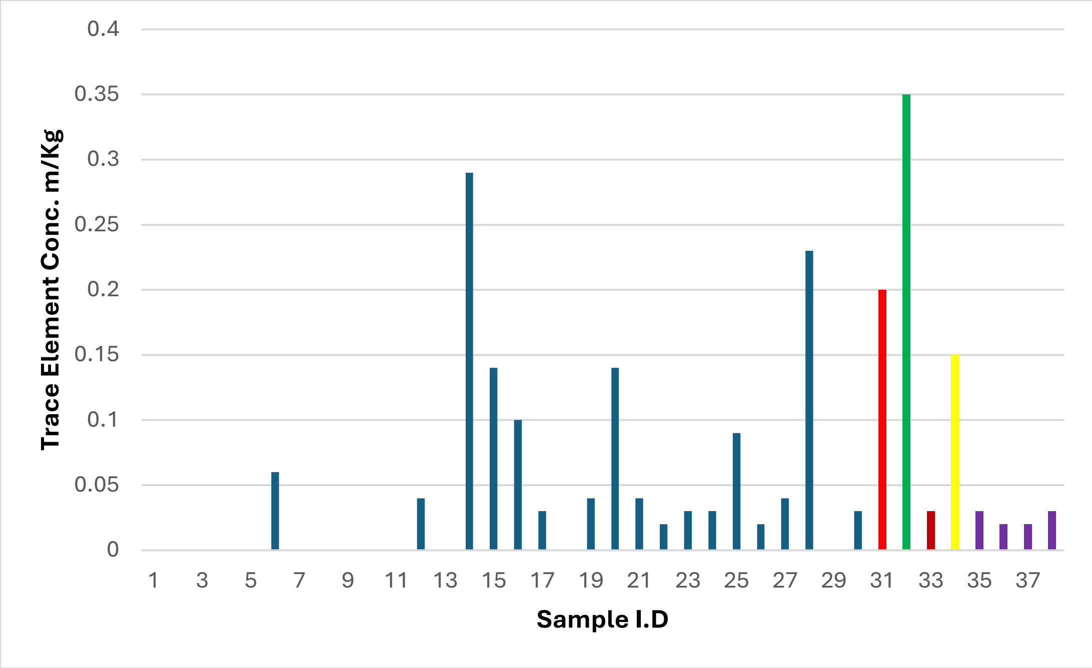

Figure 5: Concentration of Cadmium in Farm Soil of the Study Area.

Conc. CA MS AVG AVD CTR 1,2,3, and 4

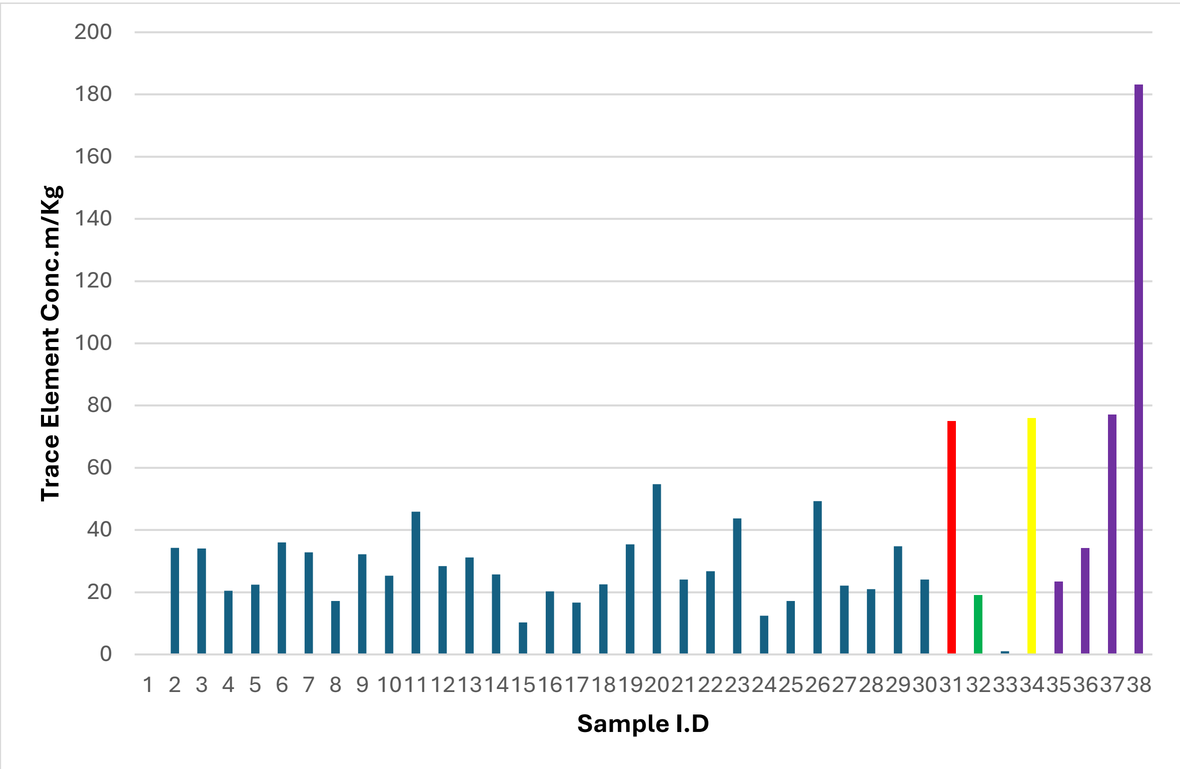

Figure 6: Concentration of Nickel in Farm Soil of the Study Area.

Conc. CA MS AVG AVD CTR 1,2,3, and 4

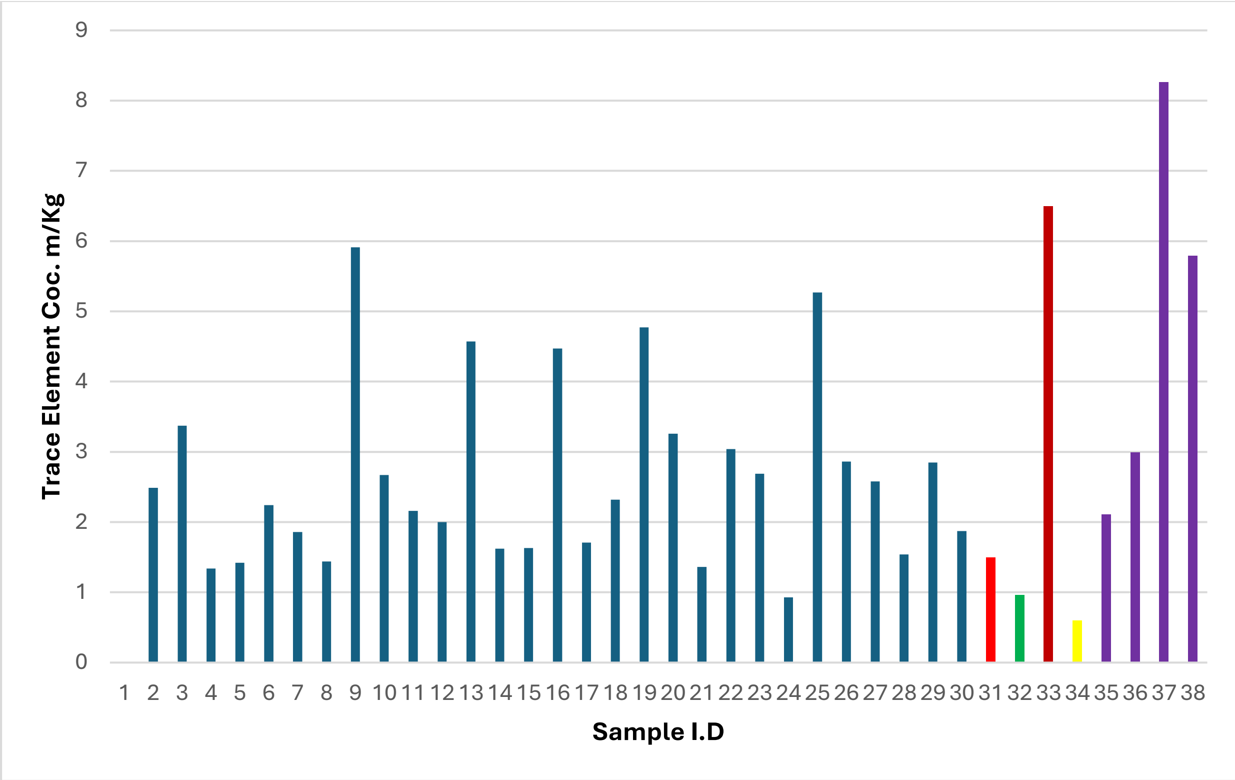

Figure 7: Concentration of Molybdenum in Farm Soil of the Study Area.

Conc. CA MS AVG AVD CTR 1,2,3, and 4

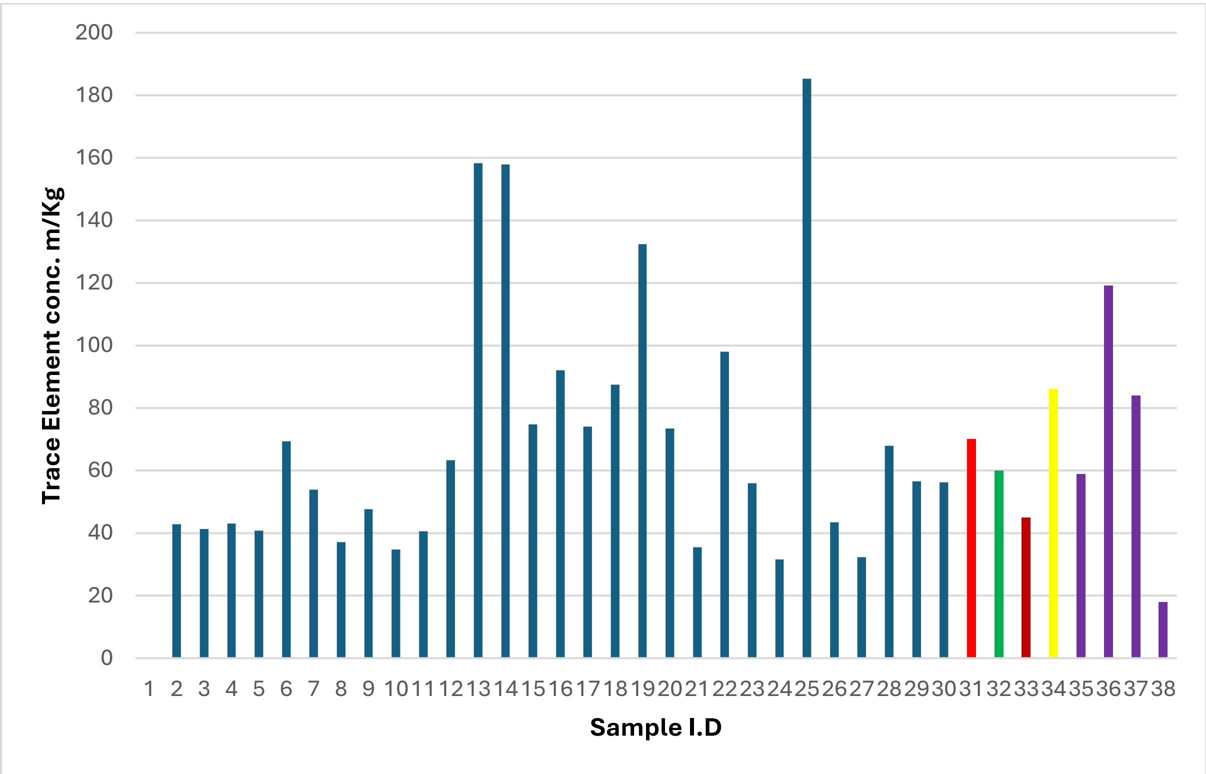

Figure 8: Concentration of Zinc in Farm Soil of the Study Area.

Conc. CA MS AVG AVD CTR 1,2,3, and 4

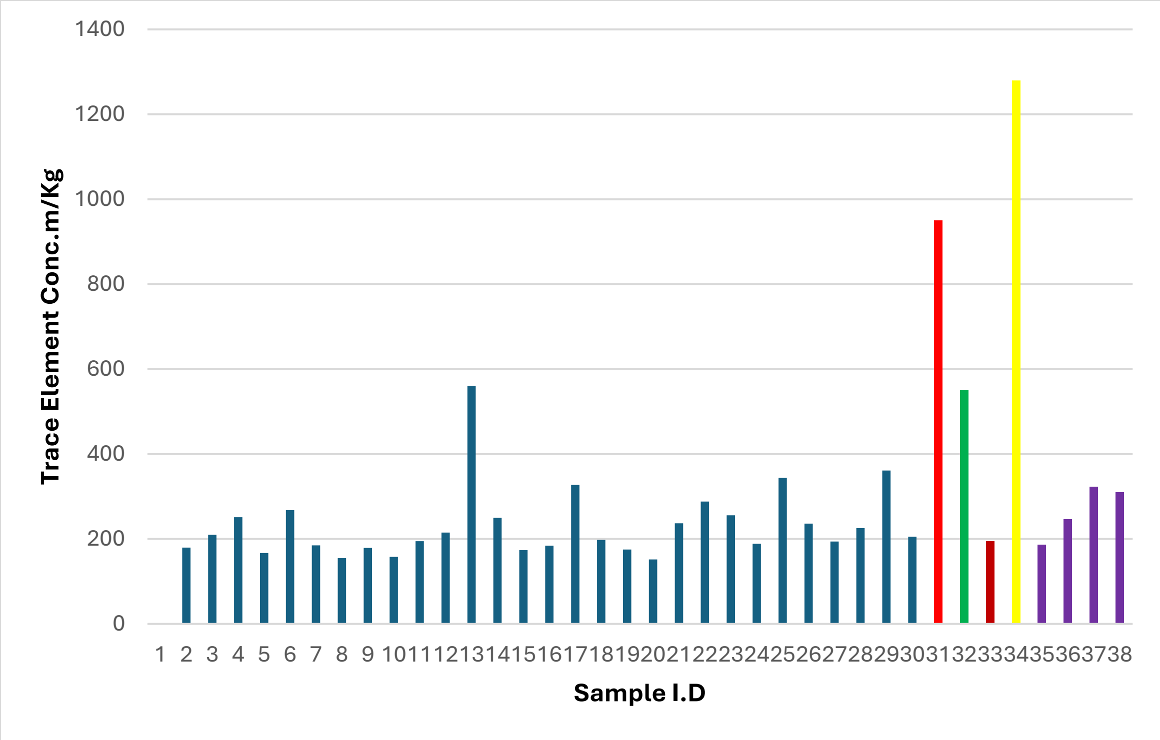

Figure 9: Concentration of Manganese in Farm Soil of the Study Area.

Conc. CA MS AVG AVD CTR 1,2,3, and 4

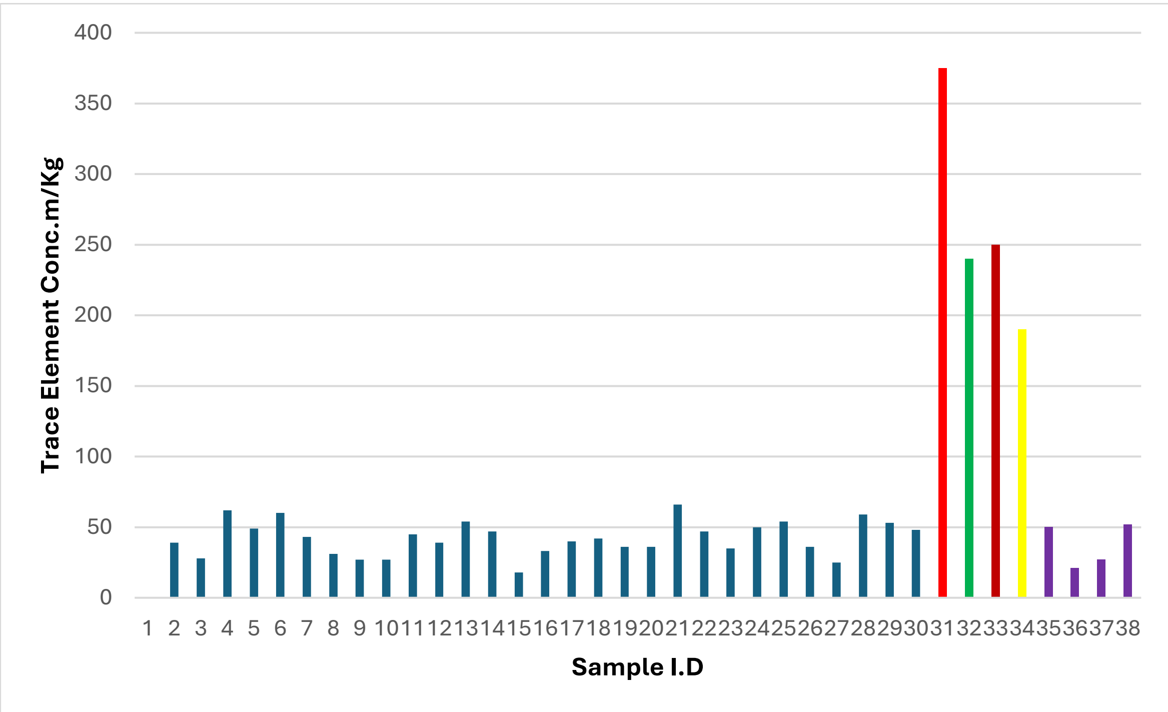

Figure. 10: Concentration of Strontium in Farm Soil of the Study Area.

Conc. CA MS AVG AVD CTR 1,2,3, and 4

Cerium (Ce)

100% of the samples are above the mean crustal abundance in soil and the average concentration in dolerite. Only 8% of the samples are above the average concentration in granite, and 100% are above controls 3 and 4, with 38% of the samples having concentrations above the first and second controls (Fig 11).

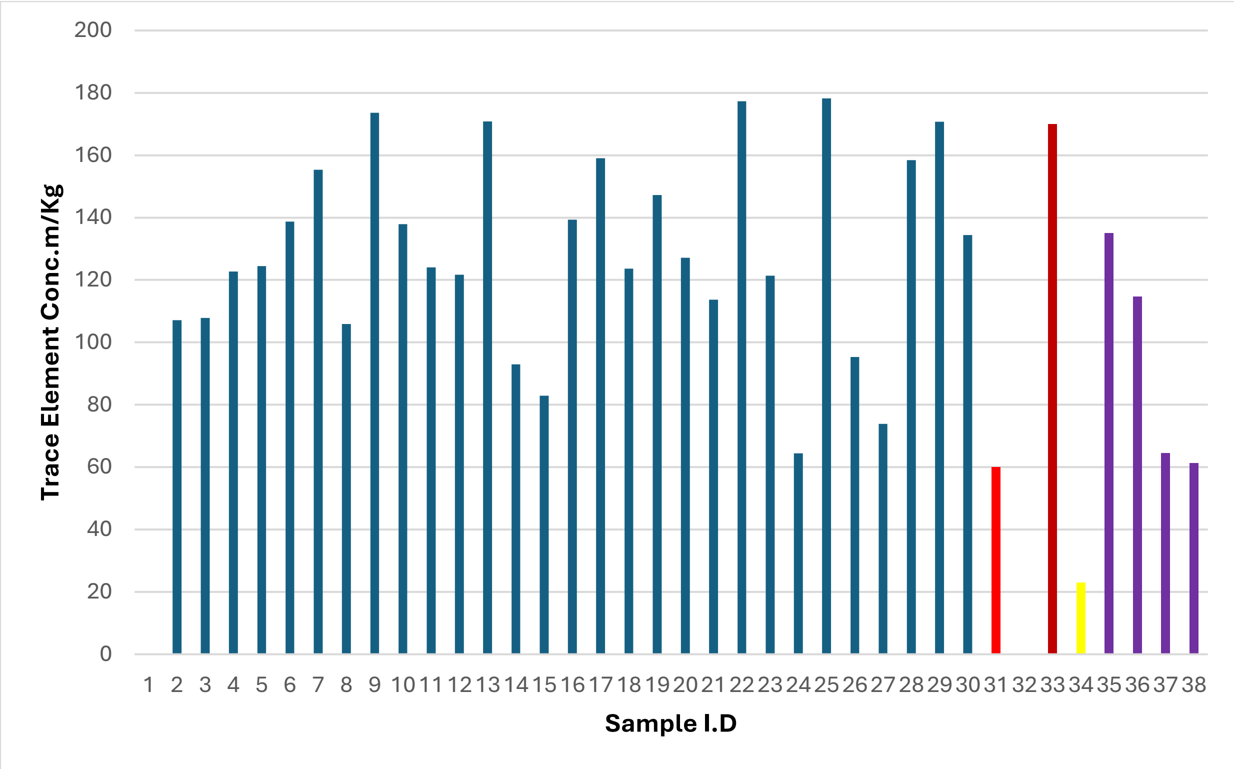

Figure. 11: Concentration of Cerium in Farm Soil of the Study Area.

Conc. CA MS AVG AVD CTR 1,2,3, and 4

Silver (Ag)

Silver concentrations in the farm soils were detected only in Samples 2 and 22, with values ranging from approximately 115 to 120 mg/kg, while all other samples recorded negligible or non-detectable levels; these elevated concentrations exceed natural background levels in the crust, soils, and common host rocks by over 1000 times (Fig 12), indicating localized contamination likely from nearby agrochemical input, or irrigation with polluted water, as further emphasized by the much lower baseline levels (~0.1 mg/kg) observed in control samples.

Index of geo–accumulation

The Index of Geo-accumulation (Igeo) results (Table 4) for the farm soils indicate varying degrees of trace-element enrichment and contamination across the study area. Computed Igeo values reveal that most of the analyzed elements fall within the "unpolluted" to "unpolluted to moderately polluted" categories, suggesting that the soil is generally not heavily contaminated. However, some elements exhibit elevated contamination levels that may be associated with anthropogenic activities, particularly mining-related processes and agricultural practices.

Among the analyzed elements, Cu, Cr, Cd, Ni, Zn, Mn, and Sr recorded negative Igeo values ranging from −0.59 to −3.72, which classify them as unpolluted according to Müller's classification scheme. These negative values indicate that the concentrations of these elements are close to or below background levels and therefore do not presently pose significant environmental contamination concerns. The low accumulation of these elements may reflect either minimal anthropogenic enrichment or strong lithological control in the area's soils.

Lead (Pb), arsenic (As), molybdenum (Mo), cerium (Ce), antimony (Sb), and beryllium (Be) recorded Igeo values between 0 and 1, placing them in the "unpolluted to moderately polluted" category. Although the contamination levels are low, the enrichment of these elements sugg page 42 degree of anthropogenic influence. The slightly elevated Pb and As contents may be linked to abandoned mining activities, weathering of mineralized rocks, atmospheric deposition, agrochemical application, and irrigation using mine-affected water sources. Similarly, the enrichment of Mo, Sb, and Be may reflect contributions from mineralized parent materials and historical mining operations common in the area. The presence of Ce may also indicate geogenic contributions from rare-earth-element-bearing minerals in the granitic and pegmatitic terrains of the study area.

Table 4: Index of Geo-accumulation for Farm Soils of the Study Area

Elements	**Igeo farm soils**	**Interpretation**
Cu	-2.21	Unpolluted
Pb	0.99	Unpolluted to moderately polluted
As	0.04	Unpolluted to moderately polluted
Cr	-0.71	Unpolluted
Cd	-1.94	Unpolluted
Ni	-1.10	Unpolluted
Mo	0.21	Unpolluted to moderately polluted
Zn	-0.59	Unpolluted
Mn	-2.63	Unpolluted
Sr	-3.72	Unpolluted
Ce	0.52	Unpolluted to moderately polluted
Ag	10.12	Extremely polluted
Ba	3.48	Strongly polluted
Sb	0.55	Unpolluted to moderately polluted
Be	0.43	Unpolluted to moderately polluted

Contamination Factor for Farm Soils of the Study Area.

Table 5 shows that Cu, Cr, Cd, Ni, Zn, Mn, and Sr exhibit low contamination; Pb, As, Mo, Sb, and Be exhibit moderate contamination; and Ag and Ba exhibit very high contamination. The results show that 46% of the trace elements in the farm soil have low contamination factors, 40% have moderate contamination factors, and 14% have high contamination factors. Figures 12a–12q show the distribution of contamination factors for the elements.

Table 5: Contamination Factor for Farm Soils of the Study Area.

S/N	Element	CF-Farm	Interpretation
1	Cu	0.32	Low
2	Pb	2.97	Moderate
3	As	1.54	Moderate
4	Cr	0.91	Low
5	Cd	0.39	Low
6	Ni	0.38	Low
7	Mo	1.74	Moderate
8	Zn	0.99	Low
9	Mn	0.24	Low
10	Sr	0.11	Low
11	Ce	2.15	Moderate
12	Ag	1664.29	Very high
13	Ba	16.75	Very high
14	Sb	2.2	Moderate
15	Ba	1.11	Moderate

Discussion

Distribution Pattern of Trace Elements

The distribution pattern of potentially harmful elements (PHEs) in farm soils in the Jos–Barkin Ladi mining environment exhibits considerable spatial variability, reflecting both lithological controls and anthropogenic contamination associated with historical mining activities. Elevated concentrations of Pb, Ba, Ce, Zn, and Mn observed in several samples indicate enrichment processes linked to abandoned mine tailings, mine pond irrigation, and weathering of mineralized rocks. Similar distribution patterns have been reported in abandoned mining environments worldwide, where elevated concentrations of Pb, Zn, As, and Ba are commonly associated with the dispersion of mine waste and tailings weathering (Alloway, 2013; Li et al., 2014; Wei, H., 2018; Yap et al., 2020). Studies on abandoned mine sites in Jos, Nigeria, have also documented elevated Pb concentrations in agricultural soils associated with historical mining activities (Nganje et al., 2010; Olarinoye et al., 2021). The heterogeneous distribution of trace elements observed in this study is therefore consistent with contamination patterns typical of abandoned mining terrains globally.

Geogenic and Anthropogenic Sources

The geochemical behavior of the analyzed elements suggests both geogenic and anthropogenic sources. Elements such as Cr and Ni appear to be largely controlled by the parent lithology of the Younger Granite Province and associated basement rocks. Similar findings were reported by Santos et al. (2017), who attributed the enrichment of Cr and Ni in tropical soils to the weathering of mafic and granitic rocks. Odewumi (2024) similarly reported lithological control of Cr and Ni in stream sediments on the Jos Plateau. Manganese enrichment in the present study also appears to be largely geogenic, influenced by tropical weathering and redox conditions within the soils. Cerium enrichment reflects the rare-earth affinity of granitic and pegmatitic terrains, consistent with previous studies on the Jos Plateau geology (MacLeod et al., 1971; Odewumi, 2025).

In contrast, elevated concentrations of Pb, As, Zn, Ag, and Ba strongly indicate anthropogenic contributions associated with abandoned tin–columbite mining activities. Similar enrichment of Pb and As in mining-impacted agricultural soils has been reported in Nigeria, Cameroon, and South Africa (Nganje et al., 2010; Asaah et al., 2015; Adomako et al.,2018; Baloyi et al., 2024). Lead enrichment, in particular, is commonly linked to sulfide mineral weathering, tailings dispersion, and atmospheric deposition from abandoned mine sites (Olarinoye et al., 2021; Ayeni, J. K., 2025). The extremely high Ag enrichment observed in some samples suggests localized contamination hotspots, likely associated with mine wastes or contaminated irrigation water. Asaah et al. (2015) similarly reported that elevated heavy metal concentrations in agricultural soils may result from a combination of mining activities, fertilizer application, and irrigation with contaminated water sources. The moderate enrichment of Cu, Zn, Sb, and Mo observed in the present study, therefore, reflects mixed contributions from both geological and anthropogenic processes.

Comparison with International Standards

Comparison with international background values and soil quality standards further highlights the contamination status of the study area. Although there is no universally accepted WHO/FAO permissible limit for heavy metals in soils, comparison with average crustal abundances and mean soil values indicates significant enrichment in Pb, Ba, Ag, and As. Similar approaches have been used by Kumar et al. (2019) and Yap et al. (2020) in evaluating ecological risks in agricultural soils around abandoned mining areas. The elevated Pb and As concentrations observed in the present study are comparable to findings reported in contaminated agricultural soils near abandoned mining environments in Malaysia and Nigeria (Nganje et al., 2010; Yap et al., 2020). However, Cr, Ni, and Cd concentrations generally remain within acceptable ranges, suggesting relatively low ecological risk from these elements at present. Nevertheless, the persistence and cumulative nature of heavy metals in soils suggest that their accumulation may eventually increase ecological and agricultural risks.

Agricultural Implications

The agricultural implications of these findings are significant because elevated concentrations of Pb, As, Zn, and Ba may adversely affect soil quality, microbial activity, and crop productivity. Chibuike and Obiora (2014) reported that heavy metal contamination may impair nutrient cycling, reduce microbial populations, and inhibit plant growth. Similar observations have been documented in contaminated agricultural soils worldwide, where prolonged accumulation of trace elements reduces long-term soil fertility and agricultural sustainability. Continuous irrigation with mine pond water in the study area may further enhance metal mobility and bioavailability in cultivated soils. Olarinoye et al. (2021) reported that irrigation with contaminated mine water significantly increases trace-element accumulation in agricultural soils surrounding abandoned mine ponds in Jos. Elevated concentrations of toxic metals in soils may also increase their uptake by crops, thereby facilitating transfer into the food chain. Ngwese et al. (2025) similarly observed significant accumulation of toxic elements in crops cultivated on mining-impacted soils in Cameroon. Therefore, the dependence of local communities on subsistence agriculture increases the importance of monitoring and managing contaminated agricultural soils within the study area.

Human Health Implications

From a human health perspective, the elevated concentrations of toxic trace elements in farm soils pose risks through dietary exposure, direct soil contact, and inhalation of contaminated dust. Lead is particularly important because it is a cumulative toxicant capable of causing neurological, hematological, cardiovascular, and developmental disorders, especially in children (WHO, 2021). Similar health concerns associated with Pb contamination around abandoned mine sites in Jos were reported by Nganje et al. (2010). Arsenic exposure is also associated with carcinogenic and systemic health effects following prolonged exposure (WHO, 2018). Although Cd concentrations in the present study are relatively low, cadmium remains environmentally significant due to its nephrotoxic and bioaccumulative properties (WHO, 2020). The localized extreme enrichment of Ag and elevated Ba concentrations further indicate contamination hotspots that may constitute additional toxicological concerns for nearby populations. Tchounwou et al. (2012) similarly emphasized that prolonged exposure to toxic metals through contaminated soils and food chains may result in severe environmental and public health consequences. Overall, the findings of this study demonstrate that abandoned mining activities continue to affect the geochemical quality of agricultural soils in the Jos–Barkin Ladi area, necessitating ongoing environmental monitoring, remediation, and improved agricultural management practices to safeguard both environmental quality and public health.

SUMMARY AND CONCLUSION

The study assessed potentially harmful elements in farm soils surrounding abandoned tin–columbite mine sites within the Jos–Barkin Ladi area of north-central Nigeria. The results indicate that trace element concentrations are influenced by both lithological characteristics of the Younger Granite terrain and anthropogenic inputs associated with historical mining activities.

Most elements fall within the unpolluted to moderately polluted categories based on the geo-accumulation assessment, although Ba and Ag show significant enrichment. Lead concentrations exceeded background levels in most samples, suggesting persistent mining-related contamination. Chromium and nickel were largely controlled by geogenic processes, while Pb, Ba, As, and Ag reflected anthropogenic influence.

Although the contamination levels are not uniformly severe, the enrichment of selected toxic elements suggests potential long-term implications for soil quality and agricultural sustainability. Additional studies involving bioavailability assessment, crop uptake analysis, and human health risk evaluation are recommended to better constrain environmental and public health implications in the study area.

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