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ORIGINAL RESEARCH ARTICLE

Quantification of Pollution Index of Selected Heavy Metals in Agricultural Soils in Kafin Hausa Area, Northwest Nigeria

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ABSTRACT

In this study, the level of heavy metals contamination in agricultural soils in Kafin Hausa, Nigeria, was investigated and characterised using the Instrumental Neutron Activation Analysis technique via the Nigeria Research Reactor-1. Fifteen soil samples were collected from five different sampling sites and analysed for eight heavy metals: aluminium (Al), arsenic (As), barium (Ba), iron (Fe), holmium (Ho), potassium (K), magnesium (Mg), and rubidium (Rb). Heavy metal pollution indices were estimated using the geo-accumulation index (I_{geo}), enrichment factor (EF), contamination factor (CF), and pollution load index (PLI). The results showed that the mean I_{geo} indexes of Al (-3.09), As (-4.88), Ba (-0.89), Fe (-3.53), K (-2.20), and Mg (-4.95) were lower than zero, indicating that the soil of the studied region was uncontaminated by these metals. The mean EF of Ho was significantly higher than other metals, indicating that the soil is enriched with this metal. As (0.40) and Mg (0.36) had the lowest EF values. Similarly, the mean CF of all metals was lower than 1, suggesting minimal or low contamination. In contrast, Ho (1.60) exhibits the highest CF value, signifying moderate contamination. The PLI values for all metals were between 0.16 and 0.51, indicating that the studied area is unpolluted. There are strong correlations between all the elements, with p-values at 0.01 level, particularly for K – Rb, Ba – K, and Ba – Rb, with values ranging from 0.94 to 0.94. Hence, the results of this study suggest that the agricultural soils in Kafin Hausa are uncontaminated by heavy metals.

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INTRODUCTION

Heavy metals are naturally occurring elements found in the Earth's crust (Tchounwou et al., 2012). In agricultural soils, heavy metals are influenced by human activities like mining, industrial processes, and agrochemicals (Mensah et al., 2021; Yaradua et al., 2020). These heavy metals in the soil can be absorbed by plants and enter the food chain, resulting in health risks for humans and animals. Sherameti and Varma (2015) highlighted that consuming food contaminated with heavy metals may cause abnormal metabolic reactions in humans. Besides that, heavy metal exposure in soils can undermine crop growth and reduce crop productivity, as reported by several studies (Han & Gu, 2023; Jiang et al., 2021; Usman et al., 2022). To reduce the exposure risk and understand the pollution and potential risks associated with metal contamination, it is essential to quantify pollution indices for heavy metals in agricultural soils (Jiang et al., 2021). Various analytical techniques, including atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), energy-dispersive X-ray fluorescence

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(EDXRF) spectroscopy, and instrumental neutron activation analysis (INAA) have been employed to quantify heavy metal concentrations in diverse sources, such as air, water, soil, and food (Chandrasekaran et al., 2015; Han & Gu, 2023; Idris et al., 2015; Mensah et al., 2021). Among these methods, INAA stands out due to its high calibration detection and measurement accuracy, attributed to using a neutron source (Agbo et al., 2016; Musa et al., 2012). Pollution indices, such as the geo-accumulation index (Igeo) and pollution load index (PLI), have proven effective in assessing the extent of contamination (Han and Gu, 2023). Moreover, Igeo and PLI provide a classification system based on the numerical value (Wang et al., 2023). Notably, these empirical indices offer a straightforward, comparable method for determining the extent of contamination caused by heavy metals. Consequently, monitoring heavy metal pollution levels in the soil is essential for sustainable agricultural practices.

In the specific context of the Kafin Hausa area in northwest Nigeria, this study aims to quantify the concentrations and pollution indices of targeted heavy metals (aluminium, arsenic, barium, iron, holmium, potassium, magnesium, and rubidium) in agricultural soils through sampling and INAA laboratory analysis. The findings of this study will contribute to the existing knowledge of heavy metal pollution in agricultural soils. It will also provide valuable information for policymakers, farmers, and environmentalists to make informed decisions regarding land use practices, crop selection, and potential remediation strategies. Furthermore, this will mitigate the adverse effects of heavy metal contamination, promote sustainable agriculture, and safeguard the health and well-being of the local population in the study area.

THEORY OF POLLUTION INDICES

Pollution Index

The pollution index is a numerical metric used to measure the pollution level in a place. It is based on factors such as air and water quality and the concentration of harmful chemicals and gases (Huang et al., 2019; Mensah et al., 2021). Governments and environmental agencies generally employ it to monitor pollution levels, evaluate the occurrence of major and trace elements in the environment, and adopt suitable mitigation measures (EPA, 2009; WHO, 2011). Among the quantified indicators for pollution indices reported by several investigations are the geo-accumulation index (Igeo), the contamination factor (CF) and degree of contamination (C_d), the pollution load index (PLI), and the enrichment factor (EF) (Bhakta et al., 2022; Paternie et al., 2023; Yaradua et al., 2020). These indicators show the permitted amounts of pollution-related characteristics.

Geo-accumulation index and Enrichment factor

The geo-accumulation index (I_{geo}) measures the degree of sediment contamination by heavy metals (Bhakta et al., 2022). In 1986, Georg Müller proposed a mathematical formula to calculate the Igeo (Yaradua et al., 2020). It is calculated by comparing the concentration of a heavy metal in sediment to the background concentration of that metal in the Earth's crust. Mathematically, the I_{geo} can be expressed as follows:

$$I_{geo} = \text{Log}_2\left(\frac{C_n}{1.5\,C_B}\right) \qquad (1)$$

Where C_n is the measured metal concentration in the sample, and C_B is the geochemical background concentration of the same metal. The constant factor of 1.5 reduces the impact of probable lithogenic changes in baseline values caused by human activities. In 1986, Muller established seven categories for contamination classification based on the rising numerical value of the I_{geo} index (Wang et al., 2023). these are: (Class 0) $I_{geo} \leq 0$, indicates uncontaminated, (Class 1) $0 < I_{geo} < 1$ suggests uncontaminated to moderate contamination; (Class 2) $1 < I_{geo} < 2$ shows moderate contamination; (Class 3) $2 < I_{geo} < 3$ shows moderate to heavily contaminated, (Class 4) $3 < I_{geo} < 4$ signifies heavily contaminated; (Class 5) $4 < I_{geo} < 5$ suggests heavily to extremely contaminated, and (Class 6) $I_{geo} \geq 5$ indicates the sample is extremely contaminated.

On the other hand, the enrichment factor (EF) is also used to evaluate the impact of both natural and human activities on accumulating environmental elements (Han & Gu, 2023). Several studies show elements such as Fe and Al have the highest geochemical background concentrations among other metals like Ca, Mn, Sc, and Ti (Li et al., 2021; Martínez-Guijarro et al., 2019; Wang et al., 2023). Therefore, they are used as the background concentration. The *EF* can be computed using Equation (2), as given by

$$EF = \frac{(C_n/\text{Fe})_{sample}}{(C_B/\text{Fe})_{Background}} \qquad (2)$$

Where the ratio of the $(C_n/\text{Fe})_{sample}$ is the measured element concentration (C_n), and Fe in soil samples and $(C_B/\text{Fe})_{Background}$ is the ratio of background concentration (C_B) and Fe in the reference soil. In this study, the background concentrations of reference elements Al (84000 mg/kg), As (13 mg/kg), Ba (362 mg/kg), Fe (65000 mg/kg), Ho (7.50 mg/kg), K (25000 mg/kg), Mg (21000 mg/kg) and Rb (50 mg/kg), respectively, were obtained from the literature (Kabata-Pendias, 2011). Furthermore, the value of *EF* is classified as follows: (0–2) minimal enrichment; (2–5) moderate enrichment; (5–20) significant enrichment; (20–40) very high enrichment; and (40 and above) extremely high enrichment (Mensah et al., 2021).

Contamination factor, the degree of soil contamination, and Pollution Load Index

The contamination factor (*CF*) is commonly used to indicate the levels of toxic element contamination in soils and sediments (Haris et al., 2017). It helps to identify and quantify the degree of contamination for individual parameters at each sampling location. The contamination factor is a ratio of the total quantity of the element found in soil to the element's standard concentration in uncontaminated soil. The formula for *CF* is given by:

$$CF = \frac{C_n}{C_B} \quad (3)$$

Where C_n is the measured concentration of the element in soil (in mg/kg), and C_B is the reference background concentration of an element in uncontaminated soil. The value of C_B for the average world soil can be obtained from the literature (Bradl, 2005; Kabata-Pendias, 2011).

Similarly, the sum of each individual contamination element is referred to as the soil contamination degree (C_d). The C_d can be calculated using the formula:

$$C_d = \sum_{n=1}^{8} CF_n \quad (4)$$

Various studies reveal that there are four different categories of soil pollution based on the CF value: CF below 1 refers to minimal contamination; ($1 \leq CF < 3$) represents moderate contamination; ($3 \leq CF < 6$) represents major contamination; and (for $CF \geq 6$) represents extremely high contamination (Haris et al., 2017; Jeyakumar et al., 2023). In contrast, C_d is divided into four categories: (for Cd below 5) low contamination; ($5 \leq C_d < 10$) moderate contamination; ($10 \leq C_d < 20$) significant contamination; and (for C_d greater than 20) extremely high contamination. Moreover, the pollution load index (PLI) is another method for quantifying heavy metal contamination levels (Maanan et al., 2015). PLI is computed as the nth root of the product of the contamination factors (Cf) of all the heavy metals present. The formula for estimating the PLI is given by:

$$PLI = \left[CF_1 \times CF_2 \times CF_3 \times \cdots \times CF_n\right]^{1/n} \quad (5)$$

Where n represents the number of metals and CF represents the contamination factor. Accordingly, a PLI value of 1 or higher denotes the presence of pollution, whereas a PLI value of less than 1 denotes the absence of pollution (Ogbeibu et al., 2014).

Statistical Analysis

To explore the correlation between heavy metal concentrations in soil samples collected from the study area, a statistical technique, Pearson product-moment correlation (PPMC), was employed. Prior studies have reported that this analysis effectively determines the level of association or variation between different elements, specifically heavy metals (Chandrasekaran et al., 2015; El-Amier et al., 2023; Ren et al., 2022). The Pearson correlation investigation was carried out in this study using SPSS version 26.

MATERIAL AND METHODS

Study area

The sampling locations encompassed the metropolitan region of Kafin Hausa, situated within Jigawa State. It is one of the 27 local government areas in the state, located in the northeastern part of the region and covering approximately 1,380 km² of land (Adamu et al., 2018; Bashir et al., 2023). Geographically, Kafin Hausa lies between 11˚00' 00" and 12˚58' 26" north latitude and 9˚ 08' 28" and 10˚ 00' 28" east longitude, as determined by Global Positioning System (GPS) coordinates. The region is primarily used for Agriculture, with millet, sorghum, maize, rice, and groundnuts being the most common crops cultivated. In addition, various livestock farming practices are prevalent, including cattle, sheep, goats, and camels. According to Adamu *et al.* (2018), the surface geology of the area is characterised by clay, clayey clay, and sandy clay soils, which are highly suitable for agricultural activities. The catchment areas for this study include Baradua, Dundu, Gafasa, Sule Lamido University (SLU), and Takauna, which were the locations where sampling and data collection were conducted.

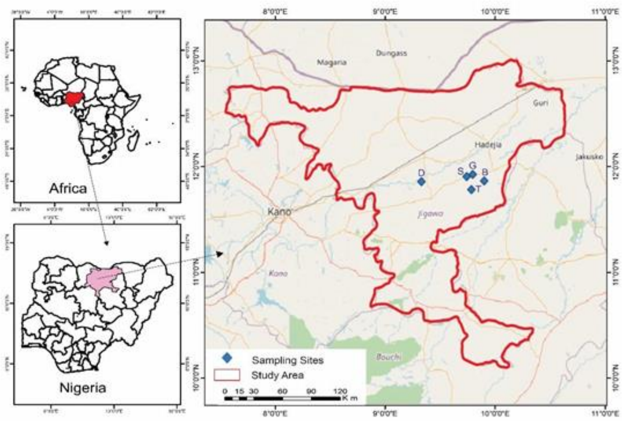

Figure 1: Location of sampling points in the study area

Sampling, Preparation, and Irradiation

A total of 15 soil samples were collected from the study area, as shown in Table 1. At each sampling area, three samples were collected from the same sampling point at different soil strata: 0–10 cm, 11–20 cm, and 21–30 cm depths. The distance between each sampling area was about 2 km. The soil samples were obtained with a means of soil auger and trowel and kept in zip-locked plastic bags with labels in accordance with the standard procedures described in the literature (Idris et al., 2015). The samples were dried, ground to fine powder, and sieved to remove debris. The mortar and pestle were cleaned between grinding with de-ionized water and acetone to avoid cross-contamination. About 250 mg of each sample was weighed, stored, and sealed in plastic bags. The samples were then characterized using the Instrumental Neutron Activation Analysis (INAA) method at the Nigeria Research Reactor-1 (NIRR-1). NIRR-1, a compact neutron source reactor developed by the China Institute of Atomic Energy (CIAE), functions at a nominal thermal power of 31 kW (Agbo et al., 2015, 2016). The reactor has a maximum operational duration of 4.5 hours at full power, primarily attributed to significant negative temperature feedback effects (Jonah et al., 2007). In this study, eight heavy metals were analysed: aluminium (Al), arsenic (As), barium (Ba), iron (Fe), holmium (Ho), potassium (K), magnesium (Mg), and rubidium (Rb).

Table 1: Description of sampling locations, Sampling point code, depth (cm) measurement, and geographical coordinates

Location	Sample Code	Depth (cm)	Geographical Coordinates	
			Latitudes (N)	Longitude (E)
Baradua	B1	0 - 10	12° 14' 50"	9° 55' 47"
	B2	11 - 20	-	-
	B3	21 - 30	-	-
Dundu	D1	0 - 10	12° 15' 09"	9° 59' 14"
	D2	11 - 20	-	-
	D3	21 - 30	-	-
Gafasa	G1	0 - 10	12° 12' 02"	10° 00' 50"
	G2	11 - 20	-	-
	G3	21 - 30	-	-
SLU	S1	0 - 10	12°13' 51"	9° 53' 12"
	S2	11 - 20	-	-
	S3	21 - 30	-	-
Takauna	T1	0 - 10	12° 08' 34"	9° 55' 15"
	T2	11 - 20	-	-
	T3	21 - 30	-	-

RESULTS AND DISCUSSION

Distribution of Heavy Metals Concentration

Table 2 shows the concentrations of heavy metals in soils collected from various locations in the study area. The lowest and highest concentrations of each metal are as follows: Al ranges from 1247 to 41570 mg/kg, As ranges from 0.42 to 1.26 mg/kg, Ba ranges from 108 to 658 mg/kg, Fe ranges from 5337 to 18170 mg/kg, Ho ranges from 7.61 to 16.60 mg/kg, K varies from 4498 to 15900 mg/kg, Mg varies from 229 to 7865 mg/kg, and Rb varies from 3.14 to 36.8 mg/kg. Similarly, the mean values for Al (17772 mg/kg), As (0.70 mg/kg), Ba (329 mg/kg), Fe (9078 mg/kg), Ho (11.97 mg/kg), K (8767 mg/kg), Mg (1178 mg/kg), and Rb (43.03 mg/kg). The lowest concentrations were found for As and Ho, while the highest concentrations were found for Al and Fe. The heavy metals' mean concentrations were also high, except for As (0.70 mg/kg).

Furthermore, the concentration of heavy metals present in the surface soils of the study area decreases in the following order: Al > Fe > K > Mg > Ba > Rb > Ho > As. This suggests that there are noticeable differences in the concentration of heavy metals in the soils of the study area. Table 3 compares the mean concentrations of heavy metals in the study area with those in other countries. The mean concentration of Al (17772 mg/kg) in the study area is lower than the concentrations reported in the literature for the Earth's crust (84000, 80500, and 99100 mg/kg) by Turekian *et al.* (1961), Yaroshevsky (2006) and Paternie *et al.* (2023). It is also lower than the concentration in the upper continental crust (77440 mg/kg) reported by Wedepohl (1995).

Moreover, As, Ba, Fe, K, and Mg concentrations in the study area are also lower than those reported for the upper continental crust and the world soil average. However, the concentrations of K and Mg in the study area are higher than the concentrations reported in a recent study by Paternie *et al.* (2023). In contrast, the concentration of Ho (11.97 mg/kg) the study area is higher than the concentrations reported for the Earth's crust (1.7, 7.5, and 1.10 mg/kg) by Yaroshevsky (2006), Turekian *et al.* (1961) and Rudnick and Gao (2013), the world soil average (0.72 mg/kg) by Kabata-Pendias (2011), and the upper continental crust (0.62 mg/kg) reported by Wedepohl (1995). However, for Rb (43.03 mg/kg), the study area is moderate and close to the world soil average (68 mg/kg) and the concentration in the Earth's crust (50 mg/kg). In general, the concentrations of heavy metals in the study area's surface soils are lower than those reported for the Earth's crust and the world soil average. However, Ho and Rb concentrations are higher than reported for these reference materials.

Geo-accumulation Index and Enrichment Factor

Table 4 summarizes the geo-accumulation indexes of the studied metals. Figure 2 shows the geo-accumulation index plot for Kafin-Hausa. From Table 4, the mean Igeo indexes of Al (-3.09), As (-4.88), Ba (-0.89), Fe (-3.53), K (-2.20), and Mg (-4.95) were lower than zero (Igeo < 0), which denote class 0, based on Muller's scale, suggesting that the soil of the study area region was uncontaminated overall by these metals except Ho (0.05). Conversely, Ho with a 0.05 (class I) is considered low- to moderately-contaminated. Similarly, the Igeo index of Ba is 0.28, 0.17, and 0.03 for the B1, B2, and B3 sites, respectively. This indicates class I corresponds to uncontaminated to moderate contamination, indicating moderate Ba metal contamination. Also, B1, B2, and B3 sites were observed to be Class I, indicating uncontaminated to moderately contaminated with Rb metal (Table 4). On the other hand, B1, B2, B3, D1, G1, G2, G3, S2, S3, and T3 sites were found to be moderately polluted by Ho metal, as seen in Figure 2.

Table 2: Data of heavy metals (concentrations ± standard deviation) in the agricultural soils of the study area.

Sites	Depth (cm)	Elements (concentration ± standard deviation) (mg/kg)							
		Al	As	Ba	Fe	Ho	K	Mg	Rb
B1	0 - 10	28400 ± 284	0.73 ± 0.09	658 ± 38	12290 ± 246	12.80 ± 1.50	15900 ± 239	1472 ± 180	78.70 ± 5.10
B2	11 - 20	28270 ± 283	0.69 ± 0.09	611 ± 39	13010 ± 260	15.85 ± 1.50	15650 ± 250	7865 ± 175	76.60 ± 5.40
B3	21 - 30	41570 ± 416	0.84 ± 0.10	554 ± 40	18170 ± 291	16.60 ± 1.40	14320 ± 243	1202 ± 185	75.30 ± 5.30
D1	0 - 10	12640 ± 316	0.49 ± 0.06	235 ± 28	6239 ± 181	14.70 ± 1.20	7254 ± 174	BDL	37.90 ± 3.60
D2	11 - 20	13770 ± 179	0.42 ± 0.04	330 ± 26	6662 ± 187	7.61 ± 0.70	7231 ± 87	733 ± 117	31.70 ± 3.60
D3	21 - 30	15020 ± 150	0.57 ± 0.05	257 ± 26	6472 ± 188	7.82 ± 0.87	8553 ± 94	664 ± 85	32.50 ± 3.60
G1	0 - 10	18970 ± 208	1.04 ± 0.06	380 ± 30	9808 ± 226	12.40 ± 0.90	9194 ± 100	922 ± 123	45.10 ± 4.00
G2	11 - 20	17340 ± 277	1.26 ± 0.07	347 ± 33	12270 ± 255	14.00 ± 1.00	8539 ± 102	726 ± 137	40.10 ± 4.20
G3	21 - 30	12830 ± 205	1.09 ± 0.07	401 ± 34	12760 ± 255	12.40 ± 0.90	8456 ± 101	679 ± 128	46.90 ± 4.30
S1	0 - 10	12400 ± 223	0.49 ± 0.06	166 ± 21	5337 ± 165	8.03 ± 0.96	6001 ± 90	345 ± 18	27.60 ± 3.90
S2	11 - 20	16630 ± 116	0.44 ± 0.15	178 ± 23	6430 ± 18.0	11.50 ± 0.90	7190 ± 103	229 ± 11	32.50 ± 3.80
S3	21 - 30	14800 ± 252	0.55 ± 0.66	213 ± 28	7174 ± 187	14.60 ± 1.20	7343 ± 147	945 ± 117	38.70 ± 3.80
T1	0 - 10	1247 ± 84	0.55 ± 0.05	299 ± 28	6429 ± 186	9.24 ± 0.80	5775 ± 81	BDL	27.70 ± 3.40
T2	11 - 20	16600 ± 232	0.62 ± 0.05	205 ± 26	6978 ± 202	9.46 ± 0.76	5599 ± 84	917 ± 140	38.90 ± 3.70
T3	21 - 30	16090 ± 257	0.73 ± 0.05	108 ± 19	6141 ± 178	12.60 ± 0.70	4498 ± 76	976 ± 147	15.20 ± 2.90
Minimum		1247	0.42	108	5337	7.61	4498	229	15.20
Maximum		41570	1.26	658	18170	16.60	15900	7865	78.70
Mean		17772	0.70	329	9078	11.97	8767	1178	43.03

Note: BDL - Below detection limit

Table 3: Comparison of heavy metal mean concentrations from various sources and countries.

Element	Mean concentration (mg/kg)						
	Kafin Hausa, NG (Study area)	**Betare-Oya-GH** (Paternie et al., 2023)	**Earth's Crust** (Rudnick & Gao, 2013)	**World-soil average** (Kabata-Pendias, 2011)	**Earth's Crust** (Yaroshevsky, 2006)	**Upper Continental Crust** (Wedepohl, 1995)	**Earth's Crust** (Turekian et al., 1961)
Al	17772	99100	-	-	80500	77440	84000
As	0.70	52	4.70	6.80	1.70	2.00	13.00
Ba	329	-	362	460	650	668	2300
Fe	9078	43500	-	-	46500	30890	65000
Ho	11.97	-	1.10	0.72	1.70	0.62	7.50
K	8767	1400	-	-	25000	28650	25000
Mg	1178	300	-	-	18700	13510	21000
Rb	43.03	-	50	68	150	110	110

Note: Nigeria (NG); Ghana (GH)

Table 4: Data of geo-accumulation index (I_{geo}) for all the sites under investigation.

Sites	Al	As	Ba	Fe	Ho	K	Mg	Rb
B1	-2.15	-4.74	0.28	-2.99	0.19	-1.24	-4.42	0.07
B2	-2.16	-4.82	0.17	-2.91	0.49	-1.26	-2.00	0.03
B3	-1.60	-4.54	0.03	-2.42	0.56	-1.39	-4.71	0.01
D1	-3.32	-5.31	-1.21	-3.97	0.39	-2.37	BDL	-0.98
D2	-3.19	-5.54	-0.72	-3.87	-0.56	-2.37	-5.43	-1.24
D3	-3.07	-5.10	-1.08	-3.91	-0.52	-2.13	-5.57	-1.21
G1	-2.73	-4.23	-0.51	-3.31	0.14	-2.03	-5.09	-0.73
G2	-2.86	-3.95	-0.65	-2.99	0.32	-2.13	-5.44	-0.90
G3	-3.30	-4.16	-0.44	-2.93	0.14	-2.15	-5.54	-0.68
S1	-3.35	-5.31	-1.71	-4.19	-0.49	-2.64	-6.51	-1.44
S2	-2.92	-5.47	-1.61	-3.92	0.03	-2.38	-7.10	-1.21
S3	-3.09	-5.15	-1.35	-3.76	0.38	-2.35	-5.06	-0.95
T1	-6.66	-5.15	-0.86	-3.92	-0.28	-2.70	BDL	-1.44
T2	-2.92	-4.98	-1.41	-3.80	-0.25	-2.74	-5.10	-0.95
T3	-2.97	-4.74	-2.33	-3.99	0.16	-3.06	-5.01	-2.30
Minimum	-6.66	-5.54	-2.33	-4.19	-0.56	-3.06	-7.10	-2.30
Maximum	-1.60	-3.95	0.28	-2.42	0.56	-1.24	-2.00	0.07
Mean	-3.09	-4.88	-0.89	-3.53	0.05	-2.20	-4.95	-0.93

Note: BDL – below detection limit

Figure 2: Plot of the geo-accumulation index of the studied area in Kafin-Hausa.

Table 5 summarizes the estimated EF values and their corresponding heavy metal site classification (SC), while Figure 3 shows the percentage chart of the enrichment factor of cultivated soil in the study area. As can be observed in Table 5, the EF ranges between 22.94 and 41.06. Based on the study findings, all the sites are highly enriched with the following metals: Al, As, Ba, Fe, Ho, K, Mg, and Rb, except for D1, which is extremely enriched with Ho (20.42). According to studies, an EF value below one reflects the natural origin of the heavy metal, while an *EF* value above one indicates enrichment due to anthropogenic input (Rumuri et al., 2021). From Table 5, the mean *EF* of Al (1.53), Ba (6.44), Fe (1.00), Ho (12.38), K (2.57), and Rb (6.22) was significantly higher than As (0.40) and Mg (0.36). The results indicate that the soil is enriched with these metals. Besides that, the results show that the anthropogenic sources are greater than the natural sources of heavy metals. However, As (0.40) and Mg (0.36) indicate they were likely associated with natural processes. This aligns with the study of Cr, Cu, Pb, Sb, and Zn, with *EF* values ranging from 0.5 to 1.5 (Han & Gu, 2023). From Figure 3, about 5% of G3, G2, and B3 are enriched; G1 and T2 were enriched by 6%, while B1, B2, D2, and D3, S1, S2, T1, and T3, respectively, were enriched by 7%. Furthermore, the maximum enrichments were found in D1 and S3, with 9% and 8%, respectively.

Table 5: The enrichment factor (EF) and site classifications (SC) data.

Sites	Al	As	Ba	Fe	Ho	K	Mg	Rb	EF Level	SC
B1	1.79	0.30	9.61	1.00	9.03	3.36	0.37	8.32	33.78	VHE
B2	1.68	0.27	8.43	1.00	10.56	3.13	1.87	7.65	34.59	VHE
B3	1.77	0.23	5.47	1.00	7.92	2.05	0.20	5.39	24.04	VHE
D1	1.57	0.39	6.76	1.00	20.42	3.02	BDL	7.90	41.06	EHE
D2	1.60	0.32	8.89	1.00	9.90	2.82	0.34	6.19	31.06	VHE
D3	1.80	0.44	7.13	1.00	10.47	3.44	0.32	6.53	31.12	VHE
G1	1.50	0.53	6.96	1.00	10.96	2.44	0.29	5.98	29.65	VHE
G2	1.09	0.51	5.08	1.00	9.89	1.81	0.18	4.25	23.81	VHE
G3	0.78	0.43	5.64	1.00	8.42	1.72	0.16	4.78	22.94	VHE
S1	1.80	0.46	5.58	1.00	13.04	2.92	0.20	6.72	31.73	VHE
S2	2.00	0.34	4.97	1.00	15.50	2.91	0.11	6.57	33.40	VHE
S3	1.60	0.38	5.33	1.00	17.64	2.66	0.41	7.01	36.03	VHE
T1	0.15	0.43	8.35	1.00	12.46	2.34	BDL	5.60	30.32	VHE
T2	1.84	0.44	5.28	1.00	11.75	2.09	0.41	7.25	30.05	VHE
T3	2.03	0.59	3.16	1.00	17.78	1.90	0.49	3.22	30.18	VHE
Minimum	0.15	0.23	3.16	1.00	7.92	1.72	0.11	3.22	22.94	
Maximum	2.03	0.59	9.61	1.00	20.42	3.44	1.87	8.32	41.06	
Mean	1.53	0.40	6.44	1.00	12.38	2.57	0.36	6.22	30.92	

Note: BDL – below detection limit, VHE – very high enrichment, and EHE – extremely high enrichment

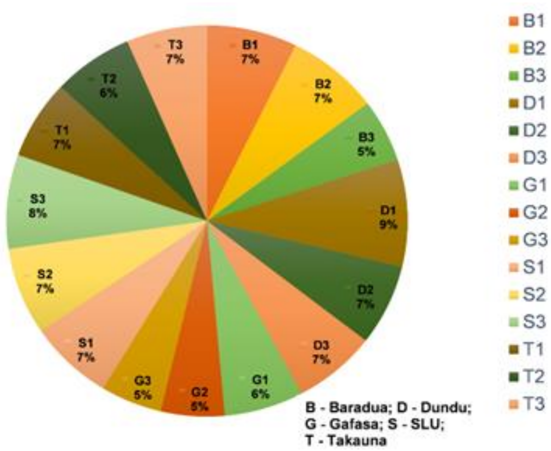

Figure 3: Percentage chart of Enrichment factor of cultivated soil in the study area

Contamination Factor, Degree of Soil Contamination, and Pollution Load Index

Table 6 summarizes data on the contamination factor, degree of soil contamination, and pollution load index. Meanwhile, Figure 4 illustrates the soil contamination factor (*CF*) at different depths (a) 0–10 cm, (b) 11–20 cm, (c) 21–30 cm, and (d) the degree of soil contamination (C_d) of agricultural soil in the study area. The calculated *CF* values for Al range from 0.19 to 0.50, for As from 0.03 to 0.10, for Ba from 0.30 to 1.82, for Fe from 0.08 to 0.28, for Ho from 1.01 to 2.21, for K from 0.18 to 0.64, for Mg from 0.01 to 0.38, and for Rb from 0.30 to 1.57 (Table 6). In Table 6, the mean *CF* values for Al (0.21), As (0.05), Ba (0.91), Fe (0.14), K (0.35), Mg (0.06), and Rb (0.86) were all lower than one (*CF* < 1), indicating minimal or low contamination. However, Ho (1.60) falls into group 1, suggesting moderate contamination. Notably, Ho, Ba, and Rb exhibit significant *CF* values compared to others at depths of 0–10 cm, 11–20 cm, and 21–30 cm (Figure 4 (a) to (c)). At a depth of 0–10 cm (Figure 4 (a)), the studied areas D1, B1, and G1 show the highest CF values for Ho, while B1 and G1 exhibit the highest values for Ba and Rb. At a depth of 11–20 cm (Figure 4 (b)), significant CF values for Ho, Ba, and Rb are observed at B2, G2, and S2, among others. Furthermore, B3 exhibits significant CF at 21–30 cm [Figure 4 (c)].

Moreover, the calculated degree of soil contamination ranges from 2.61 to 6.92. Studies suggest that a C_d below 5 indicates low contamination, while a C_d between 5 and 10 indicates moderate contamination (Han & Gu, 2023). Based on the findings of this study, B1 (6.39), B2 (6.92), and B3 (6.72) were moderately contaminated compared to other areas. Additionally, B2 and B3 have a C_d of 11%, followed by B1 with 10%. G1, G2, G3, and S3 each have a C_d of 7%, while D1 has 6%. D2, D3, S2, T1, T2, and T3 each have a C_d of 5%, and S1 agricultural soil in the study area has the lowest C_d at 4% [Figure 4 (d)]. Furthermore, the PLI values range from 0.16 to 0.51. According to the literature, a PLI value of less than 1 indicates the absence of pollution (Chandrasekaran et al., 2015). The results obtained from this study show that the studied area is unpolluted (Table 6).

Table 6: Data of soil contamination factor (CF), the degree of soil contamination (Cd), and pollution load index (PLI) of the selected locations of Kafin-Hausa

Sites	*CF*								C_d	PLI
	Al	As	Ba	Fe	Ho	K	Mg	Rb		
B1	0.34	0.06	1.82	0.19	1.71	0.64	0.07	1.57	6.39	0.41
B2	0.34	0.05	1.69	0.20	2.11	0.63	0.37	1.53	6.92	0.51
B3	0.49	0.06	1.53	0.28	2.21	0.57	0.06	1.51	6.72	0.44
D1	0.15	0.04	0.65	0.10	1.96	0.29	BDL	0.76	3.94	0.33
D2	0.16	0.03	0.91	0.10	1.01	0.29	0.03	0.63	3.18	0.21
D3	0.18	0.04	0.71	0.10	1.04	0.34	0.03	0.65	3.10	0.21
G1	0.23	0.08	1.05	0.15	1.65	0.37	0.04	0.90	4.47	0.30
G2	0.21	0.10	0.96	0.19	1.87	0.34	0.03	0.80	4.50	0.30
G3	0.15	0.08	1.11	0.20	1.65	0.34	0.03	0.94	4.50	0.29
S1	0.15	0.04	0.46	0.08	1.07	0.24	0.02	0.55	2.61	0.16
S2	0.20	0.03	0.49	0.10	1.53	0.29	0.01	0.65	3.30	0.18
S3	0.18	0.04	0.59	0.11	1.95	0.29	0.05	0.77	3.98	0.24
T1	0.01	0.04	0.83	0.10	1.23	0.23	BDL	0.55	3.00	0.23
T2	0.20	0.05	0.57	0.11	1.26	0.22	0.04	0.78	3.23	0.22
T3	0.19	0.06	0.30	0.09	1.68	0.18	0.05	0.30	2.85	0.18
Minimum	0.19	0.03	0.30	0.08	1.01	0.18	0.01	0.30	2.61	0.16
Maximum	0.50	0.10	1.82	0.28	2.21	0.64	0.38	1.57	6.92	0.51
Mean	0.21	0.05	0.91	0.14	1.60	0.35	0.06	0.86	4.18	0.28
Standard deviation	0.11	0.02	0.46	0.06	0.39	0.14	0.09	0.38	1.43	0.10
Skewness	1.15	1.04	0.82	1.15	-0.15	1.20	3.55	0.99	1.02	0.99
Kurtosis	2.75	0.18	-0.25	0.65	-1.17	0.31	13.29	0.10	-0.19	0.20

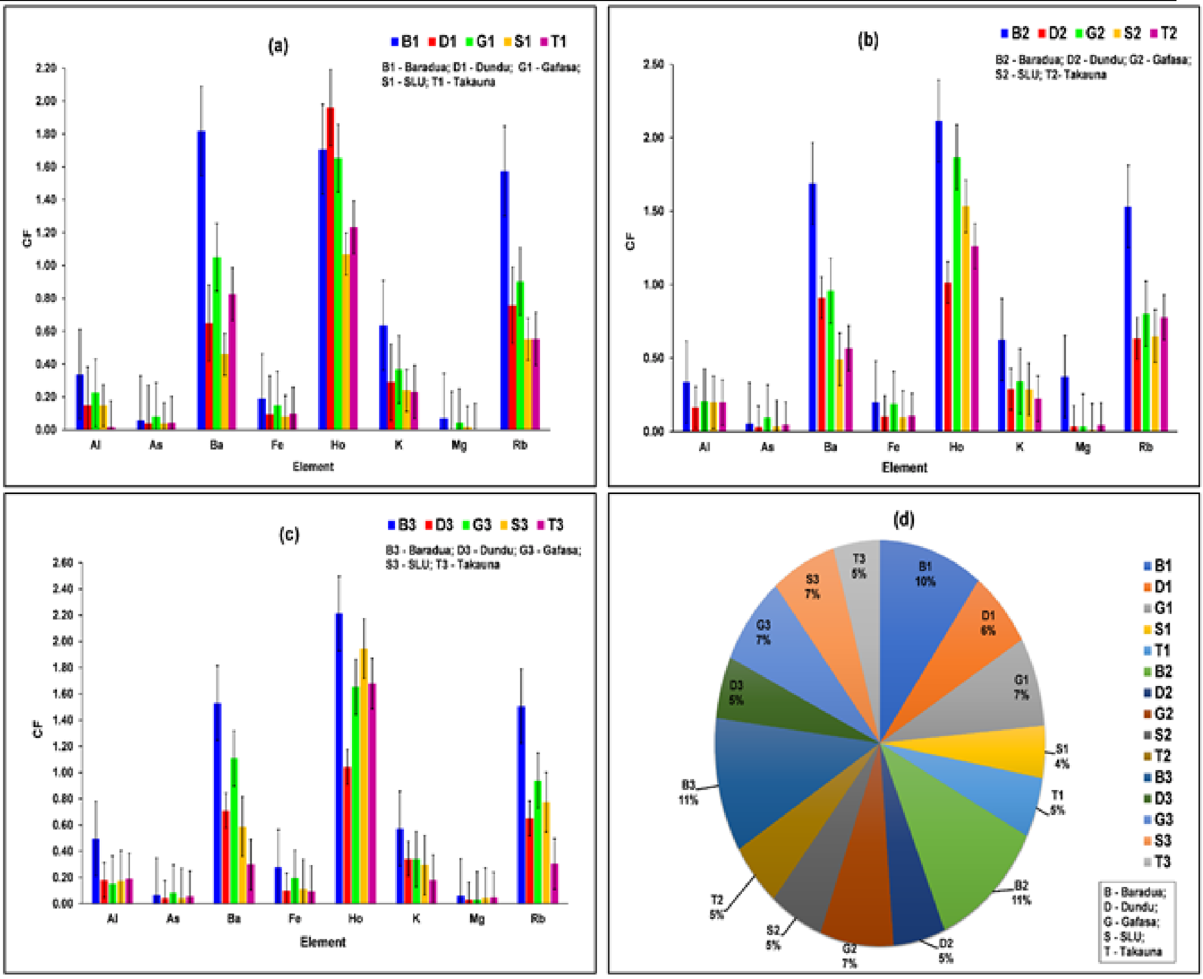

Figure 4: Evaluated contamination factor (CF) at a depth of (a) 0 - 10 cm, (b) 11 - 20 cm, (c) 21 - 30 cm, and (d) the degree of contamination (C_d) of agricultural soil in the study area.

Correlation Analysis

In order to assess the level of association between multiple metals, a correlation analysis was performed using the Pearson product-moment correlation coefficient (PPMC). Table 7 displays the correlation matrix obtained. The analysis revealed significant and robust correlations among the metals present in the agricultural soil samples. The results show strong positive correlations at p-values of 0.05 and 0.01. These correlations include Al – Ba (r = 0.68), Al – Fe (r = 0.79), Al – K and Al – Rb (r = 0.81), As – Fe (r = 0.65), Ba – Fe (r = 0.83), Ba – K and Ba – Rb (r = 0.94), Fe – Ho (r = 0.67), Fe – K (r = 0.80), Fe – Rb (r = 0.83), and K – Rb (r = 0.96), respectively, all significant at the 0.01 level. Additionally, Al – Ho (r = 0.61), Ba – Mg (r = 0.56), Ho – K (r = 0.55), Ho – Rb (r = 0.60), K – Mg (r = 0.63), and Mg – Rb (r = 0.59) exhibited significant correlations at the 0.05 level. The findings of this study indicate strong correlations between all elements, potentially influenced by similar sources or the geographical distribution of the soil (Shafie et al., 2013). Wang and colleagues (2023) also reported similar findings in their recent investigation on elements (Al, Fe, K, Mg, Mn, Rb, Sr, Th, Zn, V, Ni, As, Pb, Cu, Co, and Cd). Their study highlights those metals exhibit correlations due to comparable levels of human and natural activities. In this present investigation, the findings suggest that soil complexes might influence the availability of specific metals.

Table 7: Data of the Pearson correlation coefficients for the heavy metals in Kafin Hausa

Element	Al	As	Ba	Fe	Ho	K	Mg	Rb
Al	1.00							
As	0.27	1.00						
Ba	0.68**	0.37	1.00					
Fe	0.79**	0.65**	0.83**	1.00				
Ho	0.61*	0.42	0.46	0.67**	1.00			
K	0.81**	0.26	0.94**	0.80**	0.55*	1.00		
Mg	0.46	0.07	0.56*	0.40	0.42	0.63*	1.00	
Rb	0.81**	0.29	0.94**	0.83**	0.60*	0.96**	0.59*	1.00

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

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

CONCLUSION

The present study successfully quantified and characterized the heavy metal contamination in agricultural soils in Kafin Hausa, Nigeria, utilizing the INAA technique. The study results revealed that the concentrations of all identified heavy metals were within the permissible limits established by regulatory agencies. Muller's geo-accumulation index (Igeo) revealed that most heavy metals exhibited values below zero, indicating an absence of contamination, except for Ho, which showed slight contamination (class I). Conversely, the mean EF values for Al (1.53), Ba (6.44), Fe (1.00), Ho (12.38), K (2.57), and Rb (6.22) were significantly higher compared to As (0.40) and Mg (0.36), signifying enrichment of these metals in the studied soil. Additionally, B2 has been shown to have a higher proportion of anthropogenic sources than natural sources. The highest enrichment factors were observed at the D1 (41.06) and S3 (36.03) sites. Furthermore, the CF values for most elements were below two, suggesting low contamination, with Ho showing low to moderate contamination. Ho, Ba, and Rb exhibited the highest CF values among the examined metals. Pollution load index values range from 0.16 to 0.51, signifying an absence of pollution in the studied area. Moreover, the study identified strong correlations between various elements, particularly K - Rb (r = 0.96), Ba - K (r = 0.94), and Ba - Rb (r = 0.94). These findings contribute comprehensive insights into the status and sources of heavy metal contamination in agricultural soils in Kafin Hausa, Nigeria.

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