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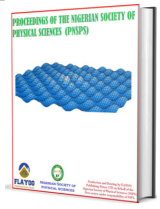

Heavy metal bioaccumulation in food crops grown around Babban Tsauni gold mines and assessment of farmland soil contamination

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A B S T R A C T

Heavy metal bioaccumulation in food crops is a serious environmental and public health concern, especially in regions affected by artisanal mining. This study assessed the bioaccumulation potential, expressed as bioaccumulation factor (BF), of selected heavy metals—lead (Pb), arsenic (As), nickel (Ni), chromium (Cr), manganese (Mn), zinc (Zn), cobalt (Co), and iron (Fe)—in twelve food crops, comprising four tubers and eight grains cultivated around the Babban Tsauni gold mines. The contamination status of nearby farmlands was also evaluated. Heavy metal concentrations were determined using instrumental neutron activation analysis (INAA) and X-ray fluorescence (XRF). The mean BF values for tubers were 19.176 (Pb), 0.015 (As), 0.101 (Ni), 0.796 (Cr), 0.079 (Mn), 2.839 (Zn), 1.334 (Co), and 0.879 (Fe), while those for grains were 43.290 (Pb), 0.258 (As), 0.419 (Ni), 2.162 (Cr), 0.152 (Mn), 3.827 (Zn), 0.529 (Co), and 0.653 (Fe). Pb showed the highest bioaccumulation in both crop groups, followed by Zn, indicating strong plant uptake in contaminated soils. The pollution load index (PLI = 2.25) indicated soil pollution, whereas the overall potential ecological risk index (RI = 87.61) indicated low ecological risk. The occurrence of Zn and Mn may be attributed mainly to natural geogenic sources rather than human activity. The elevated accumulation of Pb and Zn calls for appropriate remediation strategies, including land-use restriction, crop selection, and supervised mining in mining-impacted agricultural areas.

Keywords: Heavy metals, Bioaccumulation factor, Farm soil, Soil contamination, Gold mining.

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1. INTRODUCTION

Heavy metals (HMs) are metals or metalloids characterized by relatively high density and toxicity, even at low concentrations [1]. Some heavy metals, such as Ni, Mn, Cu, Co, Fe, and Zn, are essential and play important roles in plant and human health. Others, including Pb, As, Hg, and Cd, are non-essential and are of serious concern because they have been classified as carcinogenic even at low concentrations [1–4]. Since soil is a natural sink for heavy metals, the concentration at which these elements occur depends on the geological conditions and human activities in an area [5]. Mining, industrial discharge, urban effluents, fertilizer application, herbicides, pesticides, and irrigation with contaminated water have been identified as pathways through which heavy metals can enter the human food chain [1, 6].

Metallic pollutants in agricultural soils close to artisanal gold mining sites, followed by their absorption by food crops and in-

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gestion by humans, can pose significant health risks [7]. Farms located near mining sites, whether large or small scale, are prone to different forms of contamination regardless of the mineral being mined. Continuous excavation of soil from mine pits and acid mine drainage can mobilize heavy metals and increase their bioavailability [8]. In addition, weathered rocks, mine tailings, and toxic wastes in the form of sludge may be dispersed across mining areas and transported to nearby farmlands. Because these pollutants occur naturally, food crops grown around gold mining areas should be assessed to determine whether their concentrations are of concern.

Agricultural soils in many regions of the world are contaminated with heavy metals at varying levels. Such contamination may arise from the prolonged application of phosphate fertilizers or sewage sludge and may be further enhanced by mining activities [9]. Considering the implications for the food chain, many studies have examined the uptake of heavy metals from contaminated soils, with most reporting significant risks [3, 9–12]. The present study extends previous work on the assessment of heavy metal contamination and associated health risks in soil and food crops from the Babban Tsauni gold mines, Gwagwalada, Nigeria [5]. Other studies in this area have focused mainly on mineralogy and geological characterization [13–15]. The objectives of the present work were therefore to determine the concentrations of Cr, As, Ni, Pb, Fe, Co, Zn, and Mn in agricultural soils around the Babban Tsauni gold mine using INAA and XRF methods, estimate the bioaccumulation factor in food crops (tubers and grains), and evaluate the pollution status of the farmlands.

The study area is the remote village of Babban Tsauni and its surrounding area in the Gwagwalada Area Council of the Federal Capital Territory (FCT), Nigeria. The area spans approximately 50 km^2 and is located at latitude 9°10′0″ N and longitude 6°58′0″ E on Paiko Sheet 185 (SW). It lies approximately 10 km southwest of Izom town in Niger State and can be reached via a minor road connecting Gwagwalada–Dobi and Izom towns. The main occupation of the population is farming, although artisanal gold mining is actively carried out because of the presence of gold veins, despite their occurrence in non-commercial quantities [5]. The geology of the area has been described by Okunlola *et al.* [13] and is shown in Fig. 1.

2. THEORETICAL BACKGROUND

2.1. BIOACCUMULATION FACTOR

The bioaccumulation factor (BF) is used to estimate the extent to which food crops absorb toxic metals from soil through plant roots. The BF values were calculated using Eq. (1) [9, 16]:

$$BF = \frac{C_{\text{crop}}}{C_{\text{soil}}}, \tag{1}$$

where C_{crop} is the concentration of the heavy metal in the edible part of the food crop and C_{soil} is the concentration of the same heavy metal in the corresponding farm soil. Elevated BF values ($BF > 1$) indicate hyperaccumulation potential and suggest that such plants could be used for phytoextraction [17].

2.2. HEAVY METAL CONTAMINATION ASSESSMENT

To assess the contamination level of the agricultural soil, pollution indices were calculated using experimentally determined heavy metal concentrations. These indices include the contamination factor (CF), ecological risk factor (ER), geo-accumulation index (I_{geo}), enrichment factor (EF), pollution load index (PLI), and potential ecological risk index (RI).

2.2.1. Contamination factor

The contamination factor was used, as suggested by Harikumar *et al.* [18], to determine the extent of pollution by specific heavy metals in soil. The contamination factor was calculated using Eq. (2):

$$CF = \frac{C_f}{C_u}, \tag{2}$$

where C_f is the experimental concentration of the heavy metal in the farm soil and C_u is the experimental concentration of the same heavy metal in the uncultivated or background area. The CF categories are commonly interpreted as low contamination ($CF < 1$), moderate contamination ($1 \leq CF < 3$), considerable contamination ($3 \leq CF < 6$), and very high contamination ($CF \geq 6$) [19, 20].

2.2.2. Geo-accumulation index

The geo-accumulation index (I_{geo}), first suggested by Müller [20], compares the concentration of a specific heavy metal in the farm soil with its background concentration while accounting for natural variation. It was evaluated using Eq. (3) [21]:

$$I_{\text{geo}} = \log_2\left(\frac{C_f}{1.5C_u}\right), \tag{3}$$

where C_f is the concentration of the heavy metal in the farm soil, C_u is the geochemical background concentration in the uncultivated area, and the factor 1.5 accounts for possible variations in background data due to geological differences [20]. The I_{geo} classification ranges from 0 to 6 [5, 19].

2.2.3. Ecological risk factor

The ecological risk factor, introduced by Hakanson [19], evaluates the potential ecological risk associated with toxic metals. It was calculated using Eq. (4):

$$ER = CF \times TRV, \tag{4}$$

where ER is the ecological risk factor, CF is the contamination factor, and TRV is the toxic-response value. The toxic-response values considered in this study were Pb = 5, As = 10, Ni = 5, Cr = 2, and Zn = 1 [5, 19, 22]. The risk categories are: $ER < 40$, low potential ecological risk; $40 \leq ER < 80$, moderate potential ecological risk; $80 \leq ER < 160$, considerable potential ecological risk; $160 \leq ER < 320$, high potential ecological risk; and $ER \geq 320$, very high ecological risk [22].

2.2.4. Enrichment factor

The enrichment factor (EF) measures the extent to which human activities, including gold mining, may have influenced heavy metal concentrations in the farm soil. The EF was evaluated using Eq. (5) [23], with Mn selected as the reference metal [5]:

$$EF = \frac{\left(C_f / C_{imf}\right)}{\left(C_u / C_{imu}\right)}, \tag{5}$$

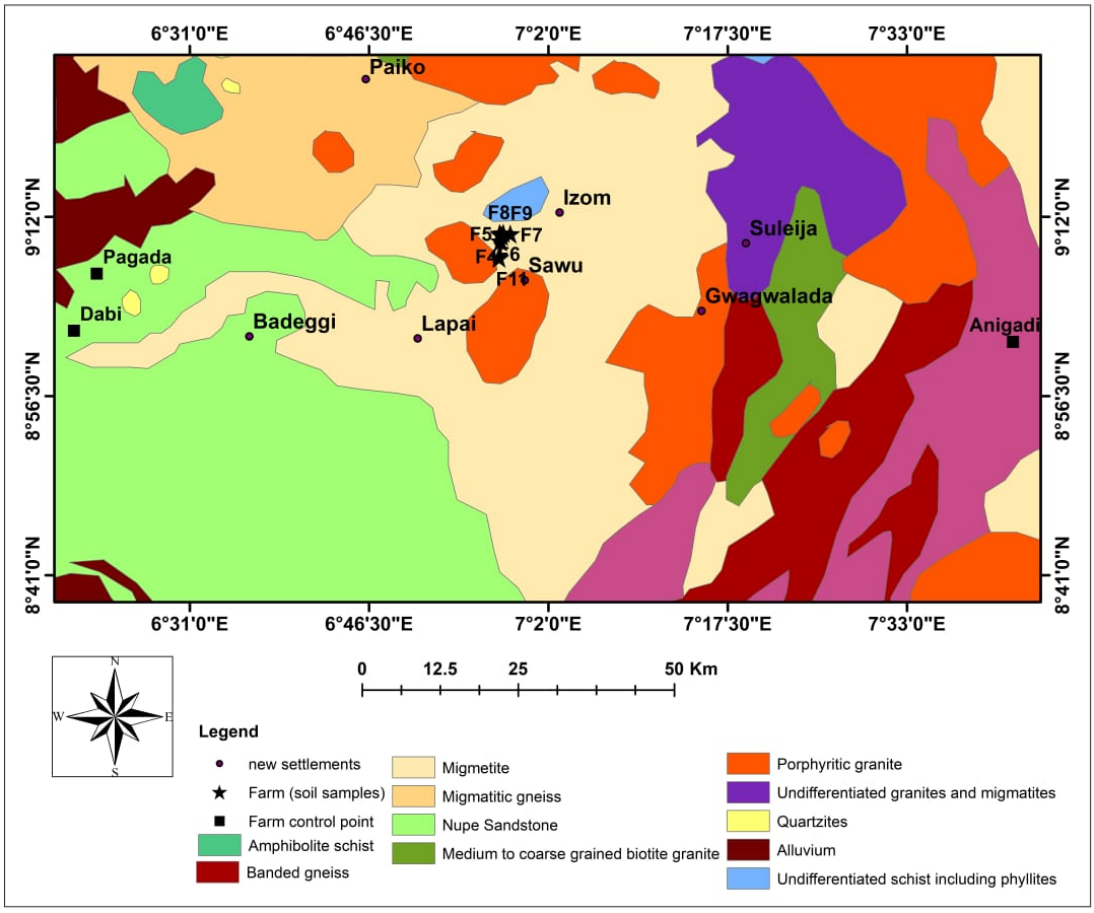

Figure 1. Geological representation of Babban Tsauni and the surrounding environs.

where C_f is the concentration of the metal in the farm soil, C_{imf} is the concentration of the immobile reference metal in the farm soil, C_u is the concentration of the metal in the uncultivated area, and C_{imu} is the concentration of the immobile reference metal in the uncultivated area. Liu *et al.* [24] and other authors [24–27] reported that if $EF \leq 1.5$, the origin of a specific heavy metal may be attributed to natural processes, whereas $EF > 1.5$ suggests anthropogenic influence. In this study, Mn was selected as the immobile element, consistent with previous work [5, 26, 27].

2.2.5. Pollution load index

The pollution load index is a statistical tool used to evaluate the overall level of heavy metal pollution in sediment, water, soil, or another environmental medium. It was calculated using Eq. (6) [1, 5, 20]:

$$PLI = (CF_1 \times CF_2 \times \cdots \times CF_n)^{1/n}, \tag{6}$$

where PLI is the pollution load index, CF is the contamination factor, and n is the number of heavy metals considered. A PLI value greater than 1 indicates progressively significant pollution, whereas $PLI < 1$ indicates that heavy metal concentrations are within the background level [20].

2.2.6. Potential ecological risk index

The potential ecological risk index (RI) measures the overall toxicity of farm soil due to the presence of heavy metals of ecological concern. It was calculated using Eq. (7), as suggested by Hakanson [19]:

$$RI = \sum_{i=1}^{n} E_r^i, \tag{7}$$

where E_r^i is the ecological risk factor of the ith heavy metal. The RI categories are: $RI < 150$, low risk; $150 \leq RI < 300$, mild risk; $300 \leq RI < 600$, significant risk; and $RI > 600$, extreme risk [5, 22, 25, 28].

3. MATERIALS AND METHODS

3.1. SAMPLING TECHNIQUE

Representative samples of soil, yams, and grains were randomly collected from nearby farmlands on the basis of availability and proximity to the gold mines, with each site and farmland having an equal probability of selection [5]. Proximal farmlands were identified for farm soil collection, with corresponding food crop samples collected at each point. A hand steel auger was used to collect farm soil after digging to a depth of 5–10 cm. The soil was further dug to collect yams, while a knife was used to cut the grains in bunches. For each farmland, soil samples were collected from five points and homogenized into one representative sample, giving a total of sixty sampling points. This procedure was adopted to ensure unbiased sampling. A similar procedure was used for the collection of food crop and control samples. In

total, twelve representative soil samples and their corresponding twelve food crop samples were collected. Control samples were collected 5 km away from the mining community. The coordinates of the sample collection sites (latitude 6°57′50″–7°10′05″ and longitude 9°9′53″–9°1′18″), together with the sample codes (Farm 1 to Farm 12 and CF 1 to CF 5 for control samples), were recorded.

3.2. SAMPLE PREPARATION

The farm soil and food crop samples were prepared according to the requirements of the two analytical methods: instrumental neutron activation analysis (INAA) and X-ray fluorescence (XRF). All samples were spread on treated polyethylene bags and dried at room temperature. For INAA, 150–200 mg of each dried sample was pulverized using porcelain. Each labeled sample was packed in a clean polyethylene container, sealed, and placed into a 7 cm^3 rabbit capsule, as described by Jonah *et al.* [29] and adopted by other studies [5, 30, 31]. Two certified reference materials with known elemental concentrations (tomato leaves, NIST 1573a, and coal fly ash, 1633c) were prepared using the same procedure. The vials containing the samples were placed into the rabbit system injector and sent to the irradiation channel through the pneumatic transfer system.

For XRF analysis, the pulverized samples were further passed through a 125 µm sieve. Then, 2 g of each sample was weighed, placed in a holder, and covered with cotton wool. Reference materials obtained from the International Atomic Energy Agency, with certificate values (Montana soil SRM 2710, IAEA Soil-7 for geological samples, and IAEA-155 for biological samples), were used for calibration. The validation of the results has been discussed in detail elsewhere [5].

3.3. EXPERIMENTAL MEASUREMENT

Instrumental neutron activation analysis, an automated sample-handling and computerized data-processing technique, was used to measure more than thirty short- and long-lived elements in each sample without chemical separation or digestion and with minimal sample preparation. Only six elements (Cr, As, Fe, Co, Zn, and Mn) were considered in this study. The relative (comparative) method was adopted to quantify metal concentrations in the samples, with correction for differences in decay between the unknown sample and the comparator standard. The mathematical expression used for this purpose is given by Hamidatou *et al.* [32]:

$$\frac{A_x}{A_{st}} = \frac{m_x}{m_{st}} \times \frac{\left(e^{-\lambda T_d}\right)_x}{\left(e^{-\lambda T_d}\right)_{st}}, \tag{8}$$

where A_x is the activity of the sample, A_{st} is the activity of the standard, m is the mass of the element, λ is the decay constant of the isotope, and T_d is the decay time. In short irradiations, the irradiation, decay, and counting times are approximately the same for all samples and standards; therefore, Eq. (8) reduces to Eq. (9):

$$C_s = C_{st} \frac{W_{st}}{W_x} \times \frac{A_x}{A_{st}}, \tag{9}$$

where C_s is the concentration of the element, W_x is the sample weight, and W_{st} is the standard weight.

The Nigeria Research Reactor-1 (NIRR-1), located at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Nigeria, was used. NIRR-1 is a miniature neutron source reactor with a neutron flux of 1×10^{11} n cm^{-2} s^{-1}. A detailed description of the sample irradiation and measurement scheme has been provided by Jonah *et al.* [29] and Odelami *et al.* [5].

Energy-dispersive X-ray fluorescence (EDXRF) analysis was carried out at the Central Laboratory, Umaru Musa Yar'adua University, Katsina. This complementary method was used to determine Ni and Pb, which were measured in percentages and converted to ppm for uniformity because these elements could not be measured conveniently by INAA without interference. The EDXRF analyzer (model ARL QUANT'X) was operated using the standard method with an accuracy of 80%. The instrument uses a miniature X-ray tube as the excitation source. The sample holders containing the samples were run under vacuum or air for 10 min and then inserted into the XRF spectrometer for elemental analysis. Characteristic X-rays emitted by the samples were captured by the detector and analyzed by computer. The energy spectrum of these characteristic X-rays was used to identify the elements present in the samples [33].

4. RESULTS AND DISCUSSION

The heavy metal concentrations in the samples are presented in Table 1. The heavy metal contents of the food crops were published previously [5] and are presented here with the values obtained in the present analysis. Among the elements analyzed in the agricultural soil, Fe (34762.83 ppm) and Pb (677.31 ppm) exceeded the WHO permissible limits, whereas the other metals were within acceptable limits. The elevated concentration of Fe may be due to its natural abundance in the Earth's crust [34]. The mineralization of the study area is characterized by Pb–Zn–Fe–Cu sulphides and magnetite, which explains the artisanal gold mining activity in the area [15]. Gold ore is also commonly associated with pyrite; oxidation of this mineral can release Fe into the soil, and the released Fe can be transported to nearby farmlands by climatic processes [30]. Similarly, the elevated Pb concentration (677.31 ppm) in the farm soil may be associated with mine tailings, waste disposal, irrigation with Pb-contaminated water, inadequate safety measures, and unregulated gold ore processing. These factors are similar to those associated with Pb contamination in Zamfara State, Nigeria, which resulted in several child fatalities [16, 35–37].

The bioaccumulation factor of heavy metals was calculated using the values presented in Table 1 and Eq. (1). The ranges and estimated mean values, including standard errors, are presented in Table 2.

The order of BF values was Pb > Zn > Co > Fe > Cr > Ni > Mn > As for yams and Pb > Zn > Cr > Fe > Co > Ni > As > Mn for grains. These trends show that Pb and Zn were significantly elevated in both crop groups. The BF value was highest for Pb in grains (43.29 ± 9.32), indicating abnormal mobility and high translocation ability and suggesting that grain crops may be suitable for phytoextraction. This result also indicates environmental contamination, an anthropogenic contribution from gold mining, and prolonged elemental transfer within the agricultural environment [35]. Because Pb is non-biodegradable and toxic,

Table 1. Average concentrations (± standard error) of elements in farm soil and crops (ppm).

Sample	Parameter	As	Pb	Ni	Mn	Cr	Zn	Co	Fe	Reference
Farm soil	Average	2.25 ± 1.05	677.31 ± 195.76	32.43 ± 4.67	881.92 ± 156.58	69.77 ± 21.76	55.84 ± 17.73	21.64 ± 5.95	34762.83	Present study
WHO	Permissible limit	20	100	50	–	100	300	50	–	[38]
Tubers	Average	0.32 ± 0.22	665.0 ± 106.07	36.30 ± 7.49	37.1 ± 43.31	34.2 ± 39.87	146.00 ± 27.79	5.39 ± 7.97	16661.5	[5]
Grains	Average	0.28 ± 0.21	1363.30 ± 1144.31	28.36 ± 6.92	97.38 ± 72.84	14.45 ± 23.01	79.75 ± 61.27	1.61 ± 2.32	5415.82	[5]
FAO	Permissible limit	–	0.3	0.1	–	5.0	60.0	–	73.0	[39]

Table 2. Bioaccumulation factors in food crops (standard error).

Crops	Values	Pb	As	Ni	Cr	Mn	Zn	Co	Fe
Yam	Range	13.190–30.890	0.003–0.036	0.019–0.357	0.008–2.695	0.019–0.215	0.648–4.438	0.009–5.000	0.005–2.793
	Mean ± SE	19.176 ± 4.048	0.015 ± 0.007	0.101 ± 0.085	0.796 ± 0.635	0.079 ± 0.046	2.839 ± 0.815	1.334 ± 1.224	0.879 ± 0.656
Grains	Range	22.88–103.49	0.004–1.00	0.207–0.574	0.006–12.800	0.005–0.424	0.0002–16.933	0.001–4.007	0.001–4.830
	Mean ± SE	43.29 ± 9.32	0.258 ± 0.132	0.419 ± 0.047	2.162 ± 1.604	0.152 ± 0.054	3.827 ± 1.961	0.529 ± 0.497	0.653 ± 0.597

Table 3. Contamination assessment of the agricultural soil.

Sample	Parameter/Average	As	Pb	Ni	Mn	Cr	Zn	Co	Fe	Complex index
Farm soil	CF	2.83	9.09	1.85	1.36	1.64	1.25	2.33	2.10	PLI = 2.25
	I_{geo}	-0.72	-2.25	-2.28	-0.41	-0.55	-1.62	-0.11	0.06	–
	ER	28.32	45.49	9.27	–	3.28	1.25	–	–	RI = 87.61
	EF	2.02	10.21	2.08	1.00	1.63	1.09	1.61	1.73	–

consumption of Pb-contaminated food crops can adversely affect human health, particularly among children and other vulnerable groups [40]. These results and interpretations are consistent with previous studies [2, 41–44].

Table 3 presents the contamination level of the agricultural soil determined using both single and integrated pollution indices.

The contamination factors for all heavy metals indicated moderate contamination, except for Pb, which indicated very high contamination. The combined contamination impact of the heavy metals gave a PLI value of 2.25, indicating progressive pollution of the farmland. This pollution may be attributed to both the natural composition of the soil and the human activities occurring in the study area [5, 15]. The I_{geo} values indicated that the soils were unpolluted ($I_{geo} < 0$) with respect to all metals except Fe. This observation supports the earlier inference regarding the abundance of Fe and its occurrence in gold ore [35]. The ER values of the metals with high mobility and toxic-response values were low ($ER < 40$), except for Pb (ER = 45.49), which indicated moderate ecological risk. However, the cumulative effect of multiple elements was low (RI < 150). The EF values indicated probable anthropogenic enrichment for all elements except Mn and Zn, suggesting that Mn and Zn may have originated mainly from natural processes. Overall, the contamination assessment of the farm soil underscores potential food safety concerns [45, 46].

5. CONCLUSION

This study showed that the concentrations of heavy metals in the farm soil were generally within WHO-recommended values, except for Pb (677.31 ppm). The elevated Pb concentration in the farm soil suggests that geogenic contributions may have been further intensified by gold mining processes. Heavy metals, especially Pb, may become readily available and transferred into crops, thereby raising health concerns for the local population. The BF values for Pb were 19.176 ± 4.05 in tubers and 43.290 ± 9.32 in grains, followed by elevated values for Zn, indicating substantial transfer and absorption. Although grains showed a greater tendency for hyperaccumulation of heavy metals, they may also be suitable for phytoremediation. The PLI value of 2.25 confirms soil pollution in farmlands around the mining area, while the RI value of 87.61 indicates low overall ecological risk. The findings emphasize potential food safety concerns in crops grown around mining areas and highlight the need for continuous environmental monitoring, land-use control, crop selection, and supervised mining operations.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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