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Soil-to-Crop Transfer, Bioaccumulation, and Health Risk Assessment of Heavy Metals in Cassava Grown in Illicitly Mined Areas of Noyem and Nyafoman, Eastern Ghana

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Abstract

Introduction: Illicit mining contaminates Ghana with heavy metals, risking soil fertility, food safety, and public health. Despite concern, data on metal transfer into staple crops like cassava remains limited. This study assessed heavy metal levels in soils from illicitly mined sites at Noyem and Nyafoman and examined their transfer into cassava tubers to evaluate ecological and health risks. Soil and cassava samples were collected from mined and control sites.
Method: Concentrations of Zn, Fe, Cu, Hg, and Cd were determined by Atomic Absorption Spectrophotometry (AAS). Soil–plant transfer factors and ecological risk indices were calculated, while dietary exposure was assessed using estimated daily intake (EDI) and risk index (RI) per FAO/WHO guidelines. Data were analyzed using SPSS v20.0 with descriptive statistics and correlation analysis.
Result: Higher concentrations of Zn, Fe, Hg, and Cd were found in mined site soils versus controls. Fe levels exceeded control limits, while Zn remained below permissible limits. Mercury was detected at notable levels, consistent with Ghanaian mining studies reporting 0.68-17.03 mg/kg. Cassava tubers from mined soils showed higher Cu and Hg accumulation, exceeding FAO/WHO limits. Associations between soil and cassava Cu concentrations indicated cassava's tendency to accumulate Cu, suggesting its use in monitoring metal transfer in mining-affected agroecosystems. Zn, Hg, and Cd showed weak soil-plant relationships, reflecting differences in metal bioavailability influenced by soil pH and organic matter. Dietary risk assessment revealed long-term Cu exposure concerns, while Zn intake exceeded safety thresholds for children (RI > 1), indicating increased susceptibility.
Conclusion: Illicit mining at Noyem and Nyafoman increases heavy metal levels in soils and cassava, affecting environmental quality and public health. The findings support the need for improved regulation of illicit mining, monitoring of soils and crops, and sustainable remediation strategies to protect food security in mining-affected regions of Ghana.

Keywords: Heavy metals; illicit mining; soil-to-crop transfer; bioaccumulation; Ghana.

Introduction

Agriculture is essential for food security, soil resource management, and socio-economic development globally. [1] Soil is the foundation of agricultural productivity, which stores both essential nutrients and potentially toxic elements. [2] Heavy metals and metalloids enter soils naturally through weathering of bedrock; however, anthropogenic activities such as mining, industrial emissions, fertilizer application, and wastewater irrigation are now the dominant sources. [3, 4] Trace elements such as Fe, Mn, Co, Cu, Cr, Ni, Zn, and Mo are required in small amounts for plant, animal, and human metabolism, but at elevated levels they disrupt physiological processes and become toxic.[5,6] In contrast, Pb, Cd, Hg, V, and As have no biological role and are harmful even at very low concentrations, being associated with cancer, organ damage, and neurological disorders.[7] Their persistence and tendency to bioaccumulate make them major contaminants of concern in agriculture. Heavy metals degrade soil quality and reduce crop productivity. More critically, they accumulate in edible plant parts and enter the food chain which later affect the health of consumers. [8]

Globally, an estimated 14–17% of croplands are contaminated with metals such as Cd, Pb, and As which represents hundreds of millions of hectares with the greatest risks occurring in low- and middle-income countries. [9] In Africa, the problem is increasing. Artisanal and small-scale mining (ASM), weak regulation, and poor waste disposal practices are major drivers of soil contamination.[2] Ghana is a clear example: legal and illegal mining activities have increased concentrations of toxic elements in soils and water, threatening food production, environmental health, and livelihoods.[10] The Eastern Region, a major agricultural zone, has been particularly affected.[11] Studies show that soils used for staple and cash crops, including cocoa, are accumulating metals at concerning levels.[12]

Noyem and Nyafoman, communities in the Birim North District, present a clear case of this risk. Years of illicit mining have degraded local soils, yet farmers continue to cultivate cassava (*Manihot esculenta*) which is the district's primary staple crop on these lands. As a root crop in direct contact with soil, cassava readily absorbs heavy metals into its edible tissues. Although food processing methods like boiling can reduce metal concentrations, they may not always lower them to safe levels. [13]

Due to its extensive root–soil interaction, cassava can serve as a useful bioindicator for assessing heavy metal contamination in agricultural soils. However, data on metal accumulation in cassava and the associated dietary health risks in illicitly mined areas of Ghana remain limited. This study therefore aimed to: (1) quantify heavy metal (Cu, Zn, Fe, Hg, and Cd) concentrations in soils and cassava from illicitly mined and control sites at Noyem and Nyafoman; (2) determine soil-to-plant transfer factors; and (3) assess the potential dietary health risks for local communities through dietary exposure analysis. The findings are intended to support food safety monitoring, inform community health risk evaluations, and guide future remediation strategies in mining-affected agricultural zones.

Materials and methods

Study Area

The study was conducted at Noyem and Nyafoman, communities in the Birim North District of Ghana's Eastern Region, located about 130 km northwest of Accra. The district is bordered by Kwahu West to the north, Asante-Akyem South and Amansie East to the west, Birim South to the south, and Atiwa and Kwaebibirim to the east. It lies within the semi-deciduous forest belt, which is characterized by tall trees and evergreen undergrowth. The climate is humid tropical with a bimodal rainfall pattern, supporting both subsistence and cash crop farming. Geologically, the Birim North District is dominated by the Tarkwaian Supergroup, consisting of sandstone, quartzite, phyllite, shale, and conglomerate, with intrusions from the Dixcove Granitoids Complex [14]. The area is well known for its rich gold deposits and has been significantly impacted by illicit artisanal and small-scale mining (galamsey), which has disturbed vast tracts of land. In recent years, farmers have reoccupied some of these degraded lands and resumed cultivation, particularly of cassava (Manihot esculenta).

Sample Collection

Soil Sampling

The study area was divided into three illicitly mined sites, designated as Sites A, B, and C (Fig. 1), where farming activities had resumed after several years of mining abandonment. A total of thirty (30) soil samples were collected from the mined sites, with ten (10) samples randomly taken from each site at a depth of 0–20 cm. Surface litter was removed prior to sampling to obtain a uniform topsoil layer using a hand trowel and spade. In addition, ten (10) soil samples were collected from control sites located far from the mined areas and unaffected by mining activities, which served as reference soils. All samples were placed in clean, labeled zip-lock bags and transported to the laboratory for analysis.

The 0–20 cm depth was selected because it represents the topsoil layer most affected by human activities and is the main root zone for crops such as cassava, making it critical for assessing metal uptake and soil–plant transfer. This depth is commonly used in contamination studies to evaluate bioavailable metals and potential risks to crops and human health.

Cassava Sampling

Cassava tubers were collected from the same plots where soil samples were obtained at Sites A, B, and C, as well as from the control site. From each plot, three to five mature cassava plants were randomly uprooted to ensure representative sampling. The harvested tubers were carefully washed with deionized water to remove adhering soil particles, peeled, and cut into small uniform pieces. The samples were then oven-dried at 70 °C for 48 hours, ground into fine powder using a stainless-steel mill using a 0.5-mm sieve. Cup and blade of the grinding mill were cleaned before each sample. Samples were placed back in the oven and dried again for a constant weight and stored in airtight containers prior to heavy metal analysis.

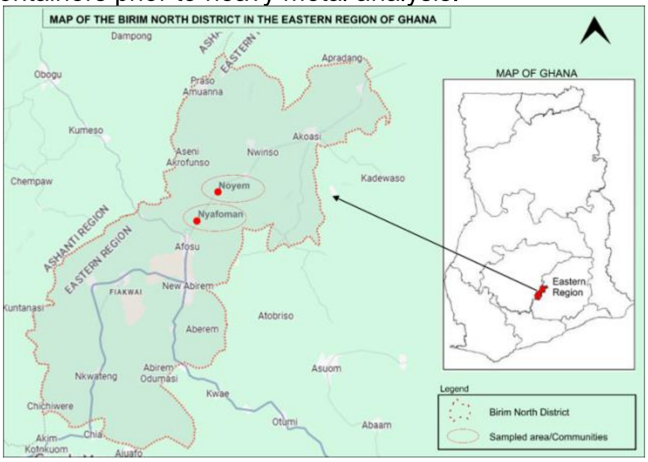

Fig. 1. Soil and cassava sample location at Noyem and Nyafoman within the Birim North District

Plant Identification and Voucher Specimen

Cassava plants (Manihot esculenta Crantz) were collected from Noyem and Nyafoman in the Birim North District of the Eastern Region, Ghana. The species was identified by a botanist from the Department of Agriculture, Kwahu West Municipal Agricultural Office, using visible plant characteristics and standard taxonomic references. Although a voucher specimen was not formally deposited, reference samples were carefully preserved and photographed for record-keeping and verification. The study followed all relevant institutional, national, and international guidelines, including those of the International Union for Conservation of Nature (IUCN) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Manihot esculenta is not listed as a threatened species on the IUCN Red List.

Sample Digestion and Heavy-Metal Analysis

Both Soil and cassava samples were digested following the methods of Motsara & Roy[15]. Soil samples were air-dried, gently crushed, and sieved through a 2 mm mesh prior to analysis. Approximately 0.5 g of soil samples were weighed into digestion vessels. Nine (9) ml of Hcl(conc) and 3ml of HNO3(conc) were then added to the already weighed soil samples in the microwave vessel. The vessel was then closed and placed in a microwave digester. The microwave was turned on for a period of 20 minutes after which digestion was complete. The samples were then removed from the microwave digester and topped up to a volume of 50ml with ultra-pure water (UPW) after the samples have been filtered into a receiving flask of volume 50mls.

Cassava samples (powdered) were digested using a wet-digestion method. About 0.5 g of each powdered cassava sample was weighed into a digestion vessel, and 10 mL of concentrated nitric acid (HNO_3) was added and swirled. The mixture placed on a hotplate in the fumehood and heated, starting at 80–90 °C and then the temperature is raised to about 150–200 °C. Heating continues until the production of red NO2 fumes ceases. The contents are further heated until the volume is reduced to 3–4 ml and becomes colourless, but it should not be dried. After cooling the contents, the volume is made up with the distilled water and filtered through No. 1 filter paper. This solution is used for nutrient estimation.

Estimation of Heavy Metals using the Atomic Absorption Spectrometer (AAS)

Heavy metal analysis was carried out following FAO standard procedures. Samples were digested using a Preekem closed-vessel microwave digester and analyzed after calibration with certified elemental standards. Mercury (Hg) was determined using a VGA-77 vapor generation accessory coupled to a Varian Atomic Absorption Spectrophotometer (AAS). Cadmium (Cd) was analyzed using a Graphite Tube Atomizer (GTA) attached to the Varian AAS, while Copper (Cu), Iron (Fe), and Zinc (Zn) were measured using the flame AAS mode.

Quality Assurance and Quality Control (QA/QC)

All reagents used were of analytical grade. Nitric acid (HNO_3), hydrochloric acid (HCl), and hydrogen peroxide (H_2O_2) were from Merck (Darmstadt, Germany), and deionized water was produced using a Millipore Milli-Q system (MilliporeSigma, USA). NIST SRM 2711a Soil was used as a standard reference material, and blank samples were included with all analyses to ensure accuracy. Ten percent of the samples were run in duplicate, with recoveries ranging from 90–105%. Detection limits were calculated as three times the standard deviation of blank readings.

Data Analysis

Descriptive statistics (mean, standard deviation) were used to summarize heavy metal concentrations in soils and cassava tubers. Soil–cassava transfer factors (TF) were calculated as the ratio of metal concentration in cassava tubers to that in soil. Pearson's correlation analysis was conducted to assess relationships between soil metal concentrations and cassava uptake. All statistical analyses were performed using SPSS version 20.0, with significance set at $p < 0.05$.

Evaluation of Cassava as a Biomarker of Soil Metal Contamination

To evaluate cassava's potential as a biomarker of soil metal contamination, soil and tuber samples were strictly paired at the plot level to ensure direct comparability. Only soil pH and selected heavy metals (Cu, Zn, Fe, Cd, and Hg) were analyzed in both in both matrices.

Transfer factors (TF) were computed as the ratio of metal concentration in cassava tubers (mg/kg, dry weight) to that in the corresponding soil sample. Pearson's correlation and linear regression analyses were conducted to assess relationships between soil and cassava metal concentrations. Results were interpreted with respect to soil pH and metal speciation to determine cassava's reliability as a bioindicator of localized contamination in post-mining soils.

Estimation of transfer factor (TF)

The transfer factor (TF) quantifies the extent to which plants absorb heavy metals from soil [16] It is expressed as the ratio of the concentration of a given metal in plant tissue to its concentration in the corresponding soil sample:

$$TF = \frac{(Conc.\ of\ heavy\ metals)_{plant}}{(Conc.\ of\ heavy\ metals)_{soil}}$$

Where C_{plant} is the concentration of a metal in cassava tubers (mg/kg), and C_{soil} is the corresponding soil concentration (mg/kg). A TF value greater than 1 indicates that the plant acts as a hyperaccumulator, while a value less than 1 suggests low accumulation capacity.

Soil–Plant Heavy-Metal Correlation

Pearson's correlation coefficient ® was calculated to evaluate the relationship between heavy metal concentrations in soils and the corresponding uptake in cassava tubers. This analysis allowed assessment of whether the levels of metals in soils significantly influenced accumulation in the edible parts of the crop. [17]

$$R = \frac{n\sum xy - \sum x \sum y}{\sqrt{[n\sum x^2][n\sum y^2(\sum y)^2]}}$$

Where x and y were the two variables, plant samples and soil sample, respectively, while n is for the pairs of observed values of these variables.18

Estimation of consumption exposure and associated health risk

Human exposure to heavy metals through cassava consumption was assessed using the Estimated Daily Intake (EDI), which represents the average daily intake of metals per unit body weight. The EDI was calculated using the formula:

$$\mathrm{EDI} = \frac{\mathrm{C \times dIR}}{\mathrm{BWa}}$$

Where C is the metal concentration in cassava (mg/kg), IRIRIR is the daily ingestion rate derived from annual cassava consumption, and BW is the average body weight.

The annual consumption of cassava-based foods was assumed to be 154 kg/person/year for adults and 120 kg/person/year for children, corresponding to daily intakes of 0.422 kg/day and 0.329 kg/day, respectively.19 Average body weights of 70 kg for adults and 15 kg for children were used.

To evaluate potential health risks, the Risk Index (RI) was computed as:

$$RI = \frac{EADI}{R_f D_o}$$

Where $R_f D_o$ represents the oral reference dose for each metal (mg/kg/day), as recommended by the United States Environmental Protection Agency.20 Metals analyzed (Cu, Zn, Fe, Cd, and Hg) were selected for their environmental relevance in gold-mining regions and potential toxicity to humans 21 22

Results

Soil Characteristics and Heavy Metal Concentrations

The physicochemical characteristics and heavy-metal concentrations in soils from the Noyem and Nyafoman illicit mined sites and the control site are presented in Table 1. Soil pH values ranged from 5.4 ± 0.15 at the control site to 6.1 ± 0.12 at Site B, which indicates slightly acidic to near-neutral conditions across the study area. Copper (Cu) levels were lowest at Site C (0.144 ± 0.022 mg/kg) and highest at Site A (0.210 ± 0.131 mg/kg), with the control site showing a markedly higher concentration (0.703 ± 0.015 mg/kg). Zinc (Zn) concentrations were elevated across all mining sites, ranging from 38.753 ± 30.98 mg/kg at Site A to 40.337 ± 2.63 mg/kg at Site C, compared with only 2.353 ± 0.015 mg/kg at the control. Iron (Fe) followed a similar pattern, with concentrations between 4.168 ± 0.23 mg/kg (Site C) and 5.452 ± 4.32 mg/kg (Site A), far above the 0.300 ± 0.020 mg/kg measured at the control. Mercury (Hg) levels varied slightly across sites, from 0.033 ± 0.012 mg/kg at Site C to 0.040 ± 0.016 mg/kg at Site A, all substantially higher than the control value of 0.00753 ± 0.00009 mg/kg. Cadmium (Cd) concentrations were also elevated at the mining sites, ranging from 0.050 ± 0.015 mg/kg at Site C to 0.073 ± 0.099 mg/kg at Site A, compared with only 0.000357 ± 0.000021 mg/kg at the control.

Table 1. Mean concentrations of heavy metals in soils from Noyem and Nyafoman area

Parameter	World Reference Values	Control Site (Mean ± SD)	Site C (Mean ± SD)	Site B (Mean ± SD)	Site A (Mean ± SD)
pH	-	5.4 ± 0.15	5.6 ± 0.10	6.1 ± 0.12	5.7 ± 0.09
Cu (mg/kg)	14	0.703 ± 0.015	0.144 ± 0.022	0.151 ± 0.026	0.210 ± 0.131
Zn (mg/kg)	62	2.353 ± 0.015	40.337 ± 2.63	39.210 ± 2.60	38.753 ± 30.98
Fe (mg/kg)	-	0.300 ± 0.020	4.168 ± 0.23	4.382 ± 0.38	5.452 ± 4.32
Hg (mg/kg)	0.1	0.00753 ± 0.00009	0.033 ± 0.012	0.035 ± 0.011	0.040 ± 0.016
Cd (mg/kg)	1.1	0.000357 ± 0.000021	0.050 ± 0.015	0.054 ± 0.013	0.073 ± 0.099

Heavy Metal Concentrations in Cassava

The table below presents the mean concentrations (± standard deviation) of selected heavy metals (Cu, Zn, Fe, Hg, Cd) and pH levels in cassava samples collected from three sites (A, B, and C) within the Birim North District. All results are expressed in mg/kg to allow comparison with international guideline values.

The cassava pH ranged from 6.2 ± 0.4 at Site C to 6.5 ± 0.3 at Site B, indicating slightly acidic to near-neutral conditions. Copper (Cu) concentrations were consistently higher across all sites (0.310–0.339 mg/kg), exceeding the FAO/WHO permissible limit of 0.05 mg/kg. Zinc (Zn) concentrations ranged from 25.1 ± 11.25 mg/kg (Site C) to 30.0 ± 12.58 mg/kg (Site B). While these values were above the European Union (20 mg/kg) guideline, they were still within the FAO/WHO permissible limit of 40 mg/kg.

Iron (Fe) was detected at a uniform concentration of 0.73 mg/kg across sites, although no specific cassava guideline exists for Fe since it is considered an essential micronutrient. Mercury (Hg) concentrations varied between 0.0182 ± 0.0140 mg/kg (Site C) and 0.0218 ± 0.0146 mg/kg (Site B), which were above the Codex Alimentarius limit of 0.01 mg/kg for root and tuber crops. Cadmium (Cd) levels ranged from 0.0187 ± 0.0117 mg/kg (Site C) to 0.0215 ± 0.0099 mg/kg (Site B), remaining below the FAO/WHO permissible limit of 0.1 mg/kg (Table 2). Representative cassava samples collected from the study sites are shown in Figure 2, illustrating the size, appearance, and condition of tubers prior to processing.

Table 2. Mean concentrations of pH and selected heavy metals in cassava samples from different sites

Parameter	Guideline / Reference Value	Control Site	Site C	Site B	Site A
pH	–	6.6 ± 0.2	6.2 ± 0.4	6.5 ± 0.3	6.3 ± 0.5
Cu (mg/kg)	0.05 (FAO/WHO, cassava)	0.25 ± 0.02	0.315 ± 0.033	0.310 ± 0.028	0.339 ± 0.035
Zn (mg/kg)	20 (EU); 40 (FAO/WHO)	18.0 ± 1.8	25.1 ± 11.3	30.0 ± 12.6	26.6 ± 10.4
Fe (mg/kg)	No cassava-specific limit	0.50 ± 0.10	0.73 ± 0.85	0.73 ± 1.15	0.73 ± 0.48
Hg (mg/kg)	0.01 (Codex Alimentarius, root/tuber foods)	0.005 ± 0.001	0.018 ± 0.014	0.022 ± 0.015	0.018 ± 0.014
Cd (mg/kg)	0.1 (FAO/WHO, root/tuber crops)	0.002 ± 0.001	0.019 ± 0.012	0.022 ± 0.010	0.019 ± 0.006

Fig.2. Representative cassava tubers collected from study sites (Noyem and Nyafoman).

Transfer Factors of Heavy Metals from Soil to Cassava

The mean transfer factors (TF) of selected heavy metals from soils to cassava tubers at the three mined sites (A, B, C) and the control site in the Birim North District are presented in the table below. Copper (Cu) TFs were higher at the mined sites (1.61–2.19) compared to the control site (0.36). Zinc (Zn), cadmium (Cd), and mercury (Hg) showed unusually high TFs at the control site (7.65, 5.60, and 0.66, respectively), despite relatively low soil concentrations. This indicates that cassava at the control site may hyperaccumulate Zn and Cd even from soils with low metal content, although small sample size, or analytical variation could also contribute to these elevated TFs. Mercury and iron TFs were within expected ranges (Table 3).

Table 3. Mean transfer factors (TF) of heavy metals from soil to cassava tubers (n=10)

Metal	Control TF	Site C TF	Site B TF	Site A TF
Cu	0.36	2.19	2.05	1.61
Zn	7.65	0.62	0.76	0.69
Fe	1.67	0.18	0.17	0.13
Hg	0.66	0.55	0.62	0.46
Cd	5.60	0.37	0.40	0.26

Correlation Between Soil and Cassava Heavy Metal Concentrations

The Pearson's correlation coefficients between heavy metal concentrations in soils and cassava tubers collected from Noyem and Nyafoman area. Copper (Cu) showed a perfect positive correlation (r = 1.00) as in the table below. This indicates that cassava uptake closely reflected soil concentrations at the sampled sites. However, this exceptionally strong relationship may also be influenced by the limited number of sampling points and the relatively narrow range of Cu concentrations, which can inflate correlation coefficients. Zinc (Zn) exhibited a moderate negative correlation (r = −0.49), which implies that higher soil Zn levels did not consistently result in higher accumulation in cassava. Mercury (Hg) and cadmium (Cd) showed negligible correlations with soil levels (r = −0.02 and r = −0.001, respectively), which indicates minimal influence of soil concentrations on cassava uptake for these metals. Iron (Fe) correlation could not be determined due to identical concentrations in cassava across all sites. These results imply that Cu accumulation in cassava is highly dependent on soil content, whereas Zn, Hg, Cd, and Fe uptake may be influenced by other environmental or physiological factors (Table 4).

Table 4. Pearson's correlation coefficients (r) between soil and cassava heavy metal concentrations

Metal	r (soil vs cassava)
Cu	1.00
Zn	−0.49
Fe	Undefined
Hg	−0.02
Cd	−0.001

Estimated Daily Intake (EADI) and Health Risk Assessment

The potential exposure and health risks from consuming cassava cultivated on illicitly mined soils at Noyem and Nyafoman area were assessed using the Estimated Average Daily Intake (EADI) and the associated Risk Index (RI) for adults and children. The EADI values for all metals were higher for children than adults due to lower body weight. Among the metals analyzed, zinc (Zn) exhibited the highest exposure levels. For children, the RI for Zn exceeded 1 at all sites (Site A: 1.94; Site B: 2.19; Site C: 1.83), indicating a potential health risk. Copper (Cu), iron (Fe), mercury (Hg), and cadmium (Cd) had RI values below 1 for both adults and children, suggesting low risk for these metals under current consumption levels (Table 5).

Table 5. Estimated Daily Intake (EADI) and Risk Index (RI) for Heavy Metals in Cassava

Metal	Site	EADI (mg/kg/day) Adult	RI Adult	EADI (mg/kg/day) Child	RI Child
Cu	A	0.00204	0.05	0.00743	0.19
	B	0.00187	0.05	0.00679	0.17
	C	0.00190	0.05	0.00690	0.17

Metal	Site	EADI (mg/kg/day) Adult	RI Adult	EADI (mg/kg/day) Child	RI Child
Zn	A	0.16033	0.53	0.58301	1.94
	B	0.18082	0.60	0.65753	2.19
	C	0.15129	0.50	0.55014	1.83
Fe	A	0.00440	0.01	0.01600	0.02
	B	0.00440	0.01	0.01600	0.02
	C	0.00440	0.01	0.01600	0.02
Hg	A	0.00011	0.11	0.00040	0.40
	B	0.00013	0.13	0.00048	0.48
	C	0.00011	0.11	0.00040	0.40
Cd	A	0.00012	0.12	0.00042	0.42
	B	0.00013	0.13	0.00047	0.47
	C	0.00011	0.11	0.00041	0.41

Discussion

This research establishes that illicit mining activities in Noyem and Nyafoman have resulted in substantial soil contamination with Zn, Fe, Hg, and Cd, and that this contamination is transferred to cassava tubers, notably with respect to Copper (Cu). This study assessed heavy metal contamination in soils and cassava cultivated in areas impacted by illicit mining activities at Noyem and Nyafoman, Eastern Ghana, using Atomic Absorption Spectrophotometry (AAS) to quantify metal concentrations. Soil-to-crop transfer factors were computed to determine the extent of metal uptake by cassava, and health risk assessments were conducted based on estimated daily intake and hazard indices. The results showed that soils from the mining areas contained increased levels of copper (Cu), zinc (Zn), iron (Fe), cadmium (Cd), and mercury (Hg) compared to the control site. Cassava samples from these areas also showed higher metal concentrations, indicating bioaccumulation from contaminated soils. Transfer factor values revealed that Zn and Cu were more readily absorbed by cassava roots, while the health risk assessment indicated potential non-carcinogenic risks associated with Cd and Hg exposure among individuals consuming cassava grown in the contaminated areas.

The concentrations of Zn, Fe, Hg, and Cd in the illicitly mined soils were significantly higher than those in the control soils. Zn and Fe exceeded control levels but remained below global reference limits, whereas Hg was detected at levels of concern due to its toxicity and persistence. These findings were similar to a recent Ghanaian study that reported mean Hg concentrations in mining soils ranging from 2.20 ± 0.14 mg/kg to 7.46 ± 2.96 mg/kg, with the highest values recorded in areas of active illegal gold mining.[23] The increased Hg levels were associated with its use in gold amalgamation, leaving residues in surrounding soils. Even the control site (Zone C) showed measurable Hg, which is attributed to its volatility and long-range atmospheric transport. This indicates that atmospheric deposition may contribute to background Hg levels even in areas without direct mining activity. Similarly, Awuah and Kyereh reported Hg concentrations between 0.68 mg/kg and 17.03 mg/kg in topsoil from the Amansie West District, with the highest levels observed in small-scale mining communities such as Abodom. [24] These values exceeded the FAO/WHO permissible limit of 0.3 mg/kg by over 50-fold, which confirms the severity of mercury contamination associated with artisanal and small-scale gold mining (ASGM) activities. Collectively, this evidence supports the present study's results, which emphasizes the persistence and intensity of Hg pollution in illicit mining areas such as Noyem and Nyafoman and underscores the long-term environmental impacts of uncontrolled mining practices.

The soil–plant transfer analysis revealed that cassava takes up metals differently depending on the element. Copper showed a very strong correlation with soil levels, which confirms that cassava readily accumulates Cu and can serve as a useful biomarker of local soil contamination. Copper is an essential micronutrient actively absorbed by plants, and its uptake is mediated by regulated transport mechanisms that can facilitate proportional accumulation when soil concentrations increase. On the other hand, zinc, mercury, and cadmium showed weak or even negative correlations, which also suggest that their uptake is more limited and influenced by factors like soil chemistry, the plant's physiology, or competition between ions. In addition, the near-perfect Cu correlation may partly reflect the relatively narrow range of soil Cu concentrations and limited sample size, which can statistically strengthen correlation coefficients. This means that while cassava can reliably signal copper contamination, the absorption of other metals is less predictable and depends on the specific conditions of the soil.

The strong positive correlation observed for Cu between soil and cassava mirrors findings in studies such as the copper fungicide soils in Ghana (Bibiani-Anhwiaso-Bekwai), where high input of Cu led to elevated soil levels and correspondingly high plant uptake.[25] Similarly, research in Tarkwa demonstrated higher bioconcentration factors for Cu compared to Hg or Cd, which showed weak uptake into cassava tubers.[26] The weak or negative correlations found for Zn, Hg and

Cd are consistent with the literature and likely reflect lower bioavailability due to soil binding (organic matter, pH), sequestration in non-edible plant parts, or diffuse and less intense sources.[27] Soils with higher organic matter content and slightly acidic to near-neutral pH, as observed in this study, can reduce the mobility of Cd and Hg through adsorption and complexation processes, thereby limiting their transfer into cassava tubers. These factors reduce the strength of the direct soil-plant relationship for those metals.

Cassava tubers from illicitly mined sites contained Cu and Hg at concentrations exceeding FAO/WHO safety limits. The estimated daily intake (EDI) indicated potential health risks from Cu with long-term consumption, while Zn intake posed an even greater concern for children (RI > 1) due to their lower body weight and higher consumption of cassava-based foods. Similar findings have been reported in Ghana, where cassava grown on mining-affected soils showed elevated metal levels, [28] and artisanal small-scale gold mining (ASGM) activities were linked to Hg contamination near processing sites. Market surveys also demonstrate that contaminated cassava products can reach consumers.[29] The increased risk in children is consistent with other dietary exposure assessments in cassava products.[30] These patterns are associated with the strong local contamination sources from mining and agriculture, combined with differences in metal bioavailability with Cu being readily accumulated by cassava, whereas Hg is volatile and often sequestered in soils.

Although Cd levels in cassava were within safety limits, its persistence and potential for bioaccumulation should not be underestimated. Chronic exposure to Cd, even at low doses, is associated with kidney dysfunction and bone damage. [31] The presence of multiple metals, some exceeding safe thresholds, suggests the potential for additive or synergistic toxic effects, which increases health risks for mining communities. [32]

Beyond health implications, heavy metal accumulation also degrades soil fertility and threatens agricultural productivity. [33] The ecological risk assessment, which showed high risk for Zn and Cd, further indicates potential long-term damage to soil ecosystems. From a policy perspective, these findings support the need for stricter enforcement of regulations against illicit mining, routine monitoring of soils and food crops in mining-prone districts, and the promotion of mercury-free gold extraction technologies. Targeted remediation measures, such as soil amendments to immobilize metals and the restriction of food-crop cultivation on highly contaminated lands, could further reduce exposure risks.

Limitations

This study has some limitations. Sampling was limited to soils and cassava from two communities (Noyem and Nyafoman), which may affect the generalizability of the results. Only selected heavy metals were analyzed, while other potentially hazardous elements and organic contaminants were not included. The cross-sectional sampling design did not account for seasonal variations in metal concentrations. Additionally, the dietary risk assessment was based on estimated intake values rather than direct biomonitoring, which may over- or underestimate actual human exposure.

Conclusions

This study showed that illicit mining activities at Noyem and Nyafoman area has resulted in considerable heavy metal contamination of soils, with evidence of transfer into cassava, a major staple crop. Elevated levels of Zn, Cu, and Hg were detected, in some cases exceeding international safety thresholds. The strong transfer of Cu from soil to cassava highlights cassava's sensitivity to soil contamination and its potential role as a bioindicator. Dietary risk assessment revealed that children, in particular, may be exposed to unsafe levels of Zn through cassava consumption, raising public health concerns for communities that rely heavily on this crop.

These findings emphasize the urgent need for stronger regulation of mining practices, consistent monitoring of soil and food safety, and the development of sustainable remediation strategies to limit heavy metal accumulation in agricultural systems. Public health education and community awareness are also critical to reducing exposure and protecting vulnerable populations. Practical follow-up actions should include routine soil and crop testing in mining-affected farmlands, targeted training programs for farmers on safe cultivation practices, and the controlled use of metal-tolerant or hyperaccumulator plant species for phytoremediation prior to food crop cultivation. Addressing these risks is essential for protecting food security, human health, and the long-term sustainability of agriculture in mining-affected regions of Ghana.

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Data availability

The datasets generated and/or analyzed in this study are not publicly accessible but can be made available by the corresponding author upon reasonable request.

Consent for publication

Not applicable

Conflict of interest

The authors declare that they have no competing interests.

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Author contributions

WAO conceived and designed the study, performed data analysis, and drafted the manuscript. EE and SF contributed to the interpretation of data and critically revised the manuscript. All authors read and approved the final manuscript.

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