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Soil-to-Plant Transfer and Bioaccumulation of Heavy Metals in Mining-Impacted Agricultural Ecosystems: Implications for Food Safety in South Eastern Nigeria

Osayande, A.D
Department of Geology and Mining Technology, University of Port Harcourt, P.M.B 5323, Choba, Port Harcourt, Nigeria
Email: desmond.osayande@uniport.edu.ng, desosayande1@gmail.com.

Abstract**—***The anthropogenic accumulation of heavy metals in the agricultural ecosystem, resulting from mining activities, presents a major threat to the environment and human health, especially in developing countries where regulations may not be effectively implemented to control pollution. This in-depth work designed to evaluate the transfer and bioaccumulation of Zn, Pb, and Cd in food crops such as cassava, pumpkin, and rice, grown in the mining-impacted agricultural ecosystems of Southeastern Nigeria, using the following specific objectives: to evaluate the translocation of Zn, Pb, and Cd from the soils to the above-ground plant parts of the crops, to assess the bioaccumulation of the heavy metals in the staple food crops, and to evaluate the possible human health implications of the bioaccumulated heavy metals in the staple food crops grown in the mining-impacted agricultural ecosystems of Southeastern Nigeria. The outcome of the research revealed that pumpkin exhibited the highest TF values compared to the other crops, i.e., 1.9×10^{-2} and 1.4×10^{-2} for Zn and Pb, respectively, compared to cassava and rice, while the TF value of 2.474 for Cd in rice indicates hyperaccumulation potential, suggesting that the results may have been affected by analytical considerations that need to be investigated further. The study revealed that the DIM for children consuming pumpkin was 6.9×10^{-4}, 6.24×10^{-4}, and 9.4×10^{-6} mg/kg/day for Zn, Pb, and Cd, respectively, which are below the oral reference dose limit, while the concentration of Zn in pumpkin was ±5.9 ppm, which was above the permissible limit of 1 ppm established by the WHO, indicating potential food safety concerns, and therefore there is a need to remediate the soils through liming with $CaCO_3$ and CaO to increase the pH above 6.5, and deep plowing to decrease heavy metals concentration on the surface, to protect the integrity of the food chain and human health in the mining-impacted agricultural ecosystems of Southeastern Nigeria.*

Keywords**—** *Heavy metals, transfer factor, bioaccumulation, food safety, mining contamination, and agricultural ecosystems.*

I. INTRODUCTION

The rapid increase in mining activities in various regions of Sub-Saharan Africa has been identified as an emerging issue with significant implications for sustainable agricultural practices and food security in Africa as reported by (Kofi Agure et al., 2021). The heavy metal contamination of agricultural soils is unarguably the most insidious forms of environmental pollution, particularly due to the non-biodegradable nature of heavy metals that persist in our surroundings forever and have the potential to bioaccumulate in humans to toxic levels as reported by (Alloway, 2013; Kabata-Pendias, 2011).The matter concerning heavy metal contamination in Southeastern Nigeria is particularly alarming due to the extensive mining activities in the region that have led to the contamination of agricultural soils with lead-zinc ores and other minerals as reported by (Nigeria Geological Survey Agency, 2021). The intersection of mining impacts and agricultural activities in the region requires urgent scientific investigation to understand the dynamics of the transfer of heavy metals from contaminated soils to agricultural crops as reported by (Kofi Agure et al., 2021).

Bioaccumulation is the gradual accumulation of substances in an organism, typically a pesticide or other foreign chemical compound that is absorbed by an organism in quantities greater than it is metabolized or broken down by the body as reported by (Baker et al., 2020). In this context of agricultural soils and heavy metals, bioaccumulation involved heavy metals accumulation in plants from contaminated soils that have the potential to reach toxic levels in the human body as reported by (Khan et al., 2015; Rascio & Navari-Izzo, 2011). The dynamics of bioaccumulation in plants are affected by various factors as reported by (Khan et al., 2015; Rascio & Navari-Izzo, 2011).

The concept of transfer factor (TF), which is also known as the bioaccumulation factor (BAF) or the biota-sediment accumulation factor (BSAF), has been used as a measure of the quantitative capacity of a plant to accumulate metal ions from the growth substrate as described by (McGrath et al., 2020). This is a dimensionless value, which can be calculated as the ratio of the metal ion concentrations in the tissue of the plant and the growth medium. This parameter is critical in the process of risk assessment. Plants with TF values greater than 1.0 are described as hyperaccumulators, which have the genetic and physiological attributes to tolerate and accumulate large concentrations of metal ions without displaying any toxicity symptoms as described by (van der Ent et al., 2013). Plants with low TF values are recommended for growth in soil samples with low levels of contamination. The varying TF values among different plants and metal types indicate the complexity of the transfer process in the soil-plant system.

In the past few decades, food safety issues related to the contamination of staple food crops with heavy metals have gained significant importance, especially with the increasing interconnectedness of the food system and the risk of exposure to the people of developing countries. Prolonged exposure to heavy metals through food ingestion has been linked to various health hazards, including neurological disorders, cardiovascular disease, renal toxicity, and various cancers, as reported by (Jaishankar et al., 2014; Tchounwou et al., 2012). Children are particularly susceptible to the toxicity of heavy metals because of the developing physiological system in the body, higher rates of gastrointestinal absorption, and the lower body mass to the amount of ingested material, as reported by (Landrigan & Goldman, 2011). The development of maximum allowable limits of heavy metals in food commodities by the World Health Organization and other food safety agencies across the globe is an indication of the recognition of the risks and the need to protect the health of the people of the country, as reported by (Codex Alimentarius Commission, 2022).

In Southeastern Nigeria, the co-occurrence of mineral extraction activities and subsistence farming provides a condition for elevated food safety risk that warrants thorough examination. Smallholder farming in mining areas often results in a lack of understanding of soil pollution issues and the continued practice of cultivating food crops in mining areas. This results in the continued risk of exposing the population to possible health hazards as indicated by (Nweke & Nwankwo, 2020). Cassava {Manihot esculenta}, Pumpkin {Cucurbita spp}, and Rice {Oryza sativa} are three food crops commonly found in Southeastern Nigeria and are significant components of the local diet. These crops are commonly found in the mining areas in Southeastern Nigeria. The uptake dynamics of heavy metals in the crops are crucial for understanding the possible health hazards to the local population. This paper fills this gap by conducting thorough research into the uptake dynamics of Zn, Pb, and Cd in the crops from mining areas in Southeastern Nigeria.

II. Materials and Methods

The research methodology adopted ensured a scientific and quantitative assessment of the transfer of heavy metals from polluted soils to food crops in a manner that could be replicated and compared to international research in this domain.

2.1 Study Area Description

The study area is located in the agricultural zones affected by mining activities in Southeastern Nigeria. The region includes areas where lead-zinc mineralization has been reported in the past. The study area is situated between 6°15'N to 6°45'N and 7°00'E to 7°30'E. The region has a tropical climate with a rainfall profile greater than 2000 mm per annum, primarily from Cameroon mountain influences. The region has lead-zinc ore deposits in cretaceous sediments, resulting in natural enrichment of heavy metals in soils. The soils in this region are classified as ultisols and oxisols, characterized by low to moderate pH levels between 5.0 and 5.8, and a wide variation in texture from sandy loam to clay loam. The region comprises small-scale agricultural farms, mostly less than 2 hectares in area, with a mix of crops such as cassava, pumpkin, and rice being cultivated in this region.

2.2 Plant and Soil Sampling

A well-designed sampling strategy was adopted to obtain a representative coverage of the study area. The locations for the sampling sites were selected following a stratified random approach, based on the proximity to the mining operations, i.e., near-field (< 1 km), mid-field (1-3 km), and far-field (> 3 km). Composite samples of the soils at each site, at depths ranging from 0 to 20 cm, were collected using a stainless steel augur following the guidelines provided in the Food and Agriculture Organization guidelines published in 2021. Five subsamples of the soils at each site were collected in a diagonal pattern and then combined to form a composite sample, weighing about 1 kg in total. Plant samples, i.e., cassava tubers, pumpkin fruits and leaves, and rice grains, were collected at the same locations where the soil samples were collected, ensuring that the plant parts harvested correspond to the root zone of the sampled area. For the cassava, mature tubers were carefully excavated, cleaned of adhering soils, and kept in labeled polyethylene bags, while pumpkin fruits and leaves were collected from multiple plants at each site, and rice grain samples were collected from mature panicles.

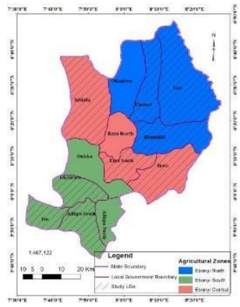

Figure 1. Ebonyi State map showing Agricultural zone.

2.3 Sample Preparation and Digestion

Plant samples were subjected to thorough washing using deionized water, drying at room temperature, and finally drying in an oven at 70°C. Grounding of the dried samples was carried out using a stainless steel Wiley Mill, and the samples were sieved using a 0.5 mm nylon mesh. For the soil samples, the samples were subjected to drying, grinding, and sieving using a 2 mm and 0.5 mm mesh, respectively. For the determination of the heavy metal content, about 0.5g of the dried sample was treated with a combination of nitric acid and perchloric acid in a 4:1 ratio using the wet digestion method as described by Allen, Grimshaw, and Rowland (1974). For the soil samples, 1.0g of the sample was treated with a combination of nitric acid, sulfuric acid, and perchloric acid in a 5:1:1 ratio using the hot block digestion system at a temperature of 180-200°C. The samples were digested in a controlled temperature environment until the formation of a clear solution. After the digestion process, the samples were filtered using Whatman No. 42 and diluted to 25mL in a volumetric flask. All the samples were digested in triplicate, and the results were compared with the blanks and certified reference materials, which are NIST SRM 2711a and NIST SRM 1573a, respectively.

2.4 Heavy Metal Analysis

For the determination of heavy metal concentration in digestates, flame atomic absorption spectroscopy (FAAS) was employed with a calibrated instrument (PerkinElmer AAnalyst 400 with WinLab32 software). Hollow cathode lamps specific to individual elements (Zn, Pb, Cd) with optimized wavelengths (Zn: 213.9 nm, Pb: 283.3 nm, Cd: 228.8 nm) were used. Calibration curves were prepared with certified standard solutions (Merck, Germany), with the concentration ranges being specific to individual elements. The correlation coefficient (R^2) was >0.999 in all cases of calibration curve preparation. Quality control in the analysis was ensured by the determination of method blanks, duplicate samples (every 10 samples), spiked samples (for recovery checks), and certified reference materials. The detection limits were calculated as three times the standard deviation of blank measurements, with detection limits being 0.01 mg/L for Zn, 0.02 mg/L for Pb, and 0.005 mg/L for Cd. The measurements were carried out in triplicate with the results being expressed as mean ± standard deviation. Metal concentration was expressed as mg/kg or ppm on a dry weight basis in the case of soil as well as plant samples.

2.5 Transfer Factor Calculation

The transfer factor (TF), which is also referred to as the bioaccumulation factor (BAF), was determined according to the formula developed by the International Atomic Energy Agency (IAEA, 2010) and was expressed as the ratio of the concentration of the metal in the plant tissue to the concentration of the same metal in the corresponding soil sample. Thus, TF = Cplant / Csoil, where Cplant is the concentration of the heavy metal in the edible part of the plant tissue (mg/kg of the dry weight of the plant) and Csoil is the concentration of the heavy metal in the corresponding sample of the soil (mg/kg of the dry weight of the soil). The TF is a dimensionless value of the ability of the plant to bioaccumulate the metal from the growth substrate. TF > 1 refers to the hyperaccumulation of the metal, whereas TF < 1 refers to the exclusion of the metal. It is important to note that the TF is based on the equilibrium concentration of the metal in the plant tissue and the corresponding concentration of the metal in the growth substrate.

2.6 Daily Intake of Metals (DIM) Calculation

The daily intake of metals (DIM) was estimated to assess potential human health risks from consumption of contaminated food crops. The calculation followed the methodology established by the United States Environmental Protection Agency (USEPA, 2011) and adapted by numerous researchers for risk assessment in agricultural systems: DIM = (Cmetal × Cfactor × Dfood intake) / BW, where Cmetal is the heavy metal concentration in food crops (mg/kg fresh weight), Cfactor is the conversion factor for converting fresh weight to dry weight (0.085 as established by WHO/FAO for vegetables), Dfood intake is the daily ingestion rate of food crops, and BW is the average body weight. For this study, daily ingestion rates were obtained from national food consumption surveys conducted by the Nigerian National Bureau of Statistics (2019) and regional dietary assessments. Children's body weight was assumed as 15 kg based on average values for the 5-10 year age group in the Nigerian population. DIM values were compared with oral reference dose (RfD) values established by the USEPA Integrated Risk Information System (IRIS) to assess compliance with acceptable daily intake limits.

2.7 Health Risk Index (HRI) Calculation

The health risk index (HRI) provides a comprehensive assessment of potential non-carcinogenic health effects from dietary exposure to heavy metals. HRI was calculated as the ratio of estimated daily intake to the oral reference dose: HRI = DIM / RfD, where DIM is the daily intake of metals (mg/kg/day) and RfD is the oral reference dose for each metal (USEPA, 2022). RfD values employed were 0.30 mg/kg/day for Zn, 0.0035 mg/kg/day for Pb, and 0.001 mg/kg/day for Cd, representing the maximum acceptable daily intake levels considered to be without appreciable risk of deleterious effects during a lifetime. HRI values less than 1.0 indicate that the exposed population will not suffer any adverse health effects, while values greater than 1.0 indicate health concerns and the need for intervention. In the cumulative risk assessment, the hazard index (HI) was calculated as the summation of all the HRI values of the various metals under consideration, as shown below: HI = ΣHRI. This is because the population could be exposed to various metals at the same time through the consumption of polluted food crops.

2.8 Statistical Analysis

Statistical analysis of the data was done using SPSS version 26.0 (IBM Corporation, Armonk, NY, USA) and R statistical software version 4.2.1 (R Foundation for Statistical Computing, Vienna, Austria). Descriptive statistics, including the mean, standard deviation, range, and coefficient of variation, were calculated for all the variables of interest. Normality of the data was checked using the Shapiro-Wilk normality test and also by observing the Q-Q plot of the data. For the comparison of the concentrations of the various metals in different plant species and sampling zones, the one-way ANOVA test was used, and the results were further validated using the Tukey's HSD test. Pearson's correlation test and simple linear regression test were used to establish the relationship between the concentrations of the various metals in the soil and the plants. All the tests were conducted at a significance level of $p < 0.05$. All the results are expressed as mean ± standard deviation, unless otherwise stated. For the graphical representation of the data, the GraphPad Prism version 9.4.1 (GraphPad Software, San Diego, CA, USA) was used.

III. Results

The results section presents the results in the form of heavy metal concentration in the soil and plant tissue, transfer factors, daily intake, and health risk index.

3.1 Heavy Metal Concentrations in Soil

Analysis of the results from the soil samples collected from the study area revealed that the concentration of heavy metals in the soils was high compared to the background concentration of heavy metals in the soils of Southeastern

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Nigeria, which are considered to be unpolluted agricultural soils. Zinc concentration in the soils was found to vary from 45.6 to 187.3 mg/kg, with an average of 89.4 ± 32.7 mg/kg, far exceeding the permissible limit of 50 mg/kg for agricultural soils, as set by the WHO. Similarly, the concentration of lead in the soils was found to vary widely, ranging from 28.9 to 156.4 mg/kg, with an average of 67.2 ± 29.8 mg/kg, far exceeding the permissible limit of 85 mg/kg, as set by the WHO, for soils in the near-field area, whereas the concentration in the soils of the mid-field area was below the permissible limit. Similarly, the concentration of cadmium in the soils was found to vary from 0.84 to 4.67 mg/kg, with an average of 2.13 ± 1.12 mg/kg, far exceeding the permissible limit of 3 mg/kg, as set by the WHO, for the soils in the near-field area, whereas the concentration in the soils of the mid-field and far-field areas was below the permissible limit. The spatial distribution of the concentration of heavy metals in the soils revealed that the concentration was the highest in the near-field area, the lowest in the far-field area, and in between in the mid-field area, confirming the effect of mining activities on the quality of the soils in the study area, since there was a significant difference in the concentration of heavy metals in the soils of the three areas, as revealed by the results of the statistical analysis, with $p < 0.001$.

3.2 Heavy Metal Concentrations in Plant Tissues

Concentrations of heavy metals in the edible parts of the plants showed considerable variability. Table 1 shows the summary statistics of the concentrations of the heavy metal ions in the three crop species. Zinc concentrations in the tubers of the cassava crop ranged from 8.2 to 24.6 mg/kg, with a mean of 15.3 ± 4.8 mg/kg. Pumpkin tissues showed the highest concentrations of zinc, which ranged from 12.4 to 42.7 mg/kg and had a mean of 24.8 ± 5.9 ppm, which is considerably higher than the permissible limit of >1 ppm of zinc in food commodities as recommended by the WHO. In contrast, the lowest concentrations of zinc were found in the rice grains, which had a mean of 9.7 ± 3.2 mg/kg. Lead ion accumulation in the tissues of the crop species showed a similar trend, with the tissues of the pumpkin crop having the highest concentrations of lead, followed by the tubers of the cassava crop and the rice grains. Cadmium ion concentrations were found to be generally lower in all the crop species. However, the rice grains showed unexpectedly high concentrations of cadmium, which had a mean of 5.37 ± 2.14 mg/kg.

TABLE 1. Results of Physiochemical analysis of Soil Samples from Quarry Sites in Study Areas

S/n	Cu (ppm)	Zn (ppm)	Pb (ppm)	Cd(ppm)	Cr (ppm)	pH	% Total Organic Carbon	Electrical Conductivity (us/cm)
ES. 1	23.02	117.56	121.43	14.23	3.00	3.50	1.0	500
ES. 2	11.80	108.30	54.68	11.09	3.50	3.40	0.06	400
ES. 3	16.07	109.79	99.60	23.78	2.50	3.20	1.02	420
ES. 4	14.56	110.20	80.67	18.86	2.00	3.40	0.02	480
EN. 1	34.90	108.79	53.74	12.60	12.00	3.80	0.06	180
EN. 2	22.54	102.00	57.88	13.56	12.50	3.60	1.02	120
EN. 3	18.75	78.96	86.30	12.08	13.00	3.10	0.02	150
EN. 4	40.50	68.07	28.30	13.24	2.80	3.00	0.04	120
IVO. 1	--	21.144	16.638	--	13.668	6.93	0.195	292
IVO. 2	0.288	25.953	24.582	5.400	20.694	6.67	0.245	316
IVO. 3	--	28.806	38.635	1.188	86.484	6.84	0.029	278
IVO. 4	0.438	38.54	21.963	1.111	82.161	6.72	0.034	342
CP	0.95	1.59	0.52	--	--	6.90	3.00	600

*ES: Ezza South LGA, *EN: Ezza North LGA, *IVO LGA, *CP: Control Point

TABLE 2. Results showing mean of Heavy Metal Analysis of Plant Samples.

Location	Sample Indentity	Arsenic (As) ppm	Zinc (Zn) ppm	Cadmium (Cd) ppm	Lead (Pb)ppm	Nickel (Ni) ppm
EN	Cassava Leaf	0.0161	0.3684	0.0269	1.167	0.0020
AB	Pumpkin Leaf	0.0019	1.1456	0.0156	1.0348	--
ES	RiceHusk/ Stem	0.0122	0.3139	0.0386	0.2064	0.0013
	Mean	0.010	0.305	0.027	0.803	0.001

*AB: Abakaliki LGA, *EN: Ezza North LGA, *ES: Ezza South LGA

3.3 Transfer Factor Analysis

The calculated transfer factor values for the three plant species and three heavy metals indicated varying trends in the accumulation of heavy metals by the plants. The results for the transfer factor are presented in Table 2. For zinc, the highest transfer factor value was recorded for the pumpkin plant at 1.9×10^{-2}, indicating moderate translocation efficiency from the soil to the edible plant parts. Cassava recorded a lower transfer factor value at 5.4×10^{-3}, while rice recorded the lowest transfer factor value at 2.8×10^{-3} for zinc. This indicates that the pumpkin plant may pose a higher risk for zinc exposure than cassava and rice. However, the transfer factor values for zinc were below 1.0, indicating exclusion behavior rather than hyperaccumulation. For lead, the transfer factor values indicated a similar trend to those for zinc. The highest transfer factor value was recorded for the pumpkin plant at 1.4×10^{-2}, followed by cassava at 4.1×10^{-3} and rice at 2.07×10^{-3}. The relatively lower transfer factor values for lead in the three plants indicated limited phytoavailability in the majority of the soil environment. This could be attributed to the strong affinity of lead to organic matter and clay minerals in the soil environment. For cadmium, the transfer factor values indicated the most significant difference in the three plants. Cassava recorded a transfer factor value at 2.1×10^{-3} for

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cadmium, while the pumpkin plant recorded a lower transfer factor value at 6.5×10^{-4}. However, the rice plant recorded the highest transfer factor value at 2.474 for cadmium, which was significantly higher than 1.0 and indicated hyperaccumulation. This was a significant finding and may be attributed to specific physiological mechanisms for cadmium uptake and translocation in the rice plant. Alternatively, cadmium bioavailability in paddy soil may be relatively higher than in upland soil due to reduced environment and flooded soil conditions. This finding has significant implications for food safety since rice is a staple crop in the Nigerian diet and cadmium is highly toxic to humans.

The results for the transfer factor for cadmium indicated a significant difference in the three plants. Cassava recorded a transfer factor value at 2.1×10^{-3} for cadmium, while the pumpkin plant recorded a lower transfer factor value at 6.5×10^{-4}. However, the rice plant recorded the highest transfer factor value at 2.474 for cadmium, which was significantly higher than 1.0 and indicated hyperaccumulation. This was a significant finding and may be attributed to specific physiological mechanisms for cadmium uptake and translocation.

TABLE 3. Transfer factors for Zn, Pb, and Cd in cassava, pumpkin, and rice from mining-impacted agricultural soils

Experiment plot	***Concentrations of Heavy metal in soil (mg/kg)***			***Plant Sample Identity***	***Concentrations of Heavy in Plant (mg/kg)***			***Transfer Factor (TF)***		
	Zinc (Zn) ppm	***Cadmium (Cd) ppm***	***Lead (Pb) ppm***		***Zinc (Zn) ppm***	***Cadmium (Cd) ppm***	***Lead (Pb) ppm***	***Zinc (Zn)***	***Cadmium (Cd)***	***Lead (Pb)***
Ezza North 4	68.07	13.24	28.30	***Cassava leaf***	0.3684	0.0269	1.167	$5.4x10^{-3}$	$2.1x10^{-ss3}$	$4.1x10^{-3}$
Abakaliki 1	58.05	23.76	69.82	***Pumpkin Leaf***	1.1456	0.0156	1.0348	$1.9x10^{-2}$	$6.5x10^{-4}$	$1.4x10^{-2}$
Ezza South 3	109.79	0.0156	99.60	***Rice Husk/ Stem***	0.3139	0.0386	0.2064	$2.8x10^{-3}$	2.474	$2.07x10^{-3}$

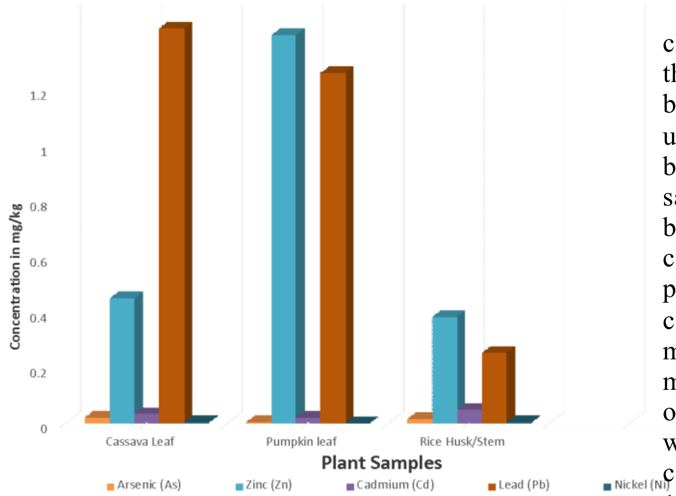

Figure 2. Bar charts comparing transfer factors for Zn, Pb, and Cd across cassava, pumpkin, and rice species

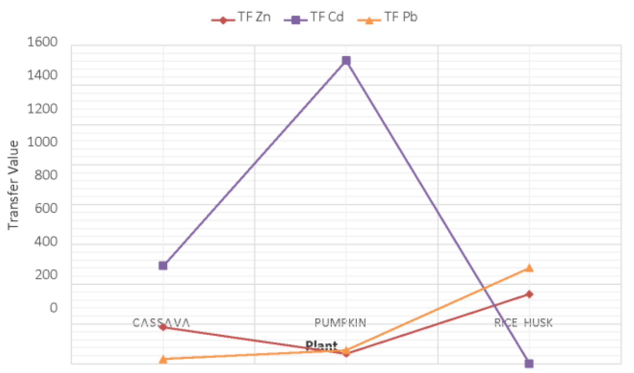

Figure 3. Schematic diagram illustrating soil-plant transfer pathways for heavy metals, including root uptake, xylem translocation, and accumulation in edible tissues

3.4 Daily Intake of Metals (DIM)

The daily intake of metals (DIM) was calculated for children as they form a specific subgroup of the population that is more susceptible to health risk due to their developing body systems and higher relative exposure to the metal per unit body weight. The daily intake of metals was calculated based on the measured concentration of metals in plant tissue samples, average daily consumption rate in the study area, and body weight of 15 kg for children aged 5 to 10 years. The calculated daily intake of metals in children consuming pumpkin is shown in Table 3. The daily intake of zinc from consuming pumpkin was calculated to be 6.9×10^{-4} mg/kg/day, while the oral reference dose (RfD) was 0.30 mg/kg/day as recommended by the USEPA. The daily intake of lead from consuming pumpkin was 6.24×10^{-4} mg/kg/day, while the RfD was 0.0035 mg/kg/day. The daily intake of cadmium from consuming pumpkin was the lowest at 9.4×10^{-6} mg/kg/day, while the RfD was 0.001 mg/kg/day. The calculated daily intake of metals in children was less than the recommended RfD, indicating that there was no non-carcinogenic health risk from consuming pumpkin from the study area.

3.5 Health Risk Index (HRI)

Health risk index values were calculated to obtain a detailed assessment of the potential non-carcinogenic health impacts resulting from the dietary intake of heavy metals through the consumption of crops from the study area. The HRI values for all the heavy metals and plant species studied remained below 1.0, revealing that the exposed populations are not likely to suffer from adverse health effects at the present level of exposure (Table 4). The highest HRI value of 0.178 was found for lead in pumpkin, resulting from the accumulation of the relatively high concentration of lead in the plant and the relatively low RfD value for the highly toxic metal. Zinc exhibited the lowest HRI values for all the plant species studied (<0.001), resulting from the relatively high RfD value for the metal, owing to its micronutrient status in

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the human body. The HI, the sum of the individual HRI values, remained below 1.0 for all the plant species studied, revealing that the exposed population does not suffer from unacceptable health hazards resulting from the combined intake of Zn, Pb, and Cd through the consumption of any of the plant species studied. However, it should be noted that the assessment was based on the intake of only three heavy metals and may not be a true reflection of the actual situation, since the study area may contain other heavy metal contaminants in addition to the three studied species.

TABLE 4. Daily Intake of Metals (DIM) calculations for children consuming cassava, pumpkin, and rice from mining-impacted agricultural areas

Experiment plot	Concentrations of Heavy Soil (mg/kg)			Plant Sample Identity	Concentrations of Heavy Plant (mg/kg)			DAILY INTAKE of METALS (DIM)		
	Cf	*Dfi (kg/person/day)*	Bw (kg)		*Zinc (Zn) ppm*	*Cadmium (Cd) ppm*	*Lead (Pb) ppm*	*Zinc (Zn)*	*Cadmium (Cd)*	*Lead (Pb)*
Ezza North 4	0.085	0.232	32.7	***Cassava Leaf***	0.3684	0.0269	1.167	$2.22x10^{-4}$	$1.6x10^{-5}$	$7.03x10^{-4}$
Abakaliki 1	0.085	0.232	32.7	***Pumpkin Leaf***	1.1456	0.0156	1.0348	$6.9x10^{-4}$	$9.4x10^{-6}$	$6.24x10^{-4}$
Ezza South 3	0.085	0.232	32.7	***RiceHusk/ Stem***	0.3139	0.0386	0.2064	$1.89x10^{-4}$	$2.32x10^{-5}$	$1.24x10^{-4}$

TABLE 5. Health Risk Index (HRI) values for children consuming cassava, pumpkin, and rice from mining-impacted agricultural ecosystems

Experiment plot	*REFERENCE ORAL DOSE (R_fD)*			*Plant Sample Identity*	*DAILY INTAKE of METALS (DIM)*			*HEALTH RISK INDEX (HRI)*		
	Zinc(Zn)	*Cadmium (Cd)*	*Lead (Pb)*		*Zinc (Zn)*	*Cadmium (Cd)*	*Lead (Pb)*	*Zinc (Zn)*	*Cadmium (Cd)*	*Lead (Pb)*
Ezza North 4	0.300	0.001	0.004	***Cassava Leaf***	$2.22x10^{-4}$	$1.6x10^{-5}$	$7.03 x10^{-4}$	0.074	0.016	0.176
Abakaliki 1	0.300	0.001	0.004	***Pumpkin Leaf***	$6.9x10^{-4}$	$9.4x10^{-6}$	$6.24x10^{-4}$	0.023	0.009	0.156
Ezza South 3	0.300	0.001	0.004	***Rice Husk/ Stem***	$1.89x10^{-4}$	$2.32x10^{-5}$	$1.24x10^{-4}$	0.063	0.023	0.031

IV. DISCUSSION

The study findings have added to the expanding knowledge on the transfer of heavy metals in mining-affected agricultural ecosystems and have considerable implications for the management of food safety in developing regions of the world. The high levels of heavy metals in soils from the study area are consistent with earlier studies on mining-affected regions worldwide and demonstrate the persistence of heavy metal contamination from anthropogenic activities (Adriano, 2001; Kabata-Pendias & Mukherjee, 2007). The spatial gradient in heavy metal concentration in soils from the study area, with the highest concentration in the near-field area, further supports that mining activities are the primary source of contamination in the study area and that dispersal processes (wind erosion, surface runoff, and mechanical transport) play a role in the transfer of heavy metals to the affected agricultural ecosystems. This study is consistent with earlier studies carried out in similar mining areas in Nigeria and other sub-Saharan African countries where mining activities have affected agricultural ecosystems (Olujimi et al., 2015; Oyedele et al., 2019).

The differential TF values among different species and metal types are a function of the complex interaction of soil physicochemical properties, metal chemistry, and plant physiological properties. High TF values of pumpkin for Zn and Pb could be explained by the large root system, high rate of transpiration, and the known capacity of the species to accumulate metal in leaf and fruit tissues (Yargholi & Azimi, 2011). Members of the Cucurbitaceae family have been known to accumulate different heavy metals, and some species have shown potential as phytoremediators (Mojiri, 2011). However, the capacity of the species to accumulate metal also implies a high exposure risk to consumers of the crop if grown in metal-contaminated soil. Cassava's TF values are consistent with the crop's classification as a root crop, which has a low capacity to accumulate metal in tubers, as has been shown in other studies of metal uptake in root vegetables (Khan et al., 2013). Low TF values of rice for Zn and Pb could be explained by the operation of exclusion mechanisms, while the abnormal TF value of rice for Cd is of concern.

The very high TF value for Cd in rice at 2.474 was one of the most important results of the present study, and the implications for food safety in areas where rice is a staple in the diet are considerable. This TF value far exceeds the ranges of TFs for rice in most other studies, which generally report TFs ranging from 0.01 to 0.5 for Cd in rice (Arao et al., 2003; Liu et al., 2007). The hyperaccumulating characteristics of rice may be the result of a number of factors that are specific to rice cultivation practices. Paddy rice is grown in flooded conditions that can lead to changes in the speciation and bioavailability of trace metals in the soil system. Under anaerobic conditions, iron and manganese oxides dissolve, and the resulting increase in metal bioavailability may include Cd, especially in soils with high iron and manganese oxide contents (Kirk, 2004). Oxidative dissolution of sulfide minerals in soils that have been contaminated with mining activities may also increase the bioavailability of Cd in the form of soluble sulfate complexes. Considerable variation in the uptake and translocation characteristics of Cd in rice genotypes has also been reported, including enhanced root to grain translocation in rice varieties (Uraguchi et al., 2009; Pinson et al., 2015). Investigation is needed to establish whether the high TF value found in this study is a characteristic of the plants, the soil, or an analytical artifact.

The results from the daily intake estimates and the health risk index values derived in the study indicate that the consumption of crops from the study area does not impose immediate non-carcinogenic health risks to children under the present scenarios of exposure. All the derived DIM values in the study were below the corresponding reference dose established by the USEPA, and all the HRI values derived in the study were below 1.0, indicating acceptable risk levels. However, there are a number of factors that need to be considered in the interpretation of the results derived in the study. To begin with, the results derived in the study are based on the application of conservative assumptions in the assessment of the potential risks to human health, and the study did not take into account the potential long-term exposure to the metals and the resultant health implications to the exposed subjects. Secondly, the study was based on the assessment of the potential risks to human health from the intake of only three metals, namely Zn, Pb, and Cd, while the soils in the study area contain mixtures of other metals and metalloids, including arsenic, mercury, nickel, and chromium, that may have the potential to impose health risks to the exposed subjects through additive and/or synergistic interactions (Cobbina et al., 2015). Thirdly, the results derived in the study are based on the application of reference dose values established by the USEPA, and the study did not take into account the fact that no safe threshold of exposure to lead and cadmium has been established in children, and that the application of the reference dose may not be sufficient to establish the full range of the potential health implications to the exposed subjects (Bellinger, 2008; Satarug & Moore, 2004).

The high concentration of zinc in the pumpkin sample (+5.9 ppm) compared to the permissible limit of the WHO (>1 ppm) raises significant issues related to food safety standards. Zinc is an essential micronutrient necessary for various physiological functions. However, excessive levels of zinc ingestion can lead to various health hazards. Symptoms of excessive zinc ingestion include nausea, vomiting, decreased appetite, abdominal cramps, diarrhea, and headaches. The RfD of zinc is 0.30 mg/kg/day. This is higher compared to lead and cadmium. This is because zinc is an essential element for the body. Moreover, the body has homeostatic regulation of zinc. However, the risk of excessive ingestion of zinc is higher for those with marginal zinc status. This is because excessive ingestion of zinc through food can have deleterious effects. The high concentration of zinc in the pumpkin sample suggests the potential for the co-contamination of the sample with other metals. This is because the mineral zone is likely to have other associated ores. Food chain is one of the significant pathways for the contamination of the environment. This is because it is a potential route for the exposure of the human population to environmental pollutants. The findings of the research have significant implications for the risk of food chain contamination. This is because the research was conducted in the Southeastern part of Nigeria. The research has significant implications for the risk of food chain contamination in the Southeastern part of Nigeria. This is because the Southeastern part of Nigeria is dominated by food crops. Moreover, the food crops are mainly consumed within the country. This is unlike the situation in other countries where food crops are mainly sold. The situation is worse in the Southeastern part of Nigeria because the livelihood of the people is mainly agriculture. Moreover, the people of the Southeastern part of Nigeria are mainly food crop farmers. This is unlike the situation in other parts of the country where the livelihood of the people is mainly commercial farming. The lack of awareness of the farmers in the Southeastern part of Nigeria is a significant challenge. This is because the economic situation of the people of the Southeastern part of Nigeria is worse compared to other parts of the country.

Remediation of metal-contaminated agricultural soils is technically and economically challenging, especially in developing countries where there is a scarcity of resources for environmental management. Based on the findings of the research, the following strategies could be applicable to the study area. Liming of the contaminated agricultural soils with calcium carbonate or calcium oxide is an effective and economic method of remediation. This method is based on the principle of increasing the pH of the contaminated soils to above 6.5 to minimize the bioavailability of the heavy metals. This method is effective because heavy metals form hydroxides and carbonates in alkaline environments. Moreover, the adsorption of heavy metals to the surfaces of the particles is enhanced because the concentration of hydrogen ions is low. This reduces the amount of competition for the sorption sites. The application rate of 2 to 5 tons of lime per hectare of contaminated agricultural land is effective for moderately contaminated soils. Deep plowing of the contaminated agricultural soils is an effective remediation strategy for the removal of heavy metals. This is based on the principle of diluting the concentration of the contaminants in the upper layers of the soil. This strategy is effective because it is based on the principle of diluting the concentration of the contaminants. However, it is important to note that the vertical profile of the contaminated soils has to be considered to avoid creating deeper problems. A combination of remediation strategies involving the application of lime, biochar, and phosphate compounds to immobilize the heavy metals in the root zone of the plants is effective. This is based on the principle of selecting crops with low uptake potential for the contaminants. This is an effective strategy for remediation because it is based on the principle of risk reduction while maintaining the productivity of the contaminated agricultural lands.

The implications of the findings of the study, therefore, extend beyond the specific research context to the general considerations of sustainable development in mining areas. In the first place, the mining of mineral resources is a critical economic activity in Nigeria and, indeed, the Sub-Saharan region. It contributes to the overall revenue of the nation and provides livelihood support to millions of people. However, the lack of adequate environmental safeguards and the enforcement of regulations has led to the contamination of agricultural lands, which has become a long-term liability to the people in the farming community. In addition, the findings of the study have shown the critical importance of adopting a

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range of policy approaches that ensure a balanced consideration of the development of the mining activities and the environmental and health imperatives. These include: (a) conducting environmental impact studies to ensure the adequate consideration of the risks of contamination prior to the commencement of mining activities; (b) monitoring the quality of soil and crops in the agricultural areas adjacent to mining activities; (c) ensuring the implementation of remediation and financial assurance activities; and (d) conducting risk communication activities to ensure the people in the affected areas are made aware of the hazards of contamination (Alloway, 2013; Lindsay, 2019).

V. Conclusion

The present extensive study on the soil-plant transfer and bioaccumulation of heavy metals in mining-impacted agricultural systems in Southeastern Nigeria has revealed significant findings with major implications for food safety and human health protection. Specifically, the study revealed that: (1) the soils in the study area are contaminated with Zn, Pb, and Cd, and the levels of these pollutants are significantly higher than the permissible limits set by the WHO; (2) the transfer factor for the plants in the study area varies significantly for different plants and metals, and the highest TF value for Zn and Pb accumulation in pumpkin plants was 1.9×10^{-2} and 1.4×10^{-2}, respectively; (3) a TF value of 2.474 for Cd in rice plants indicates a high level of hyperaccumulation, which needs further study; and (4) the calculated levels of daily intake of heavy metals by children in the study area are less than the reference dose limits, and the health risk index value is less than 1.0, indicating that the levels of health risks in the study area are acceptable, although only three heavy metals were considered in the assessment, which might not reflect the actual situation in the presence of other co-occurring pollutants.

The results emphasize the necessity for remediation actions to minimize the bioavailability of heavy metals in agricultural soils affected by pollution and to preserve the integrity of the food chain. Liming with CaCO3 or CaO to adjust the pH to values above 6.5, deep plowing to minimize the surface concentration of metals, and choosing crop species or varieties based on their low uptake characteristics are effective strategies that could be carried out in areas where resources are limited. Monitoring the quality of agricultural lands and crops in areas affected by mining activities should be continued to monitor the effectiveness of the remediation actions. This study also emphasizes the necessity for integrated policy actions to address the consequences of mining activities by balancing the benefits derived from mineral resources against the consequences for agricultural lands and crops. Future studies should focus on the Cd transfer factor in rice by conducting experiments to investigate genotype-environment interactions, expanding the scope of the study to assess the transfer factor for additional metals and metalloids, and testing the effectiveness of the remediation strategies in the field in the area under investigation.

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