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Environmental and health risk assessment of cadmium, zinc, iron, copper in crops and soil at Enugu State dumpsite

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Abstract

Contamination of soils and food crops around the Ugwuaji dumpsite in Enugu State, Nigeria was evaluated. Zinc (Zn), copper (Cu), iron (Fe), and cadmium (Cd) were determined in seventy-three (73) samples, which included pre-planting and post-harvest soils, control soils, ash from the New Artisan abattoir, and edible parts of *Dioscorea bulbifera*, *Zea mays*, and *Telfairia occidentalis*. Samples were digested with aqua regia and analyzed using atomic absorption spectrophotometry (AAS). The analytical recovery was 96% with a relative standard deviation (RSD) of 5.7%. Soil properties showed pH values between 5.2-6.7 (slightly acidic), cation exchange capacity (CEC) of 8.7-14.5 cmol/kg, and organic matter contents of 1.84-3.92%. Post-harvest soils recorded 11.33 ± 2.51 mg/kg higher concentrations of Zn and 4.64 ± 0.69 mg/kg of Cu compared to control soils, while Fe decreased to 735.47 ± 73.20 mg/kg. Cadmium was detected in one soil sample (1.14 mg/kg) and in *T. occidentalis* (0.02-2.03 mg/kg), but was not detected in *D. bulbifera* and *Z. mays*. Pollution indices revealed high Cd contamination with enrichment factor (EF $>$ 10), geoaccumulation index (Igeo $>$ 2), contamination factor (CF $>$ 6), and a pollution load index (PLI) of 1.65. The bioconcentration factor (BCF) of Zn in *T. occidentalis* was 3.98 with a translocation factor (TF) of 1.87, showing strong accumulation. Estimated daily intake (EDI) and total hazard index (THI) for adults were low (0.00042-0.00057), while children showed high THI values of 4.28 for *Z. mays* and 4.54 for *D. bulbifera*. Structural equation modeling indicated that soil pH (β = -0.62) influenced Cd mobility and its accumulation in *T. occidentalis* (β = 0.58), contributing to child-specific health risk (β = 0.79). These results highlight the need for risk control measures, including regulated ash application and crop-specific monitoring in waste-affected farmlands.

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1. Introduction

Lack of stringent environmental regularization and persistent accumulation of heavy metals due to increase urbanization and industrialization have significantly contributed to the recent increase of toxic metals and chemicals in the environment. Ayejoto *et al.* [1], Uchechukwu *et al.* [2] and Karunanidhi *et al.* [3] reported that metal mining, smelting, waste incineration, disposal of untreated pharmaceuticals, use of herbicides and indiscriminate waste disposal are the cause of rapid increase of toxic pollutants in the air, soil, and water. Toxic metals have

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been found to be non-biodegradable [4], bio accumulative in organism [5] and persistent in soils for long time [6] posing serious environmental hazards.

Nigeria and other developing countries in Africa have faced proliferation of illegal waste disposal problem caused by lack of inadequate waste disposal management technique. Most waste are often thrown into moving water or urban runoff systems when is raining, thereby enriching the environment with toxic leachates including heavy metals, herbicides and persistent organic particles that are non-biodegradable. Poor regulation of waste dumping sites also contributes to increase of heavy metals pollution of the soil, water, air and crops around the dumpsites [7, 8]. Ugwuaji and Ugwuonyeama refuse dumpsite in Enugu State, Nigeria, is one of many unregulated dumpsites at the urban and local area receiving high concentration of agricultural and industrial waste. Soil as a primary recipient of the waste becomes enriched with toxic chemical and heavy metals such as zinc, copper, iron and cadmium. Many local farmers often cultivate edible crops around the toxic laden soil and unknowingly sell the metal enriched crops to the general public [9].

Olasunkanmi *et al.* [10] and Gopi *et al.* [11] reported that while Zn, Cu, and Fe are part of the essential nutrients for enzymatic and physiological function in both plant and humans, their accumulation can block cellular processes, effect photosynthesis and subsequently compromise crop yields by causing deficiency in plants. Lala *et al.* [12] reported that Cd is a high toxic non- essential metal linked to renal dysfunctions, abnormalities of lungs function, kidney damage and carcinogenic in humans. Excessive contamination of soil used for agricultural purposes by these pollutants leads to metal uptake by food crops through mass flow or diffusion and interceptions [13]. Common crops that have high bioaccumulative with biomagnification potentials are aerial yam (*Discorea bulbifera*), carrots, potatoes, maize, lettuce, and fluted pumpkin (*Telfairia occidentallis*). These crops dietary staples in both local and urban communities at Southeastern compromising of Enugu, Anambra, Imo, Abia and Ebonyi State, Nigeria and serves as critical components of local food [14–16].

Several reports show that there's accurately study risk associated with heavy metals exposure to human, it is necessary not only to measure elemental concentration in crops and soil but to apply comprehensive assessment framework that goes beyond basic study [17, 18]. In this study, extensive methodology that was employed include: (a) Physicochemical analysis of soil to understand effect of cation exchange capacity, organic matter and pH on mobility and retention. (b) Determination of elemental concentration using atomic absorption spectrophotometer. (c) Pollution indices analysis. (d) Multivariate statistical analysis. (e) Human health risk analysis. This analysis provides knowledge of both ecological and health related risks for a nuanced interpretation of data. This study is significant in several ways; (1). It addresses a major environmental health gap in Enugu State by focusing on an under investigated and populated communities. (2). It Integrate human health modeling, food safety and soil quality assessment within a single analytical framework that aligns with one health concept advocated by WHO [19], United Nation Environmental Programme (UNEP) and Food and Agricultural Organisation (FAO) [19]. (3). It Provides current knowledge on the extent of pollution and potential pollution transfer pathways. The aim is to study the health implication of heavy metals in soil and commonly consumed crops cultivated around Ugwuaji dumpsites in other to provide a scientific bases for environmental and crops management policies.

2. Material and methods

2.1. Study area and sample collection

The study was carried out at the Ugwuaji dumpsite in Enugu State, Nigeria 1. The site receives municipal solid waste, abattoir ash, and agricultural residues. Farming activities are practiced around the dumpsite where edible crops are cultivated for local consumption.

2.2. Sample collection

2.2.1. Soil samples

Seventy-three (73) samples were collected in total, including pre-planting soils, post-harvest soils, control soils, crop tissues, and abattoir ash. Soil samples were collected from the experimental plots before planting and after harvest, together with control soils obtained from a non-contaminated site at 5 km away. Samples were taken at 0-20 cm depth using a stainless-steel auger, air-dried, ground, sieved to 2 mm, homogenized, and stored in pre-cleaned polyethylene bags.

2.2.2. Crop samples

Two staple crops (*Zea mays* (maize) and *Dioscorea bulbifera* (aerial yam)) were planted on the study plots at the dumpsite. At maturity, twelve (12) composite samples of maize grains and aerial yam tubers were harvested from each quadrant of the plots, giving a total of twenty-four (24) composite crop samples. Each composite was formed from five randomly selected plants. In addition, fresh leaves of *Telfairia occidentalis* (fluted pumpkin), which naturally grows on the dumpsite, were collected (5 g per sample). All harvested samples were placed in sterile polyethylene bags and transported to the laboratory for processing.

2.2.3. Ash samples

Two ash samples were collected from the New Artisan abattoir, where they are traditionally used for seed treatment and bird-scaring. One ash sample was included in the analysis of metal content.

2.2.4. Sample digestion and metal analysis

Soil (10 g), maize grains/tubers (10 g), *T. occidentalis* leaves (5 g), and ash (5 g) were digested using aqua regia (HNO_3: HCl = 1:3 v/v), following the procedure of Ajah *et al.* [6] with slight modifications. The mixtures were heated on a hot plate until clear fumes were obtained, cooled, filtered through Whatman No. 42 filter paper, and diluted to 100 mL with deionized water. Concentrations of Zn, Cu, Fe, and Cd

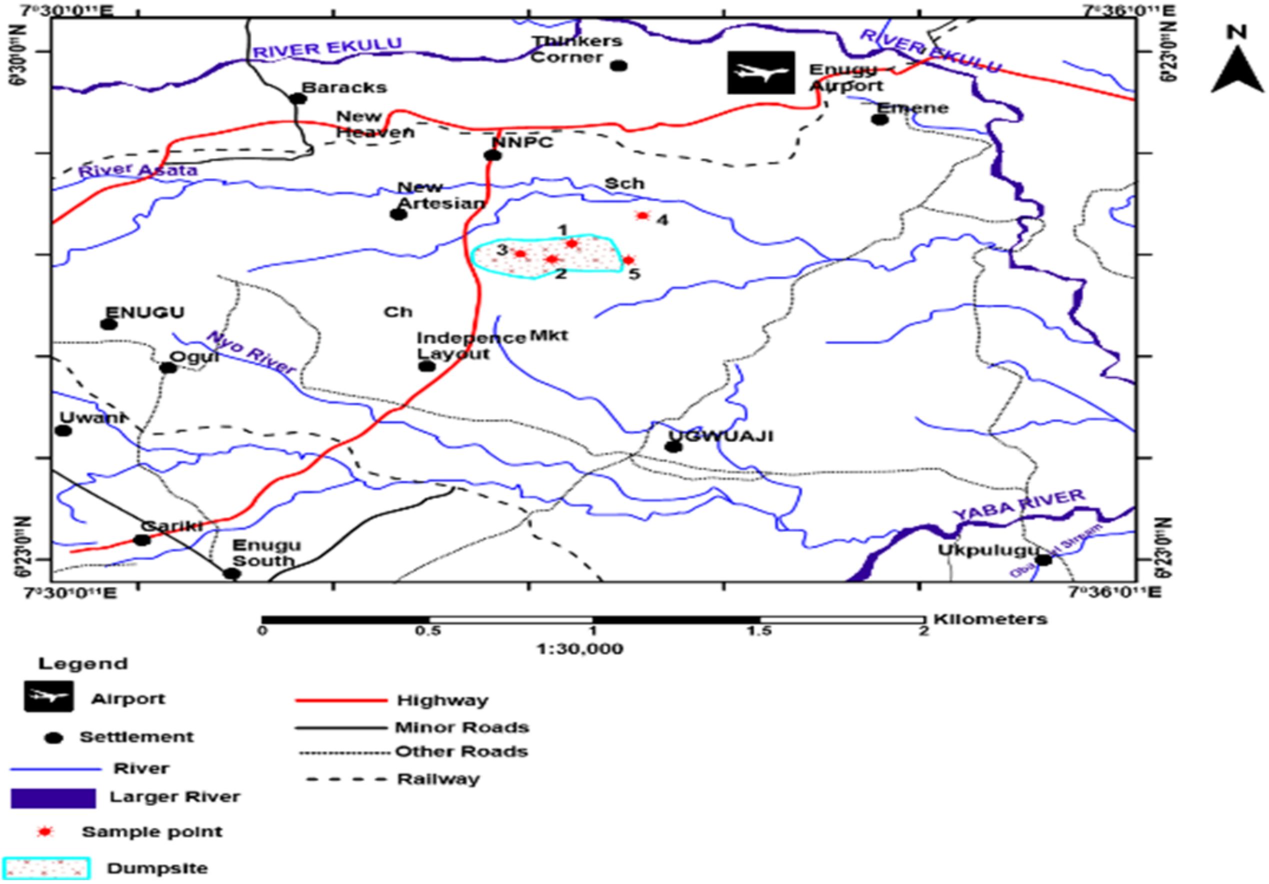


Figure 1: The study area at Ugwuaji dumpsites surrounding agricultural fields in Enugu State.

were measured using an Atomic Absorption Spectrophotometer (AAS, Shimadzu AA-7000) following standard procedures. Calibration was performed with certified reference standards, and blanks and duplicates were included to ensure analytical accuracy.

2.3. Physicochemical properties of soil

Parameters such as pH, electrical conductivity (EC), organic matter (OM), cation exchange capacity (CEC), and soil texture were determined following FAO soil analysis guidelines [6, 20].

2.4. Quality control and assurance

Recovery studies were conducted by spiking known 2 ppm and 4 ppm concentrations of metals into selected samples. Percent recovery was calculated using Equation (1):

$$\%\ \text{Recovery} = \frac{(a-b)\times 100}{c}, \tag{1}$$

where a is metal concentration in spiked sample, b is metal concentration in unspiked sample, c is amount of metal added. Analytical recovery averaged 96%, with a relative standard deviation (RSD) of 5.7%.

2.5. Pollution indices

Pollution indices were used to evaluate metal contamination severity and source:

Enrichment Factor (EF):

$$EF = \left(\frac{\frac{C_i}{C_{ref}}}{\frac{B_i}{B_{ref}}}\right). \tag{2}$$

Geoaccumulation Index (Igeo):

$$I_{geo} = \log_2\left(\frac{C_i}{1.5B_i}\right). \tag{3}$$

Contamination Factor (CF):

$$CF = \frac{C_i}{B_i}. \tag{4}$$

Pollution Load Index (PLI):

$$PLI = (CF_1 \times CF_2 \times \ldots \times CF_n)^{\frac{1}{n}}, \tag{5}$$

where C_i is the concentration of the metal in the sample and $\mathrm{B_i}$ is the background concentration (control site).

Table 1: Summary of sample types and quantities collected from the Ugwuaji dumpsite area.

Sample type	Description	Quantity	Collection method
Soil (pre-planting)	4 composite samples labeled A-D	16	4 grab samples × 4 composites
Soil (post-harvest)	Composite samples from same plots after harvest	16	4 composites per plot
Soil (control)	Collected from a nearby uncontaminated site	4	Used as reference sample
Zea mays	Edible crop tissues (grains and stems)	12	Harvested from experimental plots
Dioscorea bulbifera	Tubers and stems	12	Harvested from experimental plots
Telfairia occidentalis	Fresh leaves	12	Collected from dumpsite
Ash	Homogenized samples from 2 abattoir sources	1	Collected for analysis
Total	-	73	-

2.6. *Multivariate statistical analysis*

To identify metal interrelationships and potential sources, the following analyses were conducted using SPSS v17 and Palisade Decision Tools Suite: Pearson correlation matrix, Principal Component Analysis (PCA), and Hierarchical Cluster Analysis (HCA).

2.7. *Human health risk assessment*

2.7.1. *Estimated daily intake (EDI)*

EDI estimates the daily intake of metals via food consumption:

$$EDI = \frac{C \times IR}{BW}, \tag{6}$$

where C is metal concentration (mg/kg), IR is ingestion rate (kg/day), BW is body weight (kg).

2.7.2. *Target hazard quotient (THQ) and hazard index (HI)*

$$THQ = \frac{EF \times ED \times IR \times C}{RfD \times BW \times AT} \times 10^{-3}, \tag{7}$$

$$HI = \sum THQ_i, \tag{8}$$

where EF = exposure frequency (365 days/year), ED = exposure duration (54 years), RfD = reference dose (USEPA values: Cu 0.04, Zn 0.3, Fe 0.7, Cd 0.001 mg/kg/day) [19].

2.7.3. *Cancer risk (CR)*

For cadmium, lifetime cancer risk was calculated as:

$$CR = EDI \times SF, \tag{9}$$

where EDI (mg/kg/day) = $(C \times IR)/BW$, and SF is the carcinogenic slope factor. The slope factor used for Cd was 6.1 $(\text{mg/kg/day})^{-1}$ [19]. Exposure assumptions are: adult ingestion rate IR = 0.1 kg/day, adult body weight BW = 60 kg, child ingestion rate IR = 0.2 kg/day, child body weight BW = 16 kg. These parameter values and the SF are also reported where CR results are presented.

2.8. *Statistical analysis*

All data were subjected to descriptive and inferential statistics using SPSS v17.0. Student's t-test determined significant differences ($p < 0.05$) in metal concentrations before and after planting. Correlation analysis determined relationships among metal concentrations in soil and crops.

3. Results and discussion

3.1. *Overview of sample composition and sampling strategy*

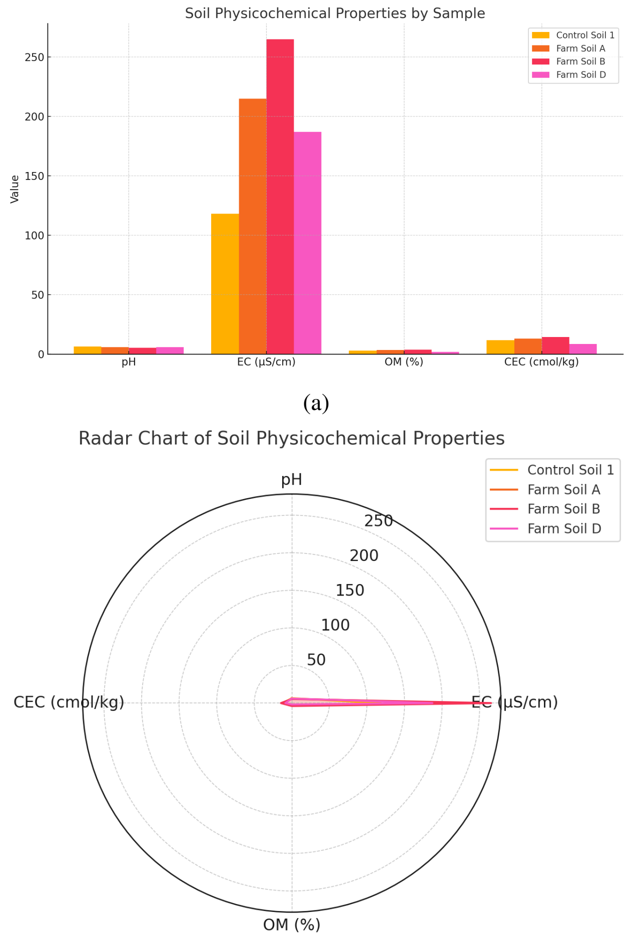
A total of 73 samples were collected and analyzed as shown in Table 1. This included soils (pre-planting, post-harvest, and controls), edible crops (*Dioscorea bulbifera, Zea mays, Telfairia occidentalis*), and ash.

Table 1 provides summary of all samples, description, quantities and method of collection at Ugwuaji dumpsites. The total number of samples analyzed in this study was 73, excluding replicates and blanks used for quality control.

3.2. *Soil physicochemical properties of soil and metal mobility*

Soil characteristics was studied to understand its role in mobilization, adsorption and bioavailability of heavy metals in the soil and plant structure. Result show that soil pH ranged from 5.2-6.7 as shown in Figure 2 indicating slightly acidic conditions, which have the tendency of increasing solubility of Cd and Zn and enhances their mobility towards plant roots [17]. Electrical Conductivity (EC) and Organic Matter (OM) result ranged from 110-265 μS/cm and 1.84% to 3.92% consistent with urban farmed soil with moderate ionic strength and salt presence likely due to ash inputs. Cation exchange capacity CEC result ranged from 8.7-14.5 cmol/kg, reflecting moderate nutrient holding capacity. Soils with moderate CEC can buffer against sudden changes in metal ion concentrations but may also retain pollutants longer. The soils were classified predominantly as loamy sand to sandy loam, with texture influencing water retention and percolation. De-Vries *et al.* [21] and Oyebamiji *et al.* [22] reported that sandy soils are typically more prone to leaching, which may redistribute contaminants vertically or laterally away from roots.

Figure 2(a) presents the comparative distribution of soil physicochemical parameters including pH, electrical conductivity (EC), organic matter (OM), and cation exchange capacity (CEC) in control and farm soils collected from the Ugwuaji dumpsite area. The bar heights reflect distinct variations across samples, with farm soils generally exhibiting higher EC and OM, consistent with ash application. Figure 2(b) shows radar chart of soil physicochemical properties. This radar plot visualizes the multidimensional variation in soil physicochemical properties (pH, EC, OM, and CEC) across selected soil samples from the Ugwuaji dumpsite surroundings. The chart shows that Farm Soils A and B display the highest values for EC and CEC,



(a)

(b)

Figure 2: (a) Bar plot and (b) radar chart of soil physicochemical properties by sample.

suggesting greater nutrient and contaminant mobility potential compared to the control.

3.3. Reliability of analytical results

Ensuring analytical precision when estimating environmental studies and human health risks is important in trace metal studies. Reliability of AAS method used was evaluated. Recovery experiments were conducted on crop samples by spiking known 2 ppm and 4 ppm concentration of metals into representative matrices. According to FAO and IUPAC guidelines [18, 20], acceptable recovery values for trace metal analysis typically range from 70% to 130%, with RSD values under 10% considered statistically robust [18]. In this study, recovery rates result for Cu, Zn, Fe, and Cd fell within 90-128%, and RSD ranged between 4.2% and 6.5%, confirming method reliability. The highest recovery was observed for 128% Fe as shown in Table 2, likely due to its abundance and stable behavior during digestion. Copper also showed strong recoveries of 97-103% and minimal deviation suggesting consistent quantification. Cadmium although more volatile yielded recoveries between 90-97%, confirming the methods sensitivity and matrix compatibility. These results indicate that the AAS technique applied under aqua regia digestion is both accurate and precise.

Table 2: Percent recovery and analytical precision of heavy metals in crop samples.

Metal	Spiking(ppm)	Recovery (%)	RSD	Interpretation
Cu	2.4	97-103	4.2	Acceptable, high accuracy
Zn	2.4	93-98	6.3	Reliable, minimal interference
Fe	2.4	105-128	5.8	Excellent, slightly above 100%
Cd	2.4	90-97	6.5	Consistent within QA standards

Table 3: Mean ± SD of Cu, Zn, Fe, and Cd concentrations in soil, ash, *Zea mays*, *Dioscorea bulbifera*, and *Telfairia occidentalis* samples from Ugwuaji dumpsite area.

Sample Type	Cu	Zn	Fe	Cd
Soil (Control)	2.22 ± 0.75	5.26 ± 2.20	814.40 ± 7.52	ND
Soil (Before Planting)	3.40 ± 0.91	7.28 ± 3.90	803.04 ± 26.76	1.14 ± 0.00
Soil (After Harvest)	4.64 ± 0.69	11.33 ± 2.51	735.47 ± 73.20	ND
Ash	156.81 ± 0.00	42.07 ± 0.00	848.28 ± 0.00	ND
Telfairia occidentalis	2.46 ± 2.95	45.14 ± 13.73	150.02 ± 85.20	0.53 ± 0.85
Dioscorea bulbifera	4.14 ± 3.92	24.90 ± 6.06	107.78 ± 138.15	ND
Zea mays	4.24 ± 3.32	20.90 ± 5.06	101.78 ± 128.15	ND

Table 2 shows percent recovery and analytical precision (expressed as relative standard deviation (RSD)) for copper, zinc, iron, and cadmium in spiked and unspiked crop samples. Recovery rates ranged between 90% and 128%, with an overall average of 96% and mean RSD of 5.7% indicating high analytical accuracy and minimal matrix interference during digestion and AAS determination.

3.4. Heavy metal concentration in soil and crops

Environmental concentration and potential health risk was studied to understand the distribution of Cu, Zn, Fe, and Cd in control soil, pre-planting soil, post-harvest soil, ash used for seed treatment, *Zea mays*, *Dioscorea bulbifera*, and *Telfairia occidentalis*. As shown in Table 3, Cu and Zn concentrations increased from control to post-harvest soils suggesting enrichment from ash and agrochemical use as source of anthropogenic source. Iron levels were consistently high in soils but decreased after harvest implying plant uptake. Cadmium was only detected in one pre-planting soil sample (1.14 mg/kg) and in *T. occidentalis* (0.53 ± 0.85 mg/kg), while *Z. mays* and *D. bulbifera* showed no detectable Cd. These findings confirm localized Cd contamination and a crop-specific accumulation pattern, with leafy vegetables being more susceptible than cereals and tubers.

3.5. Copper in soil

Copper concentrations in control soil as shown from the result in Table 3 and the chart presented at Figure 3 ranged from

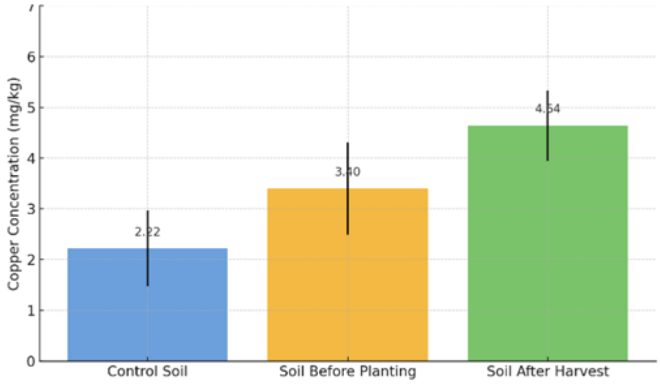


Figure 3: Copper levels in control, pre-planting and post-harvest soils.

1.67 to 3.33 mg/kg with mean of 2.22 ± 0.75 mg/kg, while pre-planting soils recorded 2.39–5.18 mg/kg with mean of 3.40 ± 0.91 mg/kg. Post-harvest soil samples showed increased Cu levels from 3.70-6.07 mg/kg with mean of 4.64 ± 0.69 mg/kg. These values are below international regulatory limits of 150 mg/kg (China EQS) [23] and 70-80 mg/kg by FEPA [20, 24]. The rise in Cu concentration in post-harvest is attributed to anthropogenic inputs from ash amendments. Despite this the values remain within safe limits, indicating minimal ecological risk but T-test result showed p ¡ 0.05 which is significant increase confirming tendency of accumulation over time.

Figure 3 illustrates the mean concentrations of copper (Cu) in control soil, pre-planting soil, and post-harvest soil samples collected from the Ugwuaji dumpsite area.

3.6. *Zinc in soil*

Zinc levels in control soils from the result ranged from 3.73–8.43 mg/kg with mean of 5.26 ± 2.20 mg/kg as shown in Table 3 and Figure 4. Pre-planting soils ranged from 2.75 to 13.17 mg/kg with mean of 7.28 ± 3.90 mg/kg, while post-harvest levels rose to 6.88–15.15 mg/kg with mean of 11.33 ± 2.51 mg/kg. All values remained well below global safety thresholds (300–400 mg/kg) [19]. The Zn increase is attributed to ash inputs, battery waste, and pesticides, consistent with findings from other urban agricultural zones at Anambra and Ebonyi State [6, 17, 25]. A significant statistical difference of p ¡ 0.05 was observed between pre- and post-harvest Zn levels.

3.7. *Iron in soil*

Iron was high in all soils but still within acceptable ranges of 7000–55000 mg/kg, China EQS [23] as shown in Table 3 and Figure 5. Control soils ranged from 805.26 to 823.69 mg/kg with mean of 814.40 ± 7.52 mg/kg. Pre-planting samples showed slightly lower Fe levels of 764.29–845.59 mg/kg with mean of 803.04 ± 26.76 mg/kg while post-harvest levels dropped further from 611.14 to 838.81 mg/kg with mean of 735.47 ± 73.20 mg/kg. The decrease in post-harvest suggests plant uptake and possible leaching with *Dioscorea spp*. known for relatively high Fe translocation [26]. The T-test result confirmed the p ¡ 0.05 decrease was statistically significant.

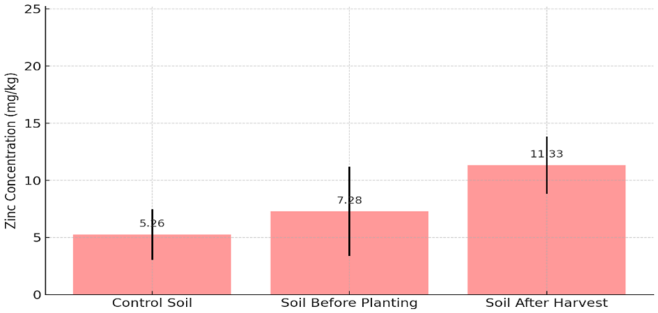


Figure 4: Zinc levels in control, pre-planting, and post-harvest soils.

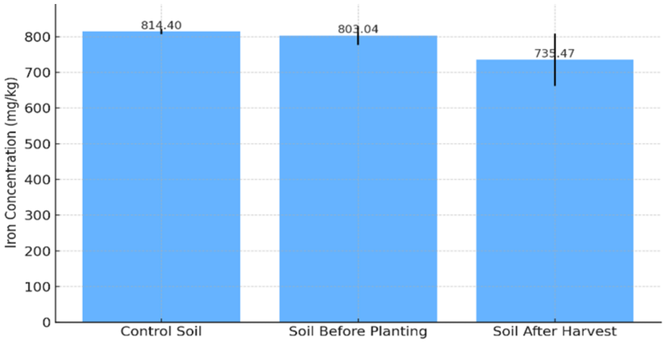


Figure 5: Iron levels in control, pre-planting, and post-harvest soils.

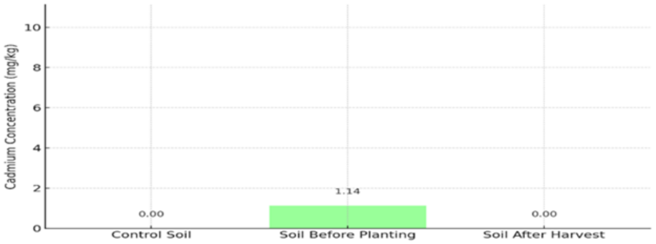


Figure 6: Cadmium levels in control, pre-planting, and post-harvest soils.

3.8. *Cadmium in soil*

Cadmium of 1.14 mg/kg was sparsely detected in soil found only at location A1 before planting as shown in Table 3 and Figure 6. This isolated detection suggests site-specific contamination likely from waste leachates and battery disposal [6, 13]. Though not widespread, the detected value exceeds FAO/WHO guideline values of 0.4-0.8 mg/kg for agricultural soils warranting constant monitoring [20].

3.9. *Metal concentrations in crops*

3.9.1. *Copper and zinc in crops*

Copper levels in *Dioscorea bulbifera* and *Zea mays* shown in Table 4 ranged from 1.84-14.81 mg/kg with mean of 4.14 ± 3.92 mg/kg which is below the FAO/WHO limits of 20 mg/kg and MHPRC limit of 10 mg/kg [27]. Zn ranged from 14.78-32.89 mg/kg with mean of 24.90 ± 6.06 mg/kg which is also

Table 4: Mean ± SD of heavy metal concentrations (mg/kg) in *Dioscorea bulbifera, Telfairia occidentalis* and *Zea mays* collected from the Ugwuaji dumpsite.

Crop Species	Cu	Zn	Fe	Cd
Zea mays	4.24 ± 3.32	20.90 ± 5.06	101.78 ± 128.15	ND
Dioscorea bulbifera	4.14 ± 3.92	24.90 ± 6.06	107.78 ± 138.15	ND
Telfairia occidentalis	2.46 ± 2.95	45.14 ± 13.73	150.02 ± 85.20	0.53 ± 0.85

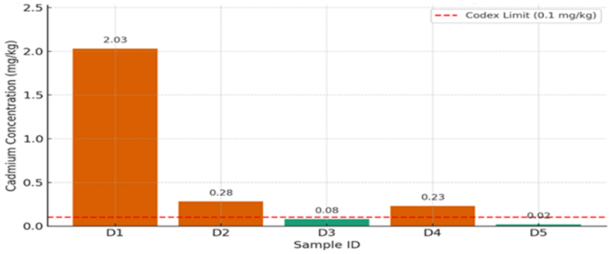


Figure 7: Cadmium levels in *Telfairia occidentalis* compared to Codex limit.

within acceptable limits [11, 20]. Elevated 42.07 mg/kg Zn in *Telfairia occidentalis* with mean of 45.14 ± 13.73 mg/kg may be attributed to ash application, electronic waste, and abattoir ash [6, 28].

3.9.2. Iron in crops

Iron levels in crops showed wide variability as shown in Table 4. The result showed that *Dioscorea bulbifera* and *Zea mays* had Fe concentrations between 0.66-392.35 mg/kg with mean of 107.78 ± 138.15 mg/kg) while *Telfairia occidentalis* Fe concentration ranged from 56.61-300.12 mg/kg with mean of 150.02 ± 85.20 mg/kg. The higher values from the results were typical plant uptake ranges mainly reflecting efficient uptake from Fe rich soils and potential contamination from ash inputs [13].

3.9.3. Cadmium in crops

Cadmium was only detected in *Telfairia occidentalis* with concentrations between 0.02–2.03 mg/kg and mean of 0.53 ± 0.85 mg/kg as shown in Table 4 and Figure 7. The 0.1 mg/kg found levels exceed the Codex Alimentarius guideline [29, 30] especially at D1 which have 2.03 mg/kg likely due to root proximity to contaminated soil as reported by Sanga *et al.* [31]. It can be seen from the result that Cd was not detected in *Zea mays* or *Dioscorea bulbifera*, indicating they are safe for consumption with respect to cadmium.

Figure 7 presents the cadmium concentrations in five samples of Telfairia occidentalis grown near the Ugwuaji dumpsite. The dashed red line indicates the Codex Alimentarius Commissions 0.1 mg/kg maximum permissible limit for cadmium in leafy vegetables. Samples D1, D2 and D4 exceeded this threshold, indicating potential dietary.

3.10. Pollution index assessment

Pollution indices such as Enrichment Factor (EF), Geoaccumulation Index (GeoI), Contamination Factor (CF), and Pollution Load Index (PLI) were studied to gain quantitative knowledge of the extent and origin of metal contamination in soil at Ugwuaji dumpsite area. These indices are critical for serving as base line in distinguishing between natural geogenic contributions and anthropogenic pollution particularly in ecologically sensitive agricultural settings.

The high EF, GeoI, and CF values for Cd were calculated based on its detection in pre-planting soils and crop tissues, although Cd was not detected in bulk post-harvest soils. This suggests that Cd was mobilized from the soil to edible plants during the growing season, even when its residual concentration in soil after harvest was below detection limits.

3.11. Enrichment factor

Effect of anthropogenic activities on Fe, Zn, Cd, and Cu accumulation in soils was evaluated by normalizing metal concentrations against a conservative reference element. Results showed that Cd had EF values > 10 in post-harvest soil samples, which according to Jiang *et al.* [32], Odewumi *et al.* [28], and Ku *et al.* [30], indicates very high enrichment and strong anthropogenic input, likely originating from battery waste, leachates, and abattoir ash. Zinc displayed moderate enrichment with EF values between 3-6, consistent with findings by Osae *et al.* [33], who reported similar Zn enrichment in peri-urban soils due to fertilizers, plastic waste, and electronic residues from leachates. Copper and Fe, on the other hand, had EF values ¡ 2, suggesting they were mainly derived from geogenic sources or represent widespread natural background levels. Overall, the EF analysis confirms Cd as the primary pollutant of concern in the Ugwuaji dumpsite soils.

3.12. Geoaccumulation index (GeoI)

The Geo index compares observed metal concentrations with background values and categorizes pollution into seven classes. In this study, Cd recorded GeoI > 2 classifying soils as moderately to strongly polluted which is GeoI Class 3. This pattern aligns with recent findings by Adu *et al.* [7] who observed similar Cd levels in soils near electronic waste disposal sites in East Africa. Zn GeoI of 0.5–1.8 suggested unpolluted to moderately polluted status. Cu and Fe remained in Class 0–1 confirming low pollution levels. These results substantiate the localized but concerning Cd hotspots compared to broader Zn dispersal from surface applications.

3.13. Contamination factor

Contamination Factor (CF) was used to evaluate the severity of heavy metal contamination in soils relative to background concentrations. Results showed that cadmium (Cd) had CF

Table 5: Pollution index summary for post-harvest soils near Ugwuaji dumpsite.

Metal	EF	Igeo	CF	PLI	Interpretation
Copper (Cu)	2.09	0.53	2.09	—	Moderate enrichment and contamination
Zinc (Zn)	3.56	1.44	2.15	—	Moderately enriched and polluted
Iron (Fe)	0.90	-0.23	0.90	—	Within background levels (no enrichment)
Cadmium (Cd)	—	—	—	—	Not detected in post-harvest soils
Overall	—	—	—	1.65	PLI > 1 indicates pollution

values greater than 6, which is classified as very high contamination. This agrees with findings by Adu *et al.* [7] from urban-agricultural interfaces in West Africa, where open waste dumping contributed to Cd enrichment. Zinc (Zn) and copper (Cu) exhibited CF values between 1.5 and 3.5, indicating moderate contamination. Iron (Fe), however, remained within the background range. These results reinforce that Cd requires urgent environmental attention due to its very high contamination level. Although Zn and Cu contamination is less severe, their moderate values suggest the potential for accumulation over time, particularly with repeated ash applications and continuous cultivation.

3.14. Pollution load index

The Pollution Load Index (PLI) integrates contamination factor (CF) values across multiple metals to provide an overall assessment of soil quality. A PLI value of 1 indicates baseline conditions, while values greater than 1 signify cumulative pollution. As shown in Table 5, PLI values exceeded 1 in most post-harvest soil samples, indicating an overall polluted condition. This confirms the presence of long-term cumulative contamination from the Ugwuaji dumpsite. Similar findings were reported by Neeraj *et al.* [34], who observed PLI > 1 in urban farmlands exposed to mixed waste effluents and cautioned that such conditions may lead to progressive declines in soil productivity and food safety.

Table 5 summarizes the pollution indices for post-harvest soils collected Ugwuaji dumpsite farm. Enrichment Factor (EF), Geoaccumulation Index (GeoI) and Contamination Factor (CF) suggest moderate contamination from Cu and Zn while Fe remains within natural background levels. Cadmium was not detected in post-harvest soil samples. The Pollution Load Index (PLI) value of 1.65 confirms cumulative anthropogenic impact and pollution of the soil environment.

It is important to note that cadmium was not detected in post-harvest soils as shown in Table 5. However, traces of Cd were found in pre-planting soils and accumulated in *T. occidentalis* roots and leaves. This explains why the enrichment factor (EF > 10), geoaccumulation index (GeoI > 2), and contamination factor (CF > 6) highlighted Cd as a contaminant of concern despite its absence in post-harvest soil sample.

Table 6: Pearson correlation coefficients among metals in soil before planting.

Metals	Cu	Zn	Fe	Cd
Cu	1.000	-0.030	0.787	ND
Zn	-0.030	1.000	0.345	ND
Fe	0.787	0.345	1.000	ND
Cd	ND	ND	ND	ND

Table 7: Pearson correlation coefficients among metals in soil after harvest.

Metals	Cu	Zn	Fe	Cd
Cu	1.000	0.071	0.079	ND
Zn	0.071	1.000	0.274	ND
Fe	0.079	0.274	1.000	ND
Cd	ND	ND	ND	ND

Table 8: Pearson correlation coefficients among metals in Dioscorea bulbifera.

Metals	Cu	Zn	Fe	Cd
Cu	1.000	0.031	-0.338	ND
Zn	0.031	1.000	-0.373	ND
Fe	-0.338	-0.373	1.000	ND
Cd	ND	ND	ND	ND

3.15. Statistical and multivariate analysis

3.15.1. Pearson correlation analysis

The result from Soil before planting show that Cu and Fe exhibited an $r = 0.787$ strong positive correlation as shown in Tables 6 - 9 suggesting a shared source such as agrochemical inputs or ash-derived contamination. This is consistent with findings by Adu *et al.* [7] who attributed such correlations to organo-metal complexes in compost amended farm. Soil after harvest from the result showed < 0.3 weak implying differential plant uptake, leaching, or selective retention mechanisms. Zn decoupling from Cu and Fe suggests its mobility may be attributed to pH or CEC variations as supported in research in acidic tropical soils by Li *et al.* [35]. Result from *Dioscorea bulbifera* show an r = -0.338 inverse correlation between Cu and Fe which may reflect competitive uptake at transporter sites in roots, supported by Shahzad *et al.* [36] findings in plant physiology studies on micronutrient antagonism.

Table 6 is the calculated result Pearson correlation coefficients for heavy Cu, Zn, Fe and Cd in soil before planting. The strong positive correlation between Cu and Fe suggests common anthropogenic inputs, likely ash and leachates. Cd was detected in only one sample and thus excluded from correlation.

Table 7 shows correlations in soil after harvest. The weaker correlations across Cu, Zn, Fe and Cd pairs suggest possible redistribution, plant uptake, altered chemical availability after cultivation. Cd remained below detection.

Table 8 presents metal correlation in Dioscorea bulbifera. Weak negative correlations between Fe and both Cu and Zn may

Table 9: Pearson correlation coefficients among metals in Zea mays.

Metals	Cu	Zn	Fe	Cd
Cu	1.000	0.051	-0.438	ND
Zn	0.051	1.000	-0.273	ND
Fe	-0.438	-0.273	1.000	ND
Cd	ND	ND	ND	ND

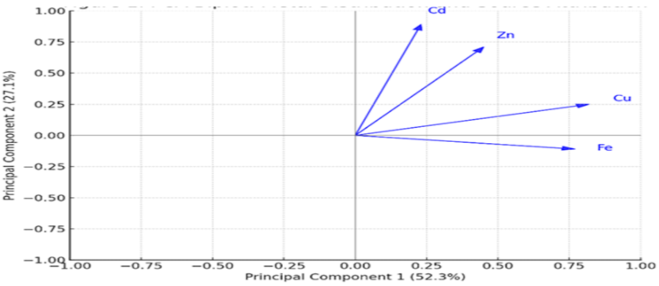


Figure 8: PCA biplot: metal distribution and source attribution.

indicate competitive inhibition or transporter-level antagonism. Cadmium was not detected.

Table 9 shows metal correlations in Zea mays. The moderate negative correlation between Fe and Cu suggests antagonistic uptake possibly due to metal transporter competition. Cadmium was not detected in maize tissues.

3.15.2. Principal component analysis (PCA)

Principal Component Analysis (PCA) was applied to identify possible sources and associations of heavy metals in the soils. Two major components were extracted, explaining 79.4% of the total variance. PC1 (52.3% of variance) was dominated by Cu and Fe, suggesting contributions from leachates, abattoir ash, and possibly mineralized bedrock. Similar associations have been reported in peri-urban soils by Adu *et al.* [7], where poultry manure and pesticide residues contributed to Cu and Fe enrichment. PC2 (27.1% of variance) was strongly influenced by Cd and Zn, indicating inputs from e-waste residues, leachates, and abattoir ash. The co-loading of Cd and Zn implies a co-pollution scenario, which is typical of informal waste disposal sites in sub-Saharan Africa, as reported by Dadebo *et al.* [18]. PCA results suggest two distinct contamination pathways: (i) Cu and Fe from mixed agricultural and ash inputs, and (ii) Cd and Zn from e-waste and leachates, with potential for combined impacts on soil quality and crop safety.

Figure 8 illustrates the loadings of copper, Zn, Fe, and Cd on the first two PC1 and PC2 principal components, which together explain 79.4% of the total variance in metal concentrations.

3.15.3. Hierarchical cluster analysis (HCA)

Hierarchical Cluster Analysis (HCA) was performed to further explore the relationships among the metals and identify possible common sources. The dendrogram shown at Figure 9 grouped the elements into two major clusters. Cluster I included Cu and Fe, which were closely associated with soil ash inputs and mineralized bedrock, reflecting a mixed geogenic-anthropogenic origin. This pattern aligns with PCA findings, where Cu and Fe dominated PC1. Cluster II consisted of Cd and Zn, which clustered together due to their strong co-occurrence in both soil and crop samples. This cluster points to anthropogenic sources such as e-waste residues, abattoir ash, and leachates. Their grouping also explains the elevated Cd and Zn observed in *Telfairia occidentalis*. The HCA results therefore confirm two distinct contamination pathways: (i) Cu and Fe linked to ash and natural background contributions, and (ii) Cd and Zn linked to anthropogenic inputs with greater food safety concerns.

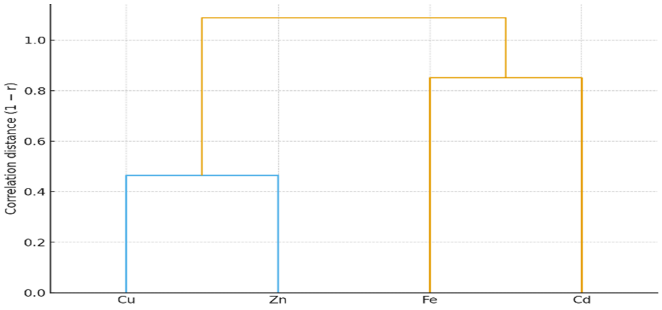


Figure 9: Hierarchical cluster analysis (HCA).

As shown in Figure 9, Cd clusters separately from the other metals, reflecting its distinct behavior in soil–plant transfer compared to Cu, Zn, and Fe.

Dendrogram of heavy metals (Cu, Zn, Fe, and Cd) based on their distribution across soil, ash, and crop samples. Clustering was performed using correlation distance (1 – Pearson's r) and average linkage (UPGMA). The dendrogram reveals similarity patterns among metals, indicating shared pathways of accumulation and mobility in the studied area.

3.16. Cadmium presence and source attribution

Cadmium limited detection but high concentration where present points to site-specific contamination rather than widespread distribution. Its presence in *Telfairia occidentalis* range from 0.02–2.03 mg/kg with mean of 0.53 ± 0.85 mg/kg and one soil sample at 1.14 mg/kg indicates surface contamination and shallow root uptake as leafy vegetables are more susceptible to foliar and rhizosphere level accumulation. No Cd was detected in *Zea mays* or *Dioscorea bulbifera*, supporting studies by Zulfiqar *et al.* [37], which found that deep rooted tubers and cereals may possess biological exclusion mechanisms and limited translocation from soil to edible parts.

3.17. Human health risk assessment

Evaluating the potential health risks associated with dietary exposure to Cu, Zn, Fe, and Cd is important, particularly in an urban agricultural setting affected by discriminate waste disposal. In this study, health risks from consuming *Zea mays* and *Dioscorea bulbifera* cultivated near the Ugwuaji and Ugwuonyeama dumpsite were assessed using standard models endorsed by the United States Environmental Protection Agency

USEPA [24] and Joint FAO/WHO Expert Committee on Food Additives JECFA [19]. The key indices used include Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Total Hazard Index (THI) for a reference adult weighing 60 kg and consuming 0.1 kg/day of crop produce.

3.17.1. Estimated daily intake (EDI) and target hazard quotient (THQ)

Estimated Daily Intake (EDI) values for Cu, Zn, and Fe in *Zea mays* and *Dioscorea bulbifera* were compared against the Provisional Maximum Tolerable Daily Intakes (PMTDI). As shown in Table 10, Cu EDI values ranged from 0.0069–0.0071 mg/kg/day, which are far below the PMTDI of 0.5 mg/kg/day. Zn exhibited EDI values between 0.020–0.025 mg/kg/day, well within the JECFA limit of 1.0 mg/kg/day. Fe recorded the highest EDI, 0.15–0.18 mg/kg/day, but this also remained below the 0.7 mg/kg/day threshold, indicating no immediate dietary concern. Cadmium was not detected in these two staple crops. THQ values for all metals in both crops were ¡1, suggesting negligible non-carcinogenic risk from their consumption. For example, Fe had THQ values of 0.00021–0.00026, which are several orders of magnitude below the risk threshold.

Table 10 summarizes the Estimated Daily Intake (EDI), Provisional Maximum Tolerable Daily Intake (PMTDI), and Target Hazard Quotient (THQ) values for Cu, Zn, Fe, and Cd in Zea mays and Dioscorea bulbifera.

These findings are consistent with Ahmad *et al.* [27], who reported similarly low THQ values for essential metals in crops cultivated on monitored farmland in southern China, and Adewale *et al.* [9], who observed THQ values ¡0.01 for Zn and Cu in maize grown near mixed-use waste sites in Lagos, Nigeria. Together, these results reinforce that metal uptake by staple crops may remain within safe limits in moderately contaminated environments, particularly when soils possess retention mechanisms such as organic matter and clay that reduce metal mobility.

3.17.2. Total hazard index (THI)

The Total Hazard Index (THI) represents the cumulative non-carcinogenic risk of exposure to multiple metals. For *Zea mays*, the THI was 0.00042, while *Dioscorea bulbifera* had a slightly higher THI of 0.00057. Both values are several orders of magnitude below the critical threshold of 1, indicating that adult consumers are not at risk of adverse health effects from these crops in the studied area. However, when child-specific exposure parameters were applied (body weight: 16 kg; ingestion rate: 0.2 kg/day, following USEPA [24] and WHO [19] dietary exposure guidelines for developing countries), the calculated THI values increased sharply to 4.28 for *Z. mays* and 4.54 for *D. bulbifera*. These values exceed the safe threshold, highlighting a substantial risk for children due to their lower body weight and relatively higher consumption rates. This finding calls for urgent public health interventions, including restricting farming around open dumpsites, routine monitoring of heavy metals in locally grown crops, and periodic dietary risk assessment for children in peri-urban farming communities.

3.18. Consideration of cadmium risk

The result shows that cadmium was not detected in either *Zea mays* or *Dioscorea bulbifera*, but it was found in *Telfairia occidentalis* with concentrations up to 2.03 mg/kg. This level is far above the Codex Alimentarius limit of 0.1 mg/kg for leafy vegetables. The presence of Cd in *T. occidentalis* indicates crop-specific accumulation, which may be due to shallow rooting systems and foliar absorption from ash inputs around the dumpsite.

Cadmium is classified by IARC as Group 1 carcinogen, and using the USEPA slope factor (6.1 mg/kg/day^{-1}), the calculated cancer risk values for *T. occidentalis* exceeded the acceptable risk range of 1×10^{-6} to 1×10^{-4}. This shows that regular consumption of the vegetable may expose consumers to long-term carcinogenic effects.

For *Z. mays* and *D. bulbifera*, all THQ and THI values were below 1, showing no immediate dietary risk. This means the staple crops grown around Ugwuaji dumpsite are relatively safe with respect to Cu, Zn, Fe and Cd. The problem remains with leafy vegetables which absorb and transfer Cd more readily. Similar observations were made by Li *et al.* [35], who reported high Cd uptake in leafy crops compared to tubers and cereals in waste-affected soils.

3.19. Cadmium cancer risk (CR)

Cadmium is a recognized human carcinogen [38], and its potential risk was therefore assessed using the USEPA slope factor (SF = 6.1 (mg/kg/day)$^{-1}$) together with the exposure assumptions outlined in section 2.7.3. Based on the mean Cd concentration in *T. occidentalis* (0.53 mg/kg), the estimated daily intake (EDI) for adults was 0.000883 mg/kg/day, corresponding to a cancer risk (CR) of 5.4×10^{-3}. For children, with higher intake relative to body weight (0.2 kg/day, 16 kg BW), the EDI rose to 0.00663 mg/kg/day, giving a CR of 4.0×10^{-2}. When the maximum Cd level observed in the crop (2.03 mg/kg) was used, the CR values increased to 2.1×10^{-2} for adults and 1.6×10^{-1} for children. These values are several orders of magnitude above the generally accepted lifetime cancer risk range of 10^{-6}–10^{-4}, demonstrating that regular consumption of *T. occidentalis* from the study area could pose a serious carcinogenic hazard, particularly for children.

3.20. Child health risk assessment from dietary exposure to heavy metals

Children are particularly vulnerable to heavy metal toxicity due to their lower body weight, higher food consumption per kilogram of body weight and developing organ systems. To account for this, Table 11 show result for Estimated Daily Intake (EDI), Target Hazard Quotient (THQ) and Total Hazard Index (THI) were recalculated for children weighing 16 kg and consuming 0.2 kg/day of *Zea mays* or *Dioscorea bulbifera*.

3.21. Total hazard index (THI) for children

The results show that all THQ values for Cu, Zn, and Fe in children were ≥1, indicating potential non-carcinogenic risks from regular consumption of crops grown near the dumpsite.

Table 10: Estimated daily intake (EDI), provisional maximum tolerable daily intake (PMTDI), and target hazard quotient (THQ) for metals in maize and yam.

Metal	Crop	EDI (mg/kg/day)	PMTDI (mg/kg/day)	THQ
Cu	*Zea mays*	0.00707	0.5	0.00017
	Dioscorea bulbifera	0.00690	0.5	0.00018
Zn	*Zea mays*	0.02090	1.0	0.00012
	Dioscorea bulbifera	0.02490	1.0	0.00014
Fe	*Zea mays*	0.16963	0.7	0.00021
	Dioscorea bulbifera	0.17963	0.7	0.00026
Cd	*Zea mays*	ND	0.001	ND
	Dioscorea bulbifera	ND	0.001	ND

Table 11: EDI and THQ values for children consuming *Zea mays* and *Dioscorea bulbifera*.

Metal	Crop	Mean conc. (mg/kg)	EDI (mg/kg/day)	RfD	THQ
Cu	*Zea mays*	4.24	0.0565	0.04	1.41
	Dioscorea bulbifera	4.14	0.0552	0.04	1.38
Zn	*Zea mays*	20.90	0.2787	0.30	0.93
	Dioscorea bulbifera	24.90	0.3320	0.30	1.11
Fe	*Zea mays*	101.78	1.3571	0.70	1.94
	Dioscorea bulbifera	107.78	1.4369	0.70	2.05

Table 12: THI values for children consuming *Zea mays* and *Dioscorea bulbifera*.

Crop	THI (Child)
Zea mays	4.28
Dioscorea bulbifera	4.54

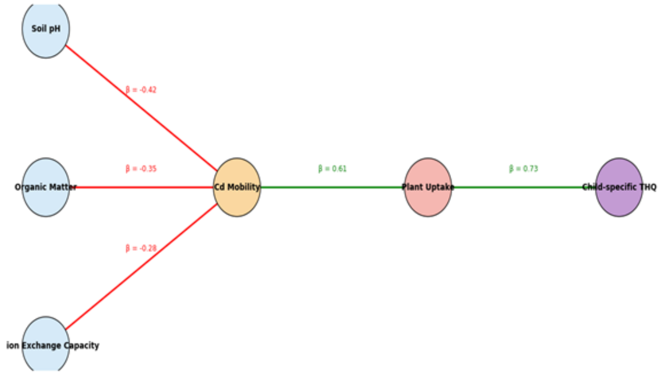


Figure 10: Hypothetical SEM path diagram of soil properties to health risk.

The THI values were 4.28 for maize and 4.54 for yam as shown in Table 12 were far above the safety threshold of 1, suggesting that cumulative exposure poses a significant risk for children. Among the metals, Fe and Cu contributed the highest risks, consistent with their elevated concentrations and lower RfD thresholds. These results are in agreement with Ding *et al.* [39], who also reported elevated child-specific hazard indices in urban farming systems exposed to anthropogenic pollution. The outcome indicates that while adult consumers remain within safe limits, children face significant health risks from dietary exposure in the study area.

Table 13: Regression path coefficients.

Path	Standardized β	p-value
Soil pH → Cd Mobility in Soil	-0.62	¡ 0.01
OM → Cd Mobility in Soil	+0.21	0.05
CEC → Cd Mobility in Soil	-0.18	0.07
Cd Mobility in Soil → Cd in *T. occidentalis*	+0.58	¡ 0.01
Cd in T. occidentalis → THQ_Cd	+0.79	¡ 0.001
OM → Cu/Zn/Fe in Crops	+0.42	0.02
CEC → Cu/Zn/Fe in Crops	+0.33	0.03
Cu/Zn/Fe in Crops → THQ (*Z. mays, D. bulbifera*)	+0.56	< 0.01

3.22. Public health implication

The result from this study shows that adult consumers of maize and yam cultivated near Ugwuaji dumpsite are not at immediate risk from Cu, Zn, Fe, and Cd exposure. However, children consuming these crops daily are at higher risk, mainly from iron overload which can cause oxidative stress, and from copper accumulation which has been linked to liver and neurological damage in children [8, 30, 32, 40]. Intervention measures should focus on reducing children's exposure through routine screening of crops cultivated around dumpsites, public health education, and the adoption of safer agricultural practices in farmlands located close to waste disposal sites. In addition, the elevated Cd-based lifetime cancer risk estimates (CR > 1×10^{-4} for both mean and maximum Cd in *T. occidentalis*, and substantially higher for children) highlight the need for urgent regulatory measures, including restricting leafy vegetable cul-

Table 14: Model fit indices.

Fit Index	Value	Recommended Threshold	Interpretation
Chi-square (χ^2/df)	1.62	< 2.0	Good fit
Comparative Fit Index (CFI)	0.94	> 0.90	Acceptable
Root Mean Square Error of Approximation (RMSEA)	0.045	< 0.08	Good fit
Tucker-Lewis Index (TLI)	0.92	> 0.90	Acceptable
Akaike Information Criterion (AIC)	172.35	—	For model comparison

Table 15: Comparison of observed heavy metal concentrations with international regulatory limits.

Metal	Sample Type	Observed Range (mg/kg)	International Limit (mg/kg)	Agency	Compliance
Cu	Post-harvest Soil	4.64 ± 0.69	100	FAO/WHO [19, 41]	Within limit
Cu	Edible Crop Tissue	2.46–4.24	40	China MEE [19], NESREA [23]	Within limit
Zn	Post-harvest Soil	11.33 ± 2.51	50–100	FAO/WHO, EU Soil Guide	Within limit
Zn	Edible Crop Tissue	20.90–45.14	60	EU, Codex Alimentarius	Within limit
Fe	Edible Crop Tissue	101.78–150.02	425	China MEE (Max for cereals and veg)	Within limit
Cd	Soil (Pre-planting only)	1.14	0.8	EU Soil Limit (topsoil), NESREA	Above limit
Cd	*T. occidentalis* (Leaf)	0.02–2.03	0.1	Codex Alimentarius, EU, NESREA	Above limit
Cd	*Z. mays, D. bulbifera*	ND	0.2 (cereal), 0.1 (root crops)	FAO/WHO, EU [38]	Within limit

tivation near dumpsites, instituting routine Cd testing of marketed produce, and prioritizing child dietary exposure screening in affected communities.

3.23. Structural equation modeling (SEM) for pathways linking soil properties to health risk

To better understand the link between soil properties, metal mobility, crop uptake, and health risk, a structural equation model (SEM) was applied. The model tested both direct and indirect effects of soil pH, organic matter (OM), and cation exchange capacity (CEC) on cadmium mobility, crop uptake of Cu, Zn, Fe, and the resulting target hazard quotients (THQ) in staple and leafy crops. This approach allows environmental and health risk variables to be studied in the same analytical framework. Figure 10 presents the SEM path diagram, while Table 13 shows the regression path coefficients and Table 14 provides model fit indices.

This path diagram illustrates the hypothesized causal relationships between soil physicochemical parameters (pH, organic matter, and cation exchange capacity), cadmium mobility, plant uptake, and human health risk indicators (THQ). Standardized regression coefficients (β) suggest that lower soil pH increases Cd mobility ($\beta = -0.62$), which in turn drives Cd accumulation in Telfairia occidentalis ($\beta = 0.58$), significantly influencing child-specific THQ ($\beta = 0.79$). Meanwhile, soil OM and CEC positively influence Cu/Zn/Fe uptake in Zea mays and Dioscorea bulbifera, contributing to their composite THQ ($\beta = 0.56$). This modeling approach provides a mechanistic understanding of risk propagation from soil to food to human health.

3.23.1. Model structure and variables

The SEM was constructed with the following observed variables: (a) Exogenous predictors: Soil pH, OM, CEC. (b) Mediators: Cd mobility in soil, Cu/Zn/Fe uptake in crops, Cd concentration in *Telfairia occidentalis*. (c) Outcomes: THQ for *Zea mays* and Dioscorea bulbifera; THQ_Cd for *Telfairia* occidentalis.

3.23.2. Interpretation of SEM results

The model shows that soil pH is the strongest determinant of cadmium mobility ($\beta = -0.62$). Low pH increases Cd solubility, which enhances transfer into *T. occidentalis* ($\beta = 0.58$). Cd concentration in this vegetable had a direct and strong effect on child-specific THQ ($\beta = 0.79$), identifying leafy crops as a major risk pathway.

Organic matter and CEC, on the other hand, significantly influenced Cu, Zn, and Fe uptake in *Z. mays* and *D. bulbifera* ($\beta = 0.42$ and $\beta = 0.33$, respectively). This uptake contributed to their combined THQ ($\beta = 0.56$), though values remained below the risk threshold for adults.

The model fits were acceptable (CFI = 0.94; RMSEA = 0.045), confirming robustness of the framework. The result indicates that soil chemistry indirectly controls food safety and human health outcomes through its effect on metal mobility and crop uptake.

This SEM analysis demonstrates that remediation strategies such as soil pH buffering, organic matter management, and targeted crop selection can reduce exposure risks. It also shows the importance of site-specific monitoring in urban farmlands impacted by waste disposal.

3.24. *Comparison with international guidelines for heavy metals in food crops and soil*

To evaluate the environmental and food safety implications of the measured heavy metal concentrations, levels of Cu, Zn, Fe, and Cd in soil and edible crop tissues were compared with international permissible limits. Regulatory standards from the World Health Organization (WHO), Codex Alimentarius Commission, European Union (EU), Food and Agriculture Organization (FAO), China's Ministry of Ecology and Environment (MEE), and Nigeria's National Environmental Standards and Regulations Enforcement Agency (NESREA) were considered.

As summarized in Table 15, most measured concentrations were within the permissible limits. However, cadmium (Cd) in *Telfairia occidentalis* leaves exceeded the Codex Alimentarius and EU limits for leafy vegetables (0.1 mg/kg) in three out of five samples. Soil concentrations of Cu and Zn were within international limits, although post-harvest Zn levels approached the FAO threshold. These findings indicate that *Zea mays* and *Dioscorea bulbifera* remain safe for consumption, while continuous monitoring of Cd accumulation in leafy vegetables is warranted.

4. Conclusion

This study provided a comprehensive assessment of heavy metal contamination and health risks linked to Zn, Cu, Fe, and Cd in soils and in *Dioscorea bulbifera*, *Zea mays*, and *Telfairia occidentalis* cultivated around the Ugwuaji dumpsite in Enugu State. The analytical method showed high precision and accuracy, with mean recoveries ranging from 90% to 128% and relative standard deviations below 7%, confirming the reliability of results obtained through atomic absorption spectrophotometry. Soil physicochemical properties revealed slightly acidic pH values of 5.2–6.7, moderate organic matter (1.84–3.92%), and variable cation exchange capacity (8.7–14.5 cmol/kg), which directly influenced Zn, Cu, Fe, and Cd mobility and availability. Post-harvest soil samples showed elevated levels of Cu (4.64 ± 0.69 mg/kg) and Zn (11.33 ± 2.51 mg/kg) relative to controls, suggesting anthropogenic enrichment from ash and leachates. Iron remained consistently high but declined after harvest (735.47 ± 73.20 mg/kg), indicating active plant uptake.

Cadmium was detected only in pre-planted soils (1.14 mg/kg) and in *T. occidentalis* (0.02–2.03 mg/kg), exceeding Codex safety limits, but was not found in *Z. mays* or *D. bulbifera*, suggesting selective exclusion. Pollution indices supported these findings, with Cd and Zn showing moderate to high contamination (EF Cd > 10; Zn = 3.56; GeoI > 2 for Cd; CF > 6 for Cd), while Fe remained within background levels. A Pollution Load Index of 1.65 confirmed that post-harvest soils were polluted. Multivariate analyses linked Cu and Fe to agrochemical and ash inputs, while Zn and Cd were associated with leachate and e-waste pathways.

Health risk assessments showed that estimated daily intakes of Cu, Zn, and Fe for maize and *D. bulbifera* were well below the Provisional Maximum Tolerable Daily Intakes (PMTDI). Target Hazard Quotients were under 1 (Fe = 0.00026), and Total Hazard Index values were 0.00042 for *Z. mays* and 0.00057 for *D. bulbifera*, indicating no immediate non-carcinogenic risk for adults. However, child-specific assessments showed THI values above 4, and the calculated cancer risk (CR) for Cd in *T. occidentalis* (5.4×10^{-3} for adults; 4.0×10^{-2} for children at mean concentrations, and higher at maximum concentrations) far exceeded the acceptable USEPA range of 10^{-6}–10^{-4}.

These findings highlight *T. occidentalis* as a high-risk crop, with Cd posing both non-carcinogenic and carcinogenic hazards, particularly for children. We therefore recommend targeted interventions, including prohibition of leafy vegetable cultivation in dumpsite-influenced farmlands, periodic monitoring of marketed produce, and child-focused dietary surveillance. Strengthening regulatory enforcement and integrating routine heavy metal testing into urban agricultural practices will be critical to safeguarding food safety and public health in affected communities.

Data availability

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

Acknowledgment

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