© JUN 2026 | IRE Journals | Volume 9 Issue 12 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I12-1719131

Assessment Of Soil-To-Cassava Transfer of Trace Metals and Associated Dietary Health Risks from Cassava (*Manihot Esculenta*) Consumption in Delta, Nigeria

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Abstract- Trace metal contamination of agricultural soils poses a significant challenge to food safety, sustainable agriculture, and public health, directly impacting the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 3 (Good Health and Well-being). This study investigated the concentrations, soil-to-crop transfer behavior, and associated health risks of copper (Cu), zinc (Zn), manganese (Mn), and lead (Pb) in agricultural soils and cassava (Manihot esculenta) cultivated across eighteen locations in Delta Central, Nigeria. Soil and cassava samples were analyzed using atomic absorption spectrometry (AAS). Mean concentrations of Cu, Zn, Mn, and Pb in soils were 0.054, 0.525, 0.720, and 2.763 mg/kg, respectively, while corresponding concentrations in cassava were 0.140, 0.370, 0.170, and 1.724 mg/kg. Metal abundance followed the order Pb > Mn > Zn > Cu in soils and Pb > Zn > Mn > Cu in cassava. Soil-to-crop transfer factors indicated relatively higher uptake efficiency for Cu and ZN compared with Mn and Pb. Although measured concentrations were below international permissible limits, Pb levels were consistently elevated in both soils and cassava, resulting in higher exposure indices. The findings highlight the potential for chronic dietary exposure to Pb and underscore the need for continuous monitoring and improved soil management practices to safeguard food safety in the region.

***Keywords:** Trace Metals, Atomic Absorption Spectrometry, Health Risk, Pollution Index, Physicochemical, Niger Delta*

I. INTRODUCTION

Rapid industrialization, urban expansion, and intensified agricultural practices have increasingly raised concerns about the accumulation of trace metals in agricultural soils. Trace metals are of particular environmental significance due to their persistence, non-biodegradable nature, potential toxicity, and capacity to accumulate within ecosystems and transfer through the food chain, especially in rapidly developing regions [1]. Contamination of agricultural soils by trace metals and metalloids is therefore recognized as a major constraint to sustainable agricultural development, threatening crop safety, food security, ecosystem integrity, and public health on a global scale [2].

Trace metals occur naturally in soils as a result of parent material weathering; however, anthropogenic inputs have become the dominant contributors in many environments. Major sources include industrial emissions, mining and smelting activities, vehicular traffic, oil and gas exploration, sewage sludge application, agrochemicals, and irrigation with contaminated water [3]. Once introduced into soil systems, trace metals may exist in multiple physicochemical forms with varying solubility, mobility, and bioavailability. Plants more readily absorb metals in exchangeable or weakly bound fractions [4], whereas those associated with residual or mineral-bound fractions are generally less mobile and biologically unavailable [5].

Excess accumulation of trace metals in soils can disrupt plant biochemical, physiological, and morphological processes, thereby impairing crop productivity and quality. Metal toxicity in plants depends on the metal type, concentration, chemical form, plant species, and duration of exposure [6]. While some metals, such as copper (Cu), zinc (Zn), manganese (Mn), and iron (Fe), are essential micronutrients required in small quantities for normal plant metabolism, elevated concentrations can induce phytotoxic effects, including oxidative stress, disruption of nutrient uptake, inhibition of photosynthesis, and reduced root development [7].

Globally, trace metal pollution constitutes a substantial proportion of soil contamination. For example, a large-scale investigation in China reported that approximately 32% of soil pollution was attributed to trace metals, compared with 68% from organic pollutants [8]. Given that agricultural soils and crops form the foundation of human and animal nutrition, the accumulation of trace metals in food-producing systems has attracted considerable scientific attention due to its long-term and often subtle effects on human health [9]. It is estimated that dietary intake through the food chain accounts for nearly 95% of total environmental trace metal exposure in human populations, highlighting the critical importance of soil–crop transfer processes [10].

Metal uptake by plants is governed not only by total soil concentration but also by metal speciation, soil properties, and plant physiological mechanisms. Soil pH, organic matter content, cation exchange capacity, microbial activity, and rhizosphere chemistry play crucial roles in controlling metal mobility and bioavailability [3]. After uptake by plant roots, trace metals may be sequestered in cell walls or vacuoles through binding with negatively charged biopolymers such as pectin, cellulose, hemicellulose, and lignin. Vacuolar sequestration often involves ATP-dependent transporters and complexation with phytochelatins, thereby limiting metal translocation to aerial and edible plant tissues [11–13].

Trace metals can enter plant roots through apoplastic (passive) or symplastic (active) pathways, and their phytotoxicity depends on absorption, translocation, and accumulation within different plant organs [14]. Although plants can metabolize certain essential metals such as Zn and Cu, prolonged exposure to elevated concentrations of both essential and non-essential metals can impair growth and development. Moreover, trace metal contamination poses serious human health risks, as chronic dietary exposure has been linked to cardiovascular diseases, neurological disorders, renal dysfunction, carcinogenic effects, and endocrine disruption [15,16].

Human exposure to trace metals presents a paradox: some metals are essential for metabolic functions, acting as enzyme cofactors and supporting growth and development, while excessive intake leads to toxicity [17,18]. For instance, Cu, Mn, Co, and Mo are required in trace amounts, yet elevated concentrations may result in oxidative damage, hormonal imbalance, neurological impairment, and increased risk of chronic diseases [18]. High zinc intake can also induce copper deficiency, illustrating the complex interactions among trace elements in the human body [19].

In agricultural systems, fertilizers and pesticides constitute major anthropogenic sources of trace metals. Phosphate fertilizers, particularly superphosphate formulations, often contain impurities such as Cd, Pb, Zn, Cu, Ni, and Cr derived from raw phosphate rock [3]. Long-term application of these inputs has been shown to increase metal concentrations in soils. Additionally, irrigation with contaminated surface water or groundwater represents a significant contamination pathway, particularly in developing countries where wastewater reuse is common. Metals introduced into water bodies through industrial, municipal, and agricultural discharges can be transported to farmlands via runoff and leaching processes.

Nigeria's agricultural system relies heavily on cereals and root tubers, which constitute staple food sources for both low- and middle-income populations [20]. Cassava (Manihot esculenta), in particular, is a major dietary component due to its high caloric value and adaptability to diverse soil conditions [21]. Delta Central, located within Nigeria's Niger Delta region, is both an agrarian and industrial hub, characterized by extensive oil and gas exploration activities alongside subsistence and commercial farming. Cassava (Manihot esculenta) is a staple crop in the region and constitutes a major source of dietary carbohydrates for local populations. These overlapping land uses increase the vulnerability of soils and food crops to trace metal contamination [22,23].

Despite its importance, comprehensive assessments of trace metal contamination in soils and cassava, and the associated health risks, remain limited for Delta

Central. This study, therefore, aims to (i) quantify Cu, Zn, Mn, and Pb concentrations in agricultural soils and cassava, (ii) evaluate soil-to-crop transfer factors and pollution indices, and (iii) assess potential health risks associated with dietary exposure for adults and children. The findings are intended to support food safety regulation, environmental management, and sustainable agricultural practices in the Niger Delta.

II. MATERIALS AND METHODS

Study location

Delta Central is located in the core of the Niger Delta region of southern Nigeria, at approximately 5.560 N latitude and 6.050 E longitude, an area of significant economic and environmental importance. The region hosts numerous local and multinational oil and gas companies engaged in exploration, production, and exportation activities, which constitute a major source of anthropogenic pressure on the environment. Alongside industrial operations, Delta Central remains predominantly agrarian, with a large proportion of rural inhabitants relying on small-scale subsistence and commercial farming for their livelihoods. Figure 1 illustrates the map of Delta Central, highlighting the specific location of the sample.

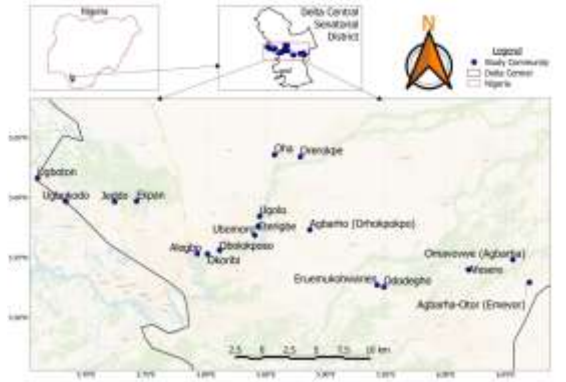

Figure 1: Overview of Delta Central with Study Locations

Geologically, the study area is characterised by coastal plain sands, deltaic sands, meander belt deposits, and alluvial sediments spanning the Oligocene to Holocene epochs. The region is underlain by superficial Quaternary deposits dominated by loose to clayey sands of the Benin Formation, which extends across the entire onshore portion of southern Nigeria [24]. These unconsolidated sediments, coupled with generally sandy soil textures, promote high permeability and limited metal retention capacity, thereby influencing trace metal mobility and bioavailability in agricultural soils.

Sampling process and preparation

A total of thirty-six samples were collected from eighteen agricultural locations, comprising eighteen soil samples and eighteen corresponding cassava tuber samples. Soil samples were collected from the root zone (1 to 30 cm depth) at points where cassava was cultivated. Cassava tubers were harvested at physiological maturity. Approximately 5 kg of soil and 3 kg of cassava were collected per site, placed in labelled polyethene bags, and transported to the laboratory. Geographic coordinates and elevation of each sampling location were recorded using a handheld GPS device. In the laboratory, soil samples were air-dried, homogenized, and sieved to remove debris before pulverization. Cassava samples were washed thoroughly, sliced, air-dried, ground into powder, and sieved. Prepared samples were stored in clean containers before analysis.

Atomic Absorption Spectrometry Analysis

Trace metal concentrations in soil and cassava samples were determined using Atomic Absorption Spectrometry (AAS), a well-established quantitative technique for elemental analysis. AAS operates on the principle that ground-state atoms absorb light at element-specific wavelengths. The degree of absorption is directly proportional to the concentration of the element present in the sample.

The AAS system consists of five main components: a radiation source, an atomization unit, a monochromator (spectroscopic system), a detector, and a data display unit. During analysis, samples are introduced into the atomizer, where they are thermally converted into free atomic vapor. When irradiated by element-specific light, the atoms absorb characteristic wavelengths, and the resulting reduction in light intensity is measured. The absorbance is subsequently converted into elemental concentration using calibration curves (Figure 2).

Atomic absorption spectrometry offers several advantages, including high selectivity, sensitivity, analytical precision, and minimal spectral interference. It is also relatively simple to operate, rapid, and suitable for routine environmental analysis. Based on the atomization technique employed, AAS methods include cold vapor atomic absorption spectrometry (CVAAS), hydride generation atomic absorption spectrometry (HGAAS), graphite furnace atomic absorption spectrometry (GFAAS), and flame atomic absorption spectrometry (FAAS). In this study, appropriate AAS techniques were applied following standard analytical protocols to ensure data accuracy and reliability [11,13,25].

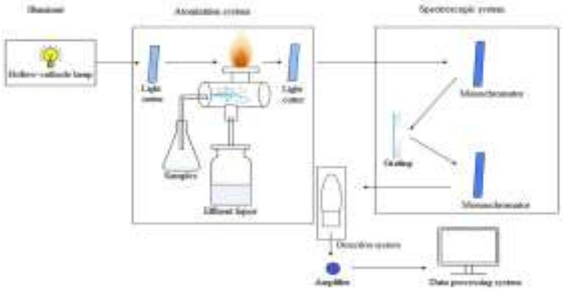

Figure 2: The operating principle schematic diagram of AAS [13]

Health risk assessment parameters

Health risk assessment was conducted to evaluate potential human exposure to trace metals through the consumption of cassava (Manihot esculenta) cultivated in Delta Central, Nigeria. The assessment incorporated soil-to-crop transfer, pollution indices, dietary exposure, and non-carcinogenic health risk estimation.

Soil-to-Crop Transfer Factor

The soil-to-crop transfer factor (TF), also referred to as the contamination factor, was used to assess the mobility and bioavailability of trace metals from soil to edible plant tissues. TF was calculated using Equation (1):

TF= (Activity Concentration of element (i) per kg dry plant mass)/(Activity Concentration of element (i)in dry soil within the rooting area) (1)

$$TF = \frac{\text{Activity Concentration of element (i) per kg dry plant mass}}{\text{Activity Concentration of element (i)in dry soil within the rooting area}} \quad (1)$$

Higher TF values indicate greater uptake efficiency and bioaccumulation potential of metals in crops [26].

Pollution Load Index

The Pollution Load Index (PLI) was employed to evaluate the overall degree of trace metal contamination in agricultural soils by integrating the contamination factors of individual metals. PLI was calculated using Equation (2):

$$PLI = \sqrt{CF_1 \times CF_2 \times CF_3 \times CF_4 \ldots CF_n} \quad 2$$

where CF represents the contamination factor for each metal. Interpretation of PLI values follows established criteria: PLI = 0 (background concentration); 1≤ PLI ≤3 (Moderately tainted); PLI >3 (Very highly tainted) [27].

Daily intake of metals

The daily intake of metals (DIM) through cassava consumption was estimated to assess dietary exposure for adults and children. DIM (mg/kg/day) was calculated using Equation (3)

$$DIM = \frac{C_{metal} \ X \ C_{factor} \ X \ DI_{food\ intake}}{BW_{average\ weight}} \quad 3$$

Where Cmetal, Cfactor, DIfood intake and BWaverage weight represent the trace metal concentrations in plants/crops (mg/kg), conversion factor, average daily intake of food crops and body weights, respectively, with varying values of DI (0.232 kg/person-day and 0.345 kg/person-day) and BW (73 kg and 32.7 kg) for adults and children [28].

Health risk index of metals

The non-carcinogenic health risk associated with trace metal exposure was evaluated using the Health Risk Index (HRI), calculated as the ratio of daily intake to the reference oral dose (RfD). HRI was computed using Equation (4):

$$HRI = \frac{DIM}{RfD} \quad 4$$

Where HRI, DIM and RfD represent the human health risk index, daily intake of metal and reference dose of metal, respectively. An HRI value less than 1 indicates no significant health risk, while values greater than 1 suggest a potential health concern [28].

III. RESULTS AND DISCUSSION

Trace metal concentrations in agricultural soils:
The result of heavy metal concentration in the soil sample and the soil texture profile of each sample across Delta Central, Nigeria, are presented in Tables 1 and 2, respectively. Table 1 summarizes the concentrations of copper (Cu), zinc (Zn), manganese (Mn), and lead (Pb) in agricultural soils across Delta Central. Copper concentrations ranged from 0.005 to 0.108 mg/kg, with a mean value of 0.054 mg/kg.
The lowest Cu concentration was recorded at Okoribi community in Uvwie LGA (LC3), characterized by sandy loam soil, while the highest concentration occurred at Agbarho community in Ughelli-North LGA (LC18), under loamy sand soil conditions (Table 2). Figure 3 compares the Cu concentration across the study locations. Predominantly, most samples within Ughelli-North (LC13, LC15, LC16, LC17, LC18) and Okpe (LC8, LC9, LC10, LC12) LGAs exhibited Cu concentrations above the overall mean for Delta Central, suggesting localized enrichment possibly linked to land-use practices and soil texture.

Table 1: Trace Metal Concentration in the Soil Sample across the Study Area

SN	Location (Community [LGA])	Location Code	Soil Sample Code	Cu ± SD (mg/kg)	Zn ± SD (mg/kg)	Mn ± SD (mg/kg)	Pb ± SD (mg/kg)
1	Eterigbe [Uvwie]	LC1	S1	0.031 ± 0.0003	0.377 ± 0.0018	0.242 ± 0.0007	2.845 ± 0.0107
2	Obolokposo [Uvwie]	LC2	S2	0.024 ± 0.0004	0.107 ± 0.0003	0.356 ± 0.0015	2.741 ± 0.0038
3	Okoribi [Uvwie]	LC3	S3	0.005 ± 0.0013	1.092 ± 0.0017	0.914 ± 0.0031	2.865 ± 0.0022
4	Alegbo [Uvwie]	LC4	S4	0.010 ± 0.0004	0.319 ± 0.0016	0.282 ± 0.0020	2.011 ± 0.0013
5	Ekpan [Uvwie]	LC5	S5	0.019 ± 0.0006	0.094 ± 0.0020	0.300 ± 0.0022	2.183 ± 0.0079
6	Ubomoro [Uvwie]	LC6	S6	0.035 ± 0.0004	0.058 ± 0.0005	0.323 ± 0.0013	3.099 ± 0.0035
7	Jeddo [Okpe]	LC7	S7	0.036 ± 0.0004	0.059 ± 0.0013	1.313 ± 0.0025	1.805 ± 0.0086
8	Ugboton [Okpe]	LC8	S8	0.066 ± 0.0003	0.172 ± 0.0018	0.349 ± 0.0020	2.980 ± 0.0004
9	Ugbokodo [Okpe]	LC9	S9	0.077 ± 0.0004	0.098 ± 0.0010	0.257 ± 0.0012	2.389 ± 0.0040
10	Ugolo [Okpe]	LC10	S10	0.061 ± 0.0004	2.533 ± 0.0039	2.115 ± 0.0020	1.932 ± 0.0029
11	Oha [Okpe]	LC11	S11	0.028 ± 0.0013	1.671 ± 0.0041	0.569 ± 0.0022	3.369 ± 0.0037
12	Orerokpe [Okpe]	LC12	S12	0.092 ± 0.0003	0.163 ± 0.0009	0.784 ± 0.0012	2.854 ± 0.0060
13	Afesere [Ughelli-North]	LC13	S13	0.076 ± 0.0006	0.167 ± 0.0003	0.994 ± 0.0016	3.121 ± 0.0042
14	Omavovwe [Ughelli-	LC14	S14	0.017 ±	2.054 ±	1.529 ±	2.551 ±

	North]			0.0005	0.0040	0.0007	0.0100
15	Agbarha-Otor [Ughelli-North]	LC15	S15	0.096 ± 0.0005	0.126 ± 0.0014	0.323 ± 0.0013	3.079 ± 0.0036
16	Ododegho [Ughelli-North]	LC16	S16	0.098 ± 0.0002	0.194 ± 0.0004	1.235 ± 0.0015	2.928 ± 0.0023
17	Eruemukohwarien [Ughelli-North]	LC17	S17	0.094 ± 0.0006	0.090 ± 0.0005	0.964 ± 0.0015	4.183 ± 0.0065
18	Agbarho [Ughelli-North]	LC18	S18	0.108 ± 0.0005	0.079 ± 0.0011	0.125 ± 0.0010	2.809 ± 0.0025
Mean value (mv)				0.054	0.525	0.720	2.763
Minimum value				0.005	0.058	0.125	1.805
Maximum value				0.108	2.533	2.115	4.183
Standard permissible limit value [35]				36.000	50.000	50.000	85.000

Table 2 Soil Profile across the study locations

SN	Location (Community [LGA])	Location Code	% Clay	% Silt	% Sand	Soil Textural Class	Soil Texture Class Code
1	Eterigbe [Uvwie]	LC1	6	6	88	Sand	S
2	Obolokposo [Uvwie]	LC2	8	8	84	Loamy Sand	LS
3	Okoribi [Uvwie]	LC3	8	16	76	Sandy Loam	SL
4	Alegbo [Uvwie]	LC4	8	8	84	Loamy Sand	LS
5	Ekpan [Uvwie]	LC5	12	24	64	Sandy Loam	SL
6	Ubomoro [Uvwie]	LC6	8	12	80	Loamy Sand	LS
7	Jeddo [Okpe]	LC7	8	22	70	Sandy Loam	SL
8	Ugboton [Okpe]	LC8	6	12	82	Loamy Sand	LS
9	Ugbokodo [Okpe]	LC9	8	6	86	Loamy Sand	LS
10	Ugolo [Okpe]	LC10	6	4	90	Sand	S
11	Oha [Okpe]	LC11	6	4	90	Sand	S
12	Orerokpe [Okpe]	LC12	6	4	90	Sand	S
13	Afesere [Ughelli-North]	LC13	8	10	82	Loamy Sand	LS
14	Omavovwe [Ughelli-North]	LC14	6	6	88	Sand	S
15	Agbarha-Otor [Ughelli-North]	LC15	8	8	84	Loamy Sand	LS
16	Ododegho [Ughelli-North]	LC16	6	10	84	Loamy Sand	LS
17	Eruemukohwarien [Ughelli-North]	LC17	8	8	84	Loamy Sand	LS
18	Agbarho [Ughelli-North]	LC18	6	10	84	Loamy Sand	LS

Zinc concentrations in soil varied from 0.058 to 2.533 mg/kg, with a mean value of 0.525 mg/kg. The minimum Zn concentration was observed at Ubomoro community in Uvwie LGA (LC6), while the maximum concentration occurred at Ugolo community in Okpe LGA (LC10), where sandy soil predominates (Tables I and 2). Locations exceeding the mean Zn concentration were fewer and spatially limited, mainly occurring in parts of Okpe (LC10, LC11), Ughelli-North (LC 14), and Uvwie (LC3) LGAs (Figure 4), indicating relatively lower and more localized Zn enrichment compared to other metals.

Manganese concentrations ranged between 0.125 and 2.115 mg/kg, with an average value of 0.720 mg/kg. The lowest Mn concentration was recorded at Agbarho community in Ughelli-North LGA (LC18), whereas the highest concentration occurred at Ugolo community in Okpe LGA (LC10), characterized by sandy soil texture. Several locations across Okpe (LC7, LC10, LC12), Ughelli-North (LC13, LC14, 16, 17), and Uvwie (LC3) LGAs recorded Mn concentrations above the regional mean (Figure 5), reflecting moderate spatial variability that may be influenced by both geogenic factors and soil physicochemical properties.

Lead exhibited the highest concentrations among the investigated metals, ranging from 1.805 to 4.183 mg/kg, with a mean value of 2.763 mg/kg. The lowest Pb concentration was observed at Jeddo community in Okpe LGA (LC7), under sandy loam soil conditions, while the highest concentration was recorded at Eruemukohwarien community in Ughelli-North LGA (LC17), associated with loamy sand soil (Tables 1 and 2). A substantial number of locations across all three LGAs recorded Pb concentrations exceeding the regional mean (Figure 6), indicating widespread Pb enrichment relative to other metals.

Overall, the frequency of locations exhibiting concentrations above the Delta Central mean followed the order Pb > Cu > Mn > Zn. This pattern highlights lead as the most spatially dominant and potentially concerning trace metal in the study area, followed by copper and manganese, while zinc showed comparatively limited exceedance. The observed distribution suggests that Pb enrichment is more extensive and consistent across the region, likely reflecting cumulative anthropogenic inputs combined with soil texture–controlled mobility.

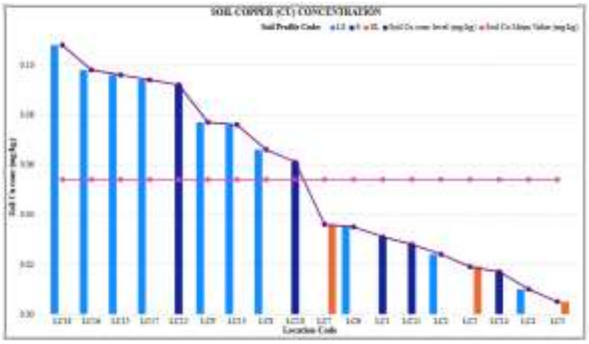

Figure 3: Soil copper concentration plot for the study locations

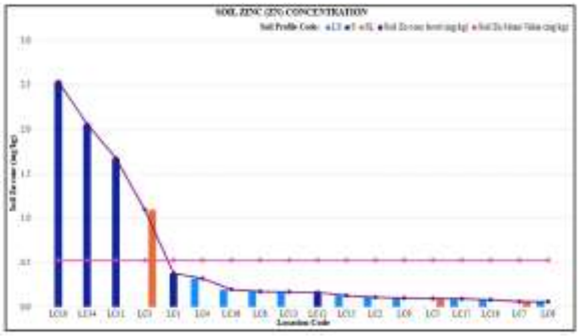

Figure 4: Soil Zinc Concentration plot for the study locations

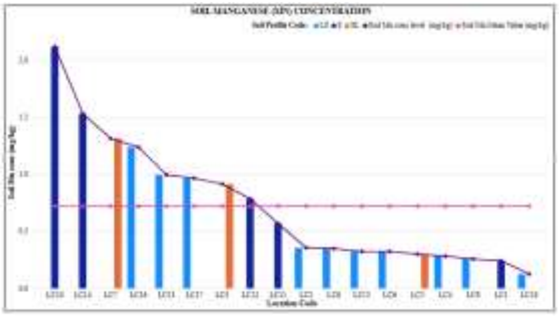

Figure 5: Soil Manganese Concentration plot for the study locations

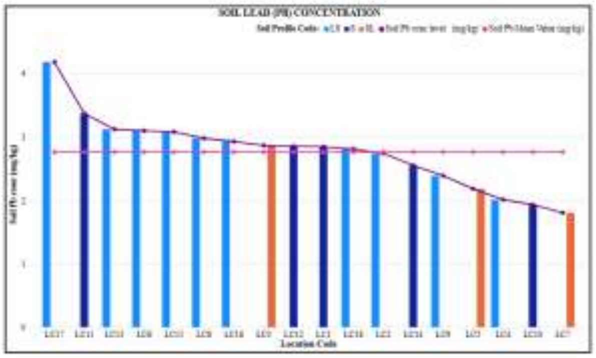

Figure 6: Soil Lead Concentration plot for the study locations

Trace metal concentrations in cassava (Manihot esculenta)

Table 3 presents the concentrations of copper (Cu), zinc (Zn), manganese (Mn), and lead (Pb) in cassava samples collected across Delta Central. Copper concentrations ranged from 0.021 to 0.963 mg/kg, with a mean value of 0.140 mg/kg.

The lowest Cu concentration was recorded at Obolokposo community in Uvwie LGA (LC2), characterized by loamy sand soil, while the highest concentration occurred at Orerokpe community in Okpe LGA (LC12), under sandy soil conditions (Tables 2 and 3). Spatial analysis indicates that only a limited number of locations, primarily within Okpe (LC7, LC8 and LC12) LGA, recorded Cu concentrations above the region (Delta central) mean (Figure 7), suggesting relatively low and localized copper accumulation in cassava.

Table 3: Trace Metal Concentration Level in the Crop Sample across the Study Area

SN	Location (Community [LGA])	Location Code	Crop Sample Code	Cu ± SD (mg/kg)	Zn ± SD (mg/kg)	Mn ± SD (mg/kg)	Pb ± SD (mg/kg)
1	Eterigbe [Uvwie]	LC1	C1	0.038 ± 0.0007	0.338 ± 0.0003	0.040 ± 0..0002	1.975 ± 0.0014
2	Obolokposo [Uvwie]	LC2	C2	0.021 ± 0.0007	0.247 ± 0.0005	0.153 ± 0.0013	1.346 ± 0.0040
3	Okoribi [Uvwie]	LC3	C3	0.059 ± 0.0006	0.573 ± 0.0022	0.013 ± 0.0004	1.774 ± 0.0027
4	Alegbo [Uvwie]	LC4	C4	0.038 ± 0.0005	0.357 ± 0.0022	0.058 ± 0.0008	1.821 ± 0.0004
5	Ekpan [Uvwie]	LC5	C5	0.062 ± 0.0002	0.347 ± 0.0006	0.358 ± 0.0006	2.021 ± 0.0004
6	Ubomoro [Uvwie]	LC6	C6	0.040 ± 0.0002	0.313 ± 0.0031	0.360 ± 0.0007	1.727 ± 0.0008
7	Jeddo [Okpe]	LC7	C7	0.148 ± 0.0003	0.240 ± 0.0017	0.243 ± 0.0026	0.266 ± 0.0021
8	Ugboton [Okpe]	LC8	C8	0.543 ± 0.0010	0.498 ± 0.0006	0.062 ± 0.0009	1.398 ± 0.0029
9	Ugbokodo [Okpe]	LC9	C9	0.037 ± 0.0006	0.205 ± 0.0014	0.060 ± 0.0008	2.820 ± 0.0016
10	Ugolo [Okpe]	LC10	C10	0.060 ± 0.0005	0.345 ± 0.0021	0.184 ± 0.0025	1.879 ± 0.0020
11	Oha [Okpe]	LC11	C11	0.121 ± 0.0004	0.464 ± 0.0006	0.160 ± 0.0015	1.378 ± 0.0031
12	Orerokpe [Okpe]	LC12	C12	0.963 ± 0.0001	0.952 ± 0.0018	0.906 ± 0.0011	0.580 ± 0.0010

13	Afesere [Ughelli-North]	LC13	C13	0.061 ± 0.0004	0.205 ± 0.0024	0.085 ± 0.0002	2.227 ± 0.0008
14	Omavovwe [Ughelli-North]	LC14	C14	0.120 ± 0.0004	0.995 ± 0.0006	0.191 ± 0.0008	1.801 ± 0.0039
15	Agbarha-Otor [Ughelli-North]	LC15	C15	0.050 ± 0.0005	0.194 ± 0.0024	0.007 ± 0.0010	1.802 ± 0.0030
16	Ododegho [Ughelli-North]	LC16	C16	0.069 ± 0.0004	0.122 ± 0.0013	0.086 ± 0.0009	2.386 ± 0.0039
17	Eruemukohwarien [Ughelli-North]	LC17	C17	0.051 ± 0.0005	0.191 ± 0.0013	0.009 ± 0.0004	1.470 ± 0.0036
18	Agbarho [Ughelli-North]	LC18	C18	0.056 ± 0.0013	0.078 ± 0.0022	0.086 ± 0.0007	2.378 ± 0.0022
Mean value (mv)				0.140	0.370	0.170	1.724
Minimum value				0.021	0.078	0.007	0.266
Maximum value				0.963	0.995	0.906	2.820
Standard permissible limit value [35]				10.000	0.600	6.640	2.000

Zinc concentrations in cassava ranged from 0.078 to 0.995 mg/kg, with a mean value of 0.370 mg/kg. The minimum Zn concentration was observed at Agbarho community in Ughelli-North LGA (LC18), while the maximum concentration occurred at Omavovwe community in the same LGA (LC14), both associated with loamy sand and sandy soils, respectively. Locations exceeding the mean Zn concentration were distributed across Okpe, Ughelli-North, and Uvwie LGAs (Figure 8), indicating moderate spatial variability and a broader distribution of zinc accumulation compared with copper.

Manganese concentrations varied between 0.007 and 0.906 mg/kg, with an average value of 0.170 mg/kg. The lowest Mn concentration was recorded at Agbarha-Otor community in Ughelli-North LGA (LC15), while the highest concentration occurred at Orerokpe community in Okpe LGA (LC12), where sandy soil predominates. Several locations across Okpe (LC7, LC10, LC12), Uvwie (LC5, LC6), and Ughelli-North (LC14) LGAs exhibited Mn concentrations above the Delta Central mean (Figure 9), reflecting moderate uptake variability likely influenced by both soil properties and plant physiological controls.

Lead recorded the highest concentrations among the assessed metals in cassava, ranging from 0.266 to 2.820 mg/kg, with a mean value of 1.724 mg/kg. The minimum Pb concentration was observed at Jeddo community in Okpe LGA (LC7), while the maximum concentration occurred at Ugbokodo community in the same LGA (LC9), associated with sandy loam and loamy sand soils, respectively. A large number of locations across all three LGAs exhibited Pb concentrations above the regional mean (Figure 10), indicating widespread Pb accumulation in cassava relative to other metals.

Overall, the frequency of locations with crop metal concentrations exceeding the Delta Central mean followed the order Pb > Mn > Zn > Cu. This pattern demonstrates that lead is the most dominant and spatially widespread contaminant in cassava, followed by manganese and zinc, while copper exhibited the lowest degree of exceedance. The results suggest that Pb poses the greatest potential dietary exposure risk among the investigated metals, consistent with its dominance in soil concentrations and subsequent soil-to-crop transfer behavior.

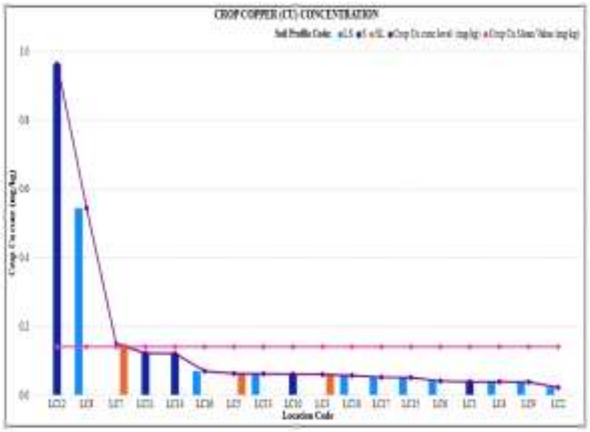

Figure 7: Crop Copper Concentration plot for the study locations

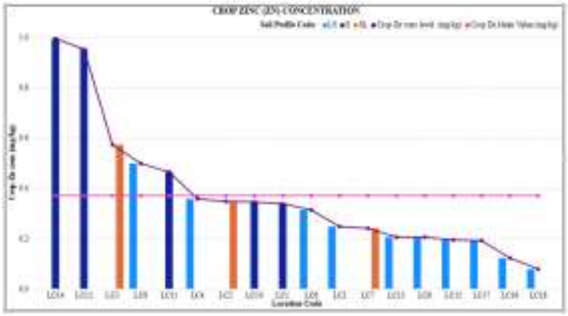

Figure 8: Crop Zinc Concentration plot for the study locations

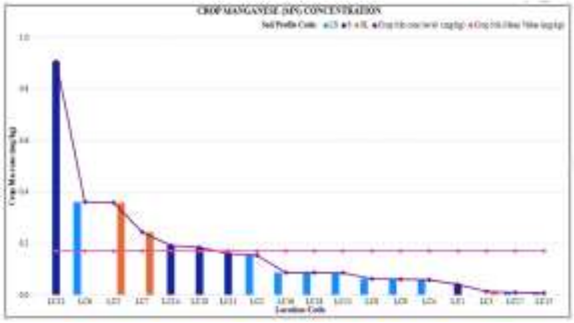

Figure 9: Crop Manganese Concentration plot for the study locations

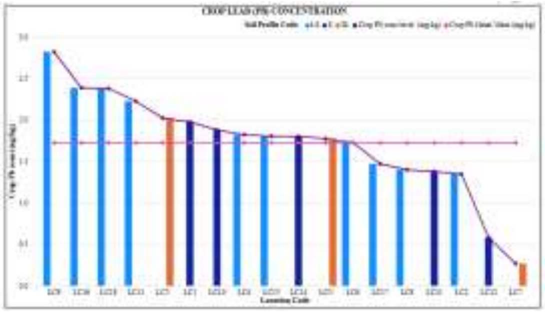

Figure 10: Crop Lead Concentration plot for the study locations

Soil-to-Crop Metal Transfer Factor (Contamination Factor)

Table 4 presents the trace metal transfer factors (TFs) from the soil to crop (Manihot esculenta) for copper (Cu), zinc (Zn), manganese (Mn), and lead (Pb) across the eighteen study locations in Delta Central. A transfer factor (TF ≥ 1) indicates effective uptake and accumulation of a metal in the crop relative to its concentration in soil.

Table 4: Trace Metals Crop-to-Soil Transfer Factor

SN	Location Code	Transfer Factor (Cu)	Transfer Factor (Zn)	Transfer Factor (Mn)	Transfer Factor (Pb)
1	LC1	1.3	0.9	0.2	0.7
2	LC2	0.9	2.4	0.5	0.5
3	LC3	11.8	0.6	0.1	0.7
4	LC4	3.8	1.2	0.3	1.0
5	LC5	3.3	3.7	1.2	1.0
6	LC6	1.2	5.4	1.2	0.6
7	LC7	4.2	4.1	0.2	0.2
8	LC8	8.3	2.9	0.2	0.5
9	LC9	0.5	2.1	0.3	1.2
10	LC10	1.0	0.2	0.1	1.0
11	LC11	4.4	0.3	0.3	0.5
12	LC12	10.5	5.9	1.2	0.3
13	LC13	0.9	1.3	0.1	0.8
14	LC14	7.1	0.5	0.2	0.8

15	LC15	0.6	1.6	0.1	0.6
16	LC16	0.8	0.7	0.1	0.9
17	LC17	0.6	2.2	0.1	0.4
18	LC18	0.6	1.0	0.7	0.9

Copper exhibited relatively high transfer efficiency across the study area. Specifically, eleven locations recorded TF values equal to or greater than 1, while seven locations had TF values below 1. This distribution indicates a generally efficient transfer of Cu from soil to cassava, reflecting its essential role in plant metabolism and active uptake mechanisms.

Similarly, zinc demonstrated favourable transfer behaviour, with twelve locations exhibiting TF values equal to or greater than 1 and six locations recording TF values below 1. The dominance of TF ≥ 1 for Zn suggests effective bioavailability and uptake by cassava across much of Delta Central. The spatial distribution of zinc transfer factors is illustrated in Figure 11.

In contrast, manganese displayed weak soil-to-crop transfer. Fifteen locations recorded Mn TF values below 1, while only three locations exhibited TF values equal to or greater than 1. This pattern suggests limited translocation of Mn from soil to cassava tubers, likely due to physiological regulation and sequestration within root tissues.

Lead also exhibited generally low transfer efficiency. Fourteen locations recorded Pb TF values below 1, with only four locations showing TF values equal to or greater than 1. Despite its relatively elevated soil concentrations, Pb uptake by cassava appears restricted, consistent with its non-essential nature and the plant's tendency to limit Pb translocation to edible tissues.

Overall, the transfer factor results indicate that cassava (Manihot esculenta) in Delta Central preferentially accumulated Cu and Zn relative to Mn and Pb when normalised to soil concentrations. This differential uptake behaviour highlights the combined influence of metal bioavailability, plant physiological demand, and soil properties. The concentration gradients and corresponding transfer patterns for individual metals are illustrated in Figure 12 – 15.

Figure 11: Soil to Crop Transfer Factor (Contamination factor) plot for the trace metals

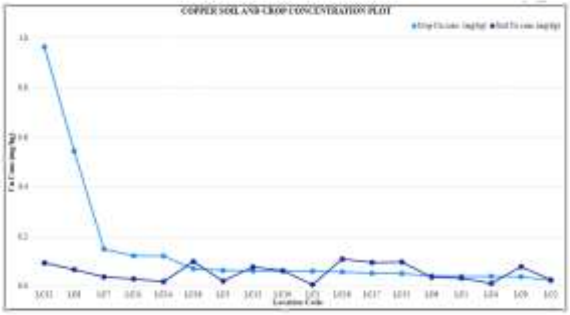

Figure 12: Copper Soil and Crop Concentration plot for the study locations

Figure 13: Zinc Soil and Crop Concentration plot for the study locations

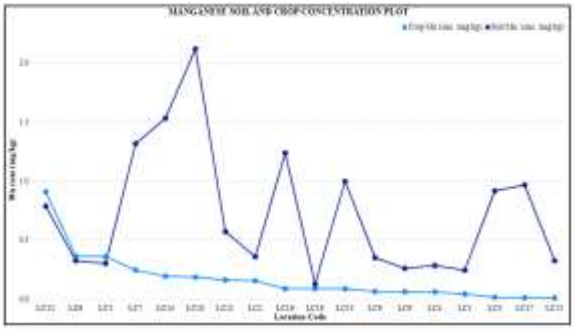

Figure 14: Manganese Soil and Crop Concentration plot for the study locations

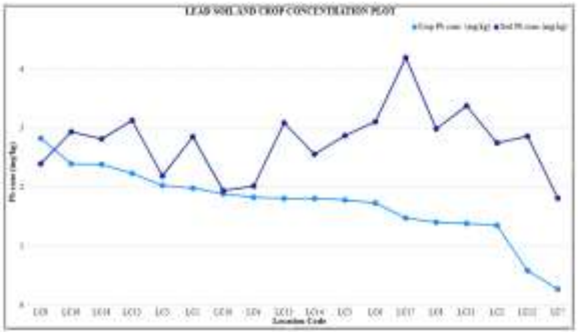

Figure 15: Lead Soil and Crop Concentration plot for the study locations

Trace metal concentration level in soil and crop

Figure 16 illustrates the relative abundance of trace metals in agricultural soils across the study locations. Lead (Pb) exhibited the highest mean concentration, followed by manganese (Mn), zinc (Zn), and copper (Cu). This trend indicates a clear dominance of Pb in the soil matrix, with the overall concentration ranking expressed as: Pb > Mn > Zn > Cu. The observed ranking reflects the combined influence of regional anthropogenic inputs and soil physicochemical properties, which govern the retention and mobility of metals in the study area.

Figure 17 presents the relative abundance of trace metals in cassava (Manihot esculenta) across the study locations. Lead (Pb) recorded the highest mean concentration in the crop samples, followed by zinc (Zn), manganese (Mn), and copper (Cu). Accordingly, the overall ranking of metal concentrations in cassava is expressed as: Pb > Zn > Mn > Cu. This pattern indicates preferential accumulation of Pb and Zn in cassava relative to Mn and Cu, reflecting differences in metal bioavailability, plant uptake mechanisms, and soil–crop interaction dynamics within the study area.

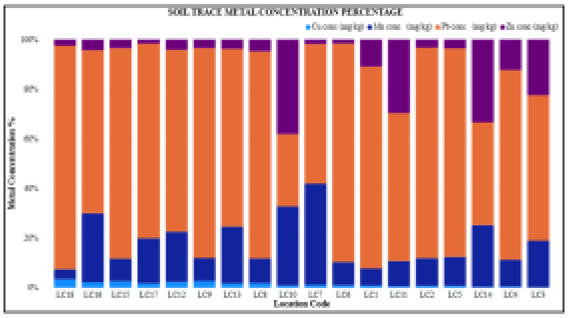

Figure 16: Soil Trace Metal Concentration percentage across the study locations

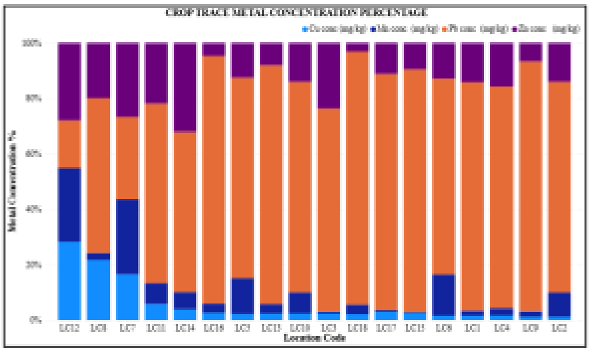

Figure 17: Crop Trace metal concentration percentage across the study locations

Trace Metals Health Parameters

Table 6 shows the Pollution Load Index across Delta Central, and Daily Intake Result for both Child and Adult for each studied trace metal, across the study locations in Delta Central.

Table 6: Pollution Load Index and Daily Intake Result

SN	Sample Location	PLI	DIM for Cu ($\times 10^{-5}$) (mg/kg-day)		DIM for Zn ($\times 10^{-5}$) (mg/kg-day)		DIM for Mn ($\times 10^{-5}$) (mg/kg-day)		DIM for Pb ($\times 10^{-5}$) (mg/kg-day)	
			Child	Adult	Child	Adult	Child	Adult	Child	Adult

	Code		Dose	Dose	Dose	Dose	Dose	Dose	Dose	Dose
1	L1	1.761	2.291	1.526	20.383	13.577	2.412	1.606	119.104	79.338
2	LC2	2.074	1.266	0.843	14.895	9.922	9.226	6.146	81.171	54.070
3	LC3	3.634	3.558	2.370	34.555	23.018	0.783	0.522	106.982	71.263
4	LC4	2.510	2.291	1.526	21.529	14.341	3.497	2.329	109.816	73.151
5	LC5	3.034	3.738	2.490	20.926	13.939	21.589	14.381	121.878	81.186
6	LC6	2.899	2.412	1.606	18.875	12.573	21.710	14.461	104.148	69.375
7	LC7	2.950	8.925	5.945	14.473	9.641	14.654	9.761	16.041	10.685
8	LC8	3.450	32.746	21.813	30.032	20.005	3.738	2.490	84.307	56.159
9	LC9	2.025	2.231	1.486	12.362	8.235	3.618	2.410	170.062	113.282
10	LC10	1.517	3.618	2.410	20.805	13.859	11.096	7.391	113.314	75.481
11	LC11	2.346	7.297	4.860	27.981	18.639	9.648	6.427	83.101	55.356
12	LC12	4.231	58.074	38.684	57.411	38.243	54.637	36.395	34.977	23.299
13	LC13	1.761	3.678	2.450	12.362	8.235	5.125	3.414	134.301	89.461
14	LC14	2.933	7.236	4.820	60.004	39.970	11.518	7.672	108.610	72.348
15	LC15	1.703	3.015	2.008	11.699	7.793	0.422	0.281	108.671	72.388
16	LC16	1.582	4.161	2.771	7.357	4.900	5.186	3.454	143.889	95.848
17	LC17	1.817	3.075	2.048	11.518	7.672	0.542	0.361	88.649	59.051
18	LC18	1.789	3.377	2.249	4.703	3.133	5.186	3.454	143.407	95.527
Mean value		2.445	8.499	5.661	22.326	14.871	10.254	6.830	104.023	69.292
Minimum value		1.517	1.266	0.843	4.703	3.133	0.422	0.281	16.041	10.685
Maximum value		4.231	58.074	38.684	60.004	39.970	54.637	36.395	170.062	113.282

According to the classification described already, Pollution Load Index (PLI) values between 1 and 3 indicate moderate contamination, whereas values greater than 3 signify high contamination. As presented in Table 6, PLI values across most study locations were below 3, suggesting generally moderate contamination levels within Delta Central. However, three locations—Ekpan community (LC5), Ugboton community (LC8), and Orerokpe community (LC12)- recorded elevated PLI values relative to other sites, indicating localised areas prone to cumulative trace metal contamination.

Daily intake of metals (DIM) differed markedly between children and adults across all trace metals, reflecting differences in body weight and consumption rates. For copper, the mean DIM values were 8.499 × 10-5 mg/kg/day for children and 5.661 × 10-5 mg/kg/day for adults. Most study locations recorded DIM values below these means, except for Jeddo (LC7), Ugboton (LC8), and Orerokpe (LC12), which exhibited elevated copper intake levels. These locations may therefore become vulnerable to copper-related exposure under scenarios of increased soil Cu concentration.

For zinc, mean DIM values were 22.326 × 10-5 mg/kg/day for children and 14.871 × 10-5 mg/kg/day for adults. The majority of locations fell below these averages; however, Okoribi (LC3), Ugboton (LC8), Oha (LC11), Orerokpe (LC12), and Omavovwe (LC14) recorded higher DIM values, identifying them as potential zinc exposure hotspots if soil Zn levels increase.

Manganese exhibited mean DIM values of 10.254 × 10-5 mg/kg/day for children and 6.830 × 10-5 mg/kg/day for adults. While most locations remained below these thresholds, Ekpan (LC5), Ubomoro (LC6), Jeddo (LC7), Ugolo (LC10), Orerokpe (LC12), and Omavovwe (LC14) showed elevated manganese intake levels, indicating localized susceptibility to Mn exposure.

Lead recorded the highest dietary intake among the assessed metals, with mean DIM values of 104.023 × 10-5 mg/kg/day for children and 69.292 × 10-5 mg/kg/day for adults. In contrast to other metals, a substantial number of locations exceeded the mean DIM values for Pb. These include Eterigbe (LC1), Okoribi (LC3), Alegbo (LC4), Ekpan (LC5), Ugbokodo (LC9), Ugolo (LC10), Afesere (LC13), Omavovwe (LC14), Agbarha-Otor (LC15), Ododegho (LC16), and Iyede (LC18). This widespread elevation indicates that Delta Central is generally vulnerable to lead exposure through dietary intake.

Overall, the combined PLI and DIM results demonstrate that while most locations exhibit moderate contamination levels, lead represents the dominant contributor to dietary exposure risk across the region, particularly for children. These findings underscore the importance of targeted monitoring and mitigation strategies focused on Pb-contaminated agricultural zones.

Health Risk indices

Table 7 presents the Health Risk Index (HRI) values for copper (Cu), zinc (Zn), manganese (Mn), and lead (Pb) resulting from the consumption of cassava (Manihot esculenta) cultivated across Delta Central. The results are evaluated separately for children and adults to account for differences in body weight and dietary exposure.

Table 7: Health risk index result

SN	Sample Location Code	HRI for Cu ($\times 10^{-4}$)		HRI for Zn ($\times 10^{-4}$)		HRI for Mn ($\times 10^{-4}$)		HRI for Pb ($\times 10^{-4}$)	
		Child	Adult	Child	Adult	Child	Adult	Child	Adult
1	L1	6.193	4.125	6.794	4.525	1.723	1.147	330.844	220.383
2	LC2	3.422	2.279	4.965	3.307	6.590	4.390	225.476	150.195
3	LC3	9.616	6.405	11.518	7.672	0.559	0.373	297.173	197.954
4	LC4	6.193	4.125	7.176	4.780	2.498	1.664	305.046	203.199
5	LC5	10.105	6.731	6.975	4.646	15.421	10.272	338.550	225.516
6	LC6	6.519	4.342	6.291	4.191	15.507	10.329	289.300	192.710
7	LC7	24.122	16.068	4.824	3.213	10.467	6.972	44.559	29.682

8	LC8	88.502	58.954	10.010	6.668	2.670	1.779	234.187	155.998
9	LC9	6.030	4.017	4.120	2.745	2.584	1.721	472.395	314.674
10	LC10	9.779	6.514	6.935	4.619	7.925	5.279	314.762	209.671
11	LC11	19.721	13.137	9.327	6.213	6.892	4.591	230.837	153.766
12	LC12	156.958	104.553	19.137	12.747	39.026	25.996	97.159	64.720
13	LC13	9.942	6.622	4.120	2.745	3.661	2.438	373.058	248.503
14	LC14	19.558	13.028	20.001	13.323	8.227	5.480	301.696	200.967
15	LC15	8.149	5.428	3.899	2.597	0.301	0.200	301.864	201.079
16	LC16	11.246	7.491	2.452	1.633	3.704	2.467	399.693	266.246
17	LC17	8.312	5.537	3.839	2.557	0.387	0.258	246.248	164.032
18	LC18	9.127	6.079	1.567	1.044	3.704	2.467	398.353	265.353
Mean value		22.971	15.301	7.441	4.956	7.324	4.879	288.955	192.480
Minimum value		3.422	2.279	1.567	1.044	0.301	0.200	44.559	29.682
Maximum value		156.958	104.553	20.001	13.323	39.026	25.996	472.395	314.674

For copper, the mean HRI values were 22.971 × 10-4 for children and 15.301 × 10-4 for adults. The majority of the study locations recorded HRI values below these means. However, Jeddo (LC7), Ugboton (LC8), and Orerokpe (LC12) exhibited elevated HRI values for Cu, identifying these locations as relatively more vulnerable to copper-related exposure through cassava consumption.

Zinc exhibited mean HRI values of 7.441 × 10-4 for children and 4.956 × 10-4 for adults. Most locations remained below the respective mean values; however, Okoribi (LC3), Ugboton (LC8), Oha (LC11), Orerokpe (LC12), and Omavovwe (LC14) showed elevated zinc-related HRI values, indicating localized potential risk associated with Zn intake.

For manganese, mean HRI values were 7.324 × 10-4 for children and 4.879 × 10-4 for adults. Elevated HRI values were observed at Ekpan (LC5), Ubomoro (LC6), Jeddo (LC7), Ugolo (LC10), Orerokpe (LC12), and Omavovwe (LC14), suggesting these locations are more susceptible to manganese-related dietary exposure.

Lead presented the highest HRI values among all assessed metals, with mean values of 288.955 × 10-4 for children and 192.480 × 10-4 for adults. In contrast to Cu, Zn, and Mn, a substantial number of locations recorded HRI values exceeding the regional mean. These include Eterigbe (LC1), Okoribi (LC3), Alegbo (LC4), Ekpan (LC5), Ugbokodo (LC9), Ugolo (LC10), Afesere (LC13), Omavovwe (LC14), Agbarha-Otor (LC15), Ododegho (LC16), and Iyede (LC18). This widespread elevation indicates that Delta Central is generally prone to lead-related health risks arising from cassava consumption.

Overall, the HRI results demonstrate that although health risks associated with Cu, Zn, and Mn are largely localized and relatively low, Pb represents the dominant contributor to potential non-carcinogenic health risk in the study area, particularly for children. These findings reinforce the need for targeted mitigation strategies and continuous monitoring of lead in agricultural systems within Delta Central.

Comparison analysis with Related Literatures

Table 8 displays a comparative result study between studies done across Nigeria by several researchers and the current study done in Delta Central.

Table 8: Crop and Soil Sample Comparison Study

Soil sample comparison						
SN	Location	Cu conc. (mg/kg)	Zn conc (mg/kg)	Mn conc. (mg/kg)	Pb conc. (mg/kg)	References
1	Ibadan, Oyo State	0.91	0.40	----	0.53	[29]
2	Coastal Communities, Ondo State	358.9	21.20	-------	2506.00	[30]
3	Ilesha LGA, Osun State	26.00	103.90	576.80	38.60	[31]
4	Umuahia, Abia State	14.20	129.01	-------	2.91	[32]
5	Rivers State	2.29	-----	47.94	3.10	[33]
6	Esit Eket, Akwa-Ibom State	24.36	134.68	1782.28	------	[34]
7	Delta Central	0.054	0.525	0.720	2.763	This Study
8	Standard Permissible Limit	36.00	50.00	50.00	85.00	[35]
Crop sample comparison						
9	Uselu and Ologbo, Edo State	0.43	5.35	0.78	-----	[36]
10	Ibadan, Oyo State	0.49	0.05	-----	0.20	[29]
11	Ilorin and Osogbom LGA, Kwara State.	0.17	0.78	----	0.31	[37]
12	Delta Central	0.140	0.370	0.170	1.724	This Study
13	Standard Permissible Limit	10.00	0.60	6.64	2.00	[35]

Based on the comparative analysis presented in Table 3.7, the mean soil copper (Cu) concentration recorded in Delta Central is lower than values reported for Oyo, Ondo, Osun, Abia, Rivers, and Akwa Ibom States. Importantly, the Delta Central mean Cu concentration is substantially below the World Health Organization (WHO) permissible limit of 36.0 mg/kg, indicating minimal copper-related soil contamination relative to both regional and international benchmarks.

Similarly, the mean soil zinc (Zn) concentration in Delta Central is lower than concentrations reported in Ondo, Osun, Abia, and Akwa Ibom States, although it exceeds the value reported for Oyo State. Despite this variation, the mean Zn concentration remains well below the WHO permissible limit value of 50.0 mg/kg, suggesting no immediate zinc contamination concern in the soils of the study area.

The mean soil manganese (Mn) concentration in Delta Central is also lower than values reported in Osun, Rivers, and Akwa Ibom States and remains below the WHO permissible limit value of 50.0 mg/kg. This indicates that manganese levels in the study area soils are within acceptable limits and comparatively lower than several other regions in southern Nigeria.

For lead (Pb), the mean soil concentration in Delta Central is lower than values reported for Ondo and Osun States, comparable to those reported for Abia and Rivers States, and higher than the value reported for Oyo State. Nonetheless, the mean soil Pb concentration in Delta Central remains below the

WHO permissible limit value of 85.0 mg/kg, indicating that, at the soil level, lead contamination is not excessive.

In terms of crop contamination, the mean copper concentration in cassava (Manihot esculenta) from Delta Central is lower than values reported for Edo and Oyo States and comparable to those reported for Kwara State. Although the values across the four regions are relatively similar, all recorded concentrations fall well below the WHO permissible limit value of 10.0 mg/kg, suggesting minimal copper accumulation in the crop.

The mean crop zinc concentration in Delta Central is lower than values reported for Edo and Kwara States but higher than the value reported for Oyo State. Nevertheless, the mean Zn concentration remains below the WHO permissible limit value of 0.60 mg/kg, indicating that zinc accumulation in cassava poses a low health risk.

For manganese, the mean crop concentration in Delta Central is lower than that reported for Edo State, and both values are below the WHO permissible limit value of 6.64 mg/kg. This suggests limited manganese transfer from soil to crop across the study area.

In contrast, the mean crop lead concentration in Delta Central exceeds values reported for Oyo and Kwara States and is close to the WHO permissible limit value of 2.0 mg/kg. This proximity to the regulatory threshold indicates that cassava cultivated in Delta Central is particularly vulnerable to lead accumulation, corroborating the elevated health risk indices observed in earlier sections.

Overall, the comparative assessment reveals that while soil and crop concentrations of Cu, Zn, and Mn in Delta Central are generally lower than or comparable to values reported in other Nigerian states and remain within international safety limits, lead represents a metal of concern. Its relatively elevated crop concentration underscores the need for continued monitoring and targeted risk mitigation to safeguard public health.

IV. CONCLUSION AND RECOMMENDATION

This study assessed the distribution, soil–crop transfer, and potential health risks of selected trace metals (Cu, Zn, Mn, and Pb) in soils and cassava (Manihot esculenta) cultivated across Delta Central, Nigeria. The results show that soil copper concentrations ranged from 0.005 to 0.108 mg/kg, with a mean value of 0.054 mg/kg. Soil zinc concentrations ranged from 0.058 to 2.533 mg/kg (mean: 0.525 mg/kg), manganese from 0.125 to 2.115 mg/kg (mean: 0.720 mg/kg), and lead from 1.805 to 4.183 mg/kg (mean: 2.763 mg/kg).

Spatial analysis revealed that lead had the highest number of locations with concentrations exceeding the Delta Central mean, followed by copper, manganese, and zinc, giving a soil metal dominance order of Pb > Cu > Mn > Zn. Notwithstanding this spatial variability, the mean soil concentrations of all assessed metals were below their respective permissible limits of 36.0 mg/kg (Cu), 50.0 mg/kg (Zn), 50.0 mg/kg (Mn), and 85.0 mg/kg (Pb).

In cassava, copper concentrations ranged from 0.021 to 0.963 mg/kg (mean: 0.140 mg/kg), zinc from 0.078 to 0.995 mg/kg (mean: 0.370 mg/kg), manganese from 0.007 to 0.906 mg/kg (mean: 0.170 mg/kg), and lead from 0.266 to 2.820 mg/kg (mean: 1.724 mg/kg). Lead again exhibited the highest number of locations exceeding the regional mean, followed by manganese, zinc, and copper, resulting in a crop metal ranking of Pb > Mn > Zn > Cu.

While mean crop concentrations of Cu, Zn, and Mn remained below their respective permissible limits of 10.0 mg/kg, 0.60 mg/kg, and 6.64 mg/kg, the mean lead concentration was close to the permissible limit of 2.0 mg/kg, indicating a heightened concern for lead accumulation in cassava. The soil–crop transfer analysis revealed that cassava absorbed copper and zinc more efficiently than manganese and lead relative to their soil concentrations. Furthermore, lead exhibited the highest overall concentration in both soil and crop matrices, with ranking orders of Pb > Mn > Zn > Cu in soil and Pb > Zn > Mn > Cu in cassava, underscoring its persistence and bioavailability in the study area.

Health risk assessment results showed that daily intake values for Cu, Zn, Mn, and Pb for both children and adults were below the WHO-recommended safe intake limits. However, lead exhibited the highest daily intake and health risk index (HRI) values, with the majority of study locations exceeding the regional mean for both age groups. This trend indicates that Delta Central is generally more vulnerable to lead-related exposure through cassava consumption, whereas elevated risks associated with Cu, Zn, and Mn were confined to fewer locations. Although all calculated HRI values were below the WHO threshold value of 1.0, suggesting that the region is not currently under a critical contamination alert, the spatial variability observed indicates localised susceptibility to trace metal accumulation, particularly lead. These findings suggest that any future increase in environmental lead inputs could significantly elevate health risks.

Based on these outcomes, it is recommended that continuous monitoring of trace metals, especially lead, be maintained in agricultural soils and food crops within Delta Central. The promotion of organic soil amendments over chemical fertilizers is advised to minimize potential metal enrichment, consistent with field observations indicating minimal fertilizer use across most study locations. Public awareness programs and site-specific risk management strategies should also be implemented to safeguard food safety and public health.

REFERENCES

[1] Oloruntoba, A., Omoniyi, A. O., Shittu, Z. A., et al. (2024). Heavy metal contamination in soils, water, and food in Nigeria from 2000 to 2019: A systematic review on methods, pollution level and policy implications. *Water, Air, & Soil Pollution*, 235(9), 574.

[2] Ren, E., Zhang, R., Qiu, X., Wang, L., Li, J., Zhao, Y., & Wang, L. (2025). Migration and transformation of heavy metals and metalloids in soil and alfalfa (*Medicago sativa* L.) mediated by citric acid–lanthanum–modified fly ash and assessment of ecological safety thresholds. *Journal of Environmental Chemical Engineering*, 13, 1–15.

[3] Rashid, A., Schutte, B. J., Ulery, A., Deyholos, M. K., Sanogo, S., et al. (2023). Heavy metal contamination in agricultural soil: Environmental pollutants affecting crop health. *Agronomy*, 13, 1–30.

[4] Li, Q., Wang, Y., Li, Y., Li, L., Tang, M., Hu, W., et al. (2022). Speciation of heavy metals in soils and their immobilization at micro-scale interfaces among diverse soil components. *Science of the Total Environment*, 825, 153862. https://doi.org/10.1016/j.scitotenv.2022.153862

[5] Adnan, M., Zhao, P., Xiao, B., Ali, M. U., & Xiao, P. (2025). Heavy metal pollution and source analysis of soils around abandoned Pb/Zn smelting sites: Environmental risks and fractionation analysis. *Environmental Technology & Innovation*, 38, 104084. https://doi.org/10.1016/j.eti.2025.104084

[6] Ghafoor, A., Latif, M., Ali, S., Munir, M., Sattar, M. N., & Alshehri, M. A. (2024). Exploring metal-based nanoparticles for boosting plant tolerance to heavy metals and trace element contamination. *Phyton*, 93(11), 1–23. https://doi.org/10.32604/phyton.2024.055898

[7] Maftukhah, R., Mentler, A., Murtiningrum, N., Hood-Nowotny, R., Zehetner, F., et al. (2025). Field application of local soil amendments to post-tin mining soils: Effects on heavy metal(loid) concentration in crops and soils. *Environmental Technology & Innovation*, 40, 1–14. https://doi.org/10.1016/j.eti.2025.104514

[8] Ma, Y., Dong, B., Bai, Y., et al. (2018). Remediation status and practices for contaminated sites in China: Survey-based analysis. *Environmental Science and Pollution Research*, 25(33), 33216–33224.

[9] Lin, H., Zhou, M., Li, B., et al. (2023). Mechanisms, application advances and future perspectives of microbial-induced heavy metal precipitation: A review. *International Biodeterioration & Biodegradation*, 178, 105544.

[10] Deng, W., Li, F., Chen, X., Guo, J., Gao, C., et al. (2025). Unraveling co-contamination characteristics of heavy metals in soil-crop systems and collaborative management of their health risk across China. *Hygiene and*

Environmental Health Advances, 16, 1–13. https://doi.org/10.1016/j.heha.2025.100151

[11] Chen, M.-Y.-X., Zhang, X.-H., Jiang, P.-P., Liu, J., You, S.-H., & Lv, Y.-R. (2022). Advances in heavy metals detoxification, tolerance, accumulation mechanisms, and properties enhancement of *Leersia hexandra* Swartz. *Journal of Plant Interactions*, 17(1), 766–778. https://doi.org/10.1080/17429145.2022.2096266

[12] Lao, R.-M., Guo, Y.-Y., Hao, W.-X., Fang, W.-J., Li, H.-Y., Zhao, Z.-W., et al. (2023). The role of lignin in the compartmentalization of cadmium in maize roots is enhanced by mycorrhiza. *Journal of Fungi*, 9(8), 852. https://doi.org/10.3390/jof9080852

[13] He, S., Niu, Y., Xing, L., Liang, Z., Song, X., Ding, M., & Huang, W. (2024). Research progress of the detection and analysis methods of heavy metals in plants. *Frontiers in Plant Science*, 1–21. https://doi.org/10.3389/fpls.2024.1310328

[14] Ghuge, S. A., Nikalje, G. C., Kadam, U. S., Suprasanna, P., & Hong, J. C. (2023). Comprehensive mechanisms of heavy metal toxicity in plants, detoxification, and remediation. *Journal of Hazardous Materials*, 450, 131039. https://doi.org/10.1016/j.jhazmat.2023.131039

[15] Guo, Z.-L., Gao, Y.-H., Yuan, X.-Q., Yuan, M.-X., Huang, L., Wang, S.-C., et al. (2023). Effects of heavy metals on stomata in plants: A review. *International Journal of Molecular Sciences*, 24(11), 9302. https://doi.org/10.3390/ijms24119302

[16] Wen, T., Cheng, Y., Yuan, Y., & Sun, R. (2025). Quantitative analysis and risk assessment of heavy metal pollution in an intensive industrial and agricultural region. *Ecotoxicology and Environmental Safety*, 289, 1–14. https://doi.org/10.1016/j.ecoenv.2024.117634

[17] Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metals toxicity and the environment. *EXS*, 101, 133–164. https://doi.org/10.1007/978-3-7643-8340-4_6

[18] Jomova, K., Makova, M., Alomar, S. Y., Alwasel, S. H., Nepovimova, E., Kuca, K., et al. (2022). Essential metals in health and disease. *Chemico-Biological Interactions*, 367, 110173. https://doi.org/10.1016/j.cbi.2022.110173

[19] Gupta, N., & Carmichael, M. F. (n.d.). Zinc-induced copper deficiency as a rare cause of neurological deficit and anemia. *Cureus*, 15, e43856. https://doi.org/10.7759/cureus.43856

[20] Ekong, G. B., Akpa, T. C., Umaru, I., Akpaowo, M. A., Yusuf, S. D., & Benson, N. U. (2021). Baseline radioactivity and associated radiological hazards in soils around a proposed nuclear power plant facility, South-South Nigeria. *Journal of African Earth Sciences*, 182, 1–8. https://doi.org/10.1016/j.jafrearsci.2021.104289

[21] Makieu, P., Kanu, M. S., Sillah, A., & Sheriff, A. (2025). Nutritional values of cassava leaves in three districts, Kenema, Kailahun, and Bo, Sierra Leone. *Food and Humanity*, 4, 100592. https://doi.org/10.1016/j.foohum.2025.100592

[22] Agbalagba, E. O., & Esi, O. E. (2023). Occupational and public risk assessment of NORMs in soil of the Niger Delta region of Nigeria after six decades of hydrocarbon exploitation. *Arabian Journal of Geosciences*, 16, 1–10. https://doi.org/10.1007/s12517-022-11151-w

[23] Mbonu, C. C., Essiett, A. A., & Ben, U. C. (2021). Geospatial assessment of radiation hazard indices in soil samples from Njaba, Imo State, South-Eastern Nigeria. *Environmental Challenges*, 4, 100117. https://doi.org/10.1016/j.envc.2021.100117

[24] Agbalagba, E. O., Nenuwe, O. N., & Owoade, L. R. (2019). Geophysical survey of groundwater potential and radioactivity assessment of soil depth lithology for drinking water-quality determination. *Environmental Earth Sciences*, 78, 1–12. https://doi.org/10.1007/s12665-018-8023-0

[25] Eskina, V. V., Dalnova, O. A., Filatova, D. G., Baranovskaya, V. B., & Karpov, Y. A. (2020). Direct precise determination of Pd, Pt and Rh in spent automobile catalyst solution by high-resolution continuum source graphite furnace atomic absorption spectrometry. *Spectrochimica*

Acta Part B, 165, 105784. https://doi.org/10.1016/j.sab.2020.105784

[26] Arafin, A. K., Bhuiyan, S., Ferdous, J., Hoque, M. A., & Rahman, A. K. (2021). Natural radiation absorbed dose rate and radiation transfer factor from soil to vegetable in selected areas of Chittagong, Bangladesh. *Journal of Southwest Jiaotong University*, 56(4), 1–13. https://doi.org/10.35741/issn.0258-2724.56.4.56

[27] Okoye, E. A., Ezejiofor, A. N., Nwaogazie, I. L., Frazzoli, C., & Orisakwe, O. E. (2022). Heavy metals and arsenic in soil and vegetation of Niger Delta, Nigeria: Ecological risk assessment. *Case Studies in Chemical and Environmental Engineering*, 6, 1–8. https://doi.org/10.1016/j.cscee.2022.100222

[28] Khan, K., Lu, Y., Khan, H., Zakir, S., Khan, I. S., Khan, A. A., & Wang, T. L. (2013). Health risks associated with heavy metals in the drinking water of Swat, Northern Pakistan. *Journal of Environmental Sciences*, 25(10), 1–193.

[29] Olayiwola, H. A., Abdulawal, L., Adewuyi, G. K., & Azeez, M. O. (2017). Heavy metal contents in soil and plants at dumpsites: A case study of Awotan and Ajakanga dumpsites, Ibadan, Oyo State, Nigeria. *Journal of Environment and Earth Science*, 7(4), 11–24.

[30] Ayedun, H. (2021). Sediment quality assessment in coastal communities of Ondo State, Nigeria. *Journal of the Chemical Society of Nigeria*, 46(5), 897–906. https://doi.org/10.46602/jcsn.v46i5.667

[31] Fagbenro, A. A., Yinusa, T. S., Ajekiigbe, K. M., & Obiajunwa, E. I. (2021). Assessment of heavy metal pollution in soil samples from a gold mining area in Osun State, Nigeria using proton-induced X-ray emission. *Scientific African*, 14, 1–14. https://doi.org/10.1016/j.sciaf.2021.e01047

[32] Ogoko, E. C., Kelle, H. I., & Njoku, C. P. (2021). Heavy metals contamination of solid waste disposal sites in Umuahia, Abia State. *Journal of the Chemical Society of Nigeria*, 46(6), 978–984. https://doi.org/10.46602/jcsn.v46i6.679

[33] Edori, O. S., Edori, E. S., & Ntembaba, S. A. (2020). Assessment of heavy metals concentrations in sediments at drainage discharge points into the New Calabar River, Rivers State, Nigeria. *International Journal of Research and Innovation in Applied Science (IJRIAS)*, 5(10), 9–13.

[34] Ubulom, S. R., Ekanim, M. P., Etim, I. N., Yawo, O. J., & Ewu-Oboho, I. (2022). Assessment of contamination status of heavy metals in sediment due to gas flaring at Esit Eket, South Eastern Nigeria. *Researchers Journal of Science and Technology*, 2(1), 50–63.

[35] World Health Organization (WHO). (1996). *WHO permissible limits for heavy metals in plants and soil*. Geneva, Switzerland.

[36] Oyareme, V., Akpogheneta, S. E., Iloba, B. N., & Ogidiagba, F. (2020). Occurrence and concentration of heavy metals in garden egg, tomatoes, cucumber and watermelon from two major markets in Edo State, Nigeria. *Food and Public Health*, 10(3), 63–67. https://doi.org/10.5923/j.fph.20201003.01

[37] Awe, A. E., Adesina, G. O., Adelasoye, S. O., Abiola, S. O., & Adeniji, A. A. (2024). Assessment of the concentration of heavy metals in two vegetables in selected urban metropolises (Ilorin and Osogbo), Nigeria. *African Journal of Agricultural Research*, 20(3), 272–277.