



## Heavy Metal Concentrations and Health Risk Assessment of Cassava Cultivated with Variable Farming Conditions

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**ABSTRACT**

This study assesses the concentrations of heavy metals and associated health risks in sun-dried cassava harvested under four distinct farming conditions in the Niger Delta, Nigeria: normal (control), inorganic fertilizer-treated, herbicide-treated, and crude oil-polluted soils. Using validated digestion protocols and spectrophotometric analysis, levels of Lead (Pb), Cadmium (Cd), Cobalt (Co), Nickel (Ni), and Chromium (Cr) were quantified. Health risk indices such as Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), Hazard Index (HI), Lifetime Cancer Risk (LCR), and Total Lifetime Cancer Risk (TLCR) were calculated for adult and child populations. Results showed that cassava from oil-polluted and chemically treated soils contained higher concentrations of heavy metals, often surpassing FAO/WHO permissible limits. THQ and HI values exceeded the safe threshold (HI > 1.0) in several samples, indicating potential non-carcinogenic health risks. LCR and TLCR values, especially for Cr and Ni, were highest in cassava from fertilizer and oil-impacted soils, exceeding the USEPA safety benchmark (1.0E-04), thus posing long-term carcinogenic risks. The study highlights the significant public health implications of current farming practices in ecologically fragile, oil-producing areas of Nigeria and calls for regulatory oversight, sustainable soil remediation, and community health awareness.

### 1. INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is a drought-tolerant root crop widely cultivated in sub-Saharan Africa and remains a staple food for over 500 million people globally, with Nigeria being its largest producer [1]. The crop's

adaptability to marginal soils and climate variability makes it an essential component of food security in the Niger Delta region. However, increasing concerns have emerged over the contamination of cassava with heavy metals due to anthropogenic activities that affect soil quality and

plant uptake capacity [2,3].

The Niger Delta region of Nigeria, characterized by rich biodiversity and extensive oil reserves, is severely impacted by crude oil spills and gas flaring [4,5]. Crude oil contamination leads to the introduction of toxic heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) into agricultural soils, posing long-term ecological and public health threats [6]. In addition, the indiscriminate use of herbicides and synthetic fertilizers further compounds soil contamination and increases the bioavailability of heavy metals that may be taken up by food crops [7,8]. Cassava, being a root crop, is particularly vulnerable to accumulating these toxicants, making it a potential vehicle for heavy metal exposure to humans through food chains.

Sun-drying, a common preservation technique for cassava in rural Nigeria, may not significantly alter the concentration of inherent heavy metals [9]. Consequently, consumers who rely on such cassava products may unknowingly ingest metal concentrations that exceed the tolerable daily intake limits set by international agencies [10,11]. Chronic exposure to heavy metals through dietary intake has been associated with various health issues, including neurotoxicity, carcinogenicity, kidney dysfunction, and reproductive disorders [12,13]. This necessitates comprehensive health risk assessments of local food crops, especially in environmentally sensitive regions like the Niger Delta.

Human exposure to toxic metals through food has been linked to serious public health effects, including carcinogenesis, neurodevelopmental disorders, renal failure, endocrine disruption, and oxidative stress [13, 14]. Risk assessment frameworks developed by the United States Environmental Protection Agency (USEPA) such as the Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Carcinogenic Risk (CR) provide robust approaches to quantify these risks based on local consumption patterns [15].

Despite growing awareness, there remain a paucity of studies investigating the combined

impact of specific farming conditions, namely crude oil exposure, herbicide usage, and inorganic fertilizer application, on heavy metal accumulation in cassava within the Niger Delta context. Existing literature often isolates these factors or lacks regional specificity [16,17]. Moreover, few studies integrate both contamination data and quantitative health risk assessments to inform policy and public health decisions.

Therefore, this study aims to evaluate the concentration of selected heavy metals in sun-dried cassava root tuber cultivated under distinct farming conditions across four regions in the Niger Delta. It further estimates potential human health risks through standard indices such as the Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Carcinogenic Risk (CR) via ingestion of sun-dried cassava. The findings will contribute to a better understanding of environmental health risks associated with cassava consumption in oil-producing regions and provide a scientific basis for regulatory interventions.

## 2. MATERIALS AND METHOD

### 2.1. *Sample Collection and Preparation*

Cassava (*Manihot esculenta*) root tubers were collected from four distinct farming environments within the Niger Delta region, each characterized by a specific cultivation practice. These included: (i) a control site with no agrochemical input (natural condition), (ii) a site where herbicides were applied during cultivation (herbicide-treated), (iii) a site treated with inorganic fertilizers (fertilizer-treated), and (iv) a site previously exposed to crude oil contamination (oil-spilled).

Upon collection, the cassava tubers were thoroughly washed multiple times with deionized water to remove soil particles and other impurities. The clean tubers were peeled to isolate the edible root portion. The peeled roots were then sliced into uniform discs approximately 10 mm thick.

The sliced samples were subsequently subjected to sun-drying on a raised, stainless-steel mesh platform under direct sunlight. Drying was conducted in an open-air environment between the hours of 9:00 AM and 4:00 PM daily, over a period of 5 to 7 days. Ambient temperature during drying

ranged from 28°C to 35°C. To minimize contamination, the drying trays were covered with fine mesh netting. The drying process continued until a constant dry weight was achieved, indicating complete dehydration.

After sun-drying, the samples were ground into a fine powder using a sterile laboratory-grade mortar and pestle. A 100 g portion of each powdered sample was separately mixed with 100 mL of distilled water. The mixtures were stirred continuously for 30 minutes and then allowed to stand undisturbed for an additional 30 minutes to facilitate sedimentation.

Filtration was carried out using Whatman No. 4 filter paper fitted on a vacuum filtration system. Both the filtrates and solid residues were carefully collected in clean, labeled containers and stored under refrigeration at 4°C until required for subsequent chemical analyses.

## 2.2 Wet Digestion for Heavy Metal Analysis

A modified wet acid digestion procedure was employed for the extraction of heavy metals from cassava powder [18, 19]. Precisely 1.0 g of each powdered sample was weighed into a 100 mL Pyrex digestion flask, to which 10 mL of concentrated nitric acid (HNO<sub>3</sub>, 65%) and 2 mL of perchloric acid (HClO<sub>4</sub>, 70%) were added. The mixture was left to pre-digest at room temperature for 30 minutes, then heated on a hot plate at 120°C until a clear digest was obtained (approximately 1–2 hours).

After cooling, the digest was filtered using Whatman No. 42 filter paper into a 50 mL volumetric flask and made up to volume with deionized water. Blanks and certified reference materials (CRM) were digested alongside the samples for quality control and validation purposes.

## 2.3 Heavy Metal Determination

The concentrations of lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and cobalt (Co) in the digested solutions were determined using an Atomic Absorption Spectrophotometer (AAS) (Model: S4=71096) equipped with appropriate hollow cathode lamps and operated under standard manufacturer-recommended conditions [20].

Calibration was performed using serial dilutions of certified standard solutions (1000 mg/L stock solutions) for each metal. Quality assurance measures included method blanks, duplicates, and spike recovery tests. Where higher sensitivity was required, Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was alternatively employed.

## 2.4 Bioaccumulation Factor (BAF)

The Bioaccumulation Factor (BAF) was calculated to evaluate the capacity of cassava to absorb and accumulate heavy metals from contaminated soils into its edible root tissues. This index reflects the transfer potential of heavy metals from soil to plant and is a critical parameter for assessing food chain contamination [21,22]. BAF was calculated using:

$$\text{BAF} = C_{\text{sun-dried cassava}} / C_{\text{soil}} \quad (1)$$

Where:

$C_{\text{sun-dried cassava}}$  = Concentration of the metal in sun-dried cassava (mg/kg dry weight)

$C_{\text{soil}}$  = Concentration of the metal in corresponding soil sample (mg/kg dry weight)

## 2.5 Health Risk Assessment

Health risk assessment was carried out using standard U.S. Environmental Protection Agency (USEPA) protocols to estimate non-carcinogenic and carcinogenic risks associated with dietary intake of heavy metals in sun-dried cassava [23].

### 2.5.1 Estimated Daily Intake (EDI)

The Estimated Daily Intake (EDI) for each metal was calculated using the equation below:

$$\text{EDI} = \frac{(C \times \text{IR} \times \text{EF} \times \text{ED})}{(\text{BW} \times \text{ATn})} \quad (2)$$

Where:

C = Metal concentration in sun-dried cassava (mg/kg)

IR = Ingestion rate (0.418 kg/day for adults; 0.209 kg/day for children) (FAO/WHO, 2019)

EF = Exposure frequency (365 days/year)

ED = Exposure duration (55 years for adults; 6

years for children)

BW = Body weight (70 kg for adults; 15 kg for children)

ATn = Averaging time (non-carcinogenic = ED × 365 days)

### 2.5.2 Target Hazard Quotient (THQ)

THQ for non-carcinogenic risk was calculated using the formula:

$$\text{THQ} = \frac{\text{EDI}}{\text{RfD}} \quad (3)$$

Where:

RfD = RfD is the reference dose for each metal (mg/kg/day). The reference dose for Pb, Cd, Cr, Ni, and Co via ingestion of sun-dried cassava was 0.0035, 0.001, 0.003, 0.02 and 0.02 [23] respectively.

### 2.5.3 Carcinogenic Risk (CR)

The **Carcinogenic Risk (CR)** was calculated for metals as:

$$\text{CR} = \text{EDI} \times \text{SF} \quad (4)$$

Where SF is the cancer slope factor (mg/kg/day). The SF via ingestion for Pb, Cd, Ni and Cr is 0.0085, 0.38, 1.7 and 0.5 respectively

## 2.6 Statistical Analysis

All measurements were conducted in triplicate. Data were analyzed using SPSS version 24. Means and Standard Error of Means (SEM) were computed, and one-way ANOVA followed by Tukey's post-hoc test was used to assess significant differences ( $p < 0.05$ ) between metal

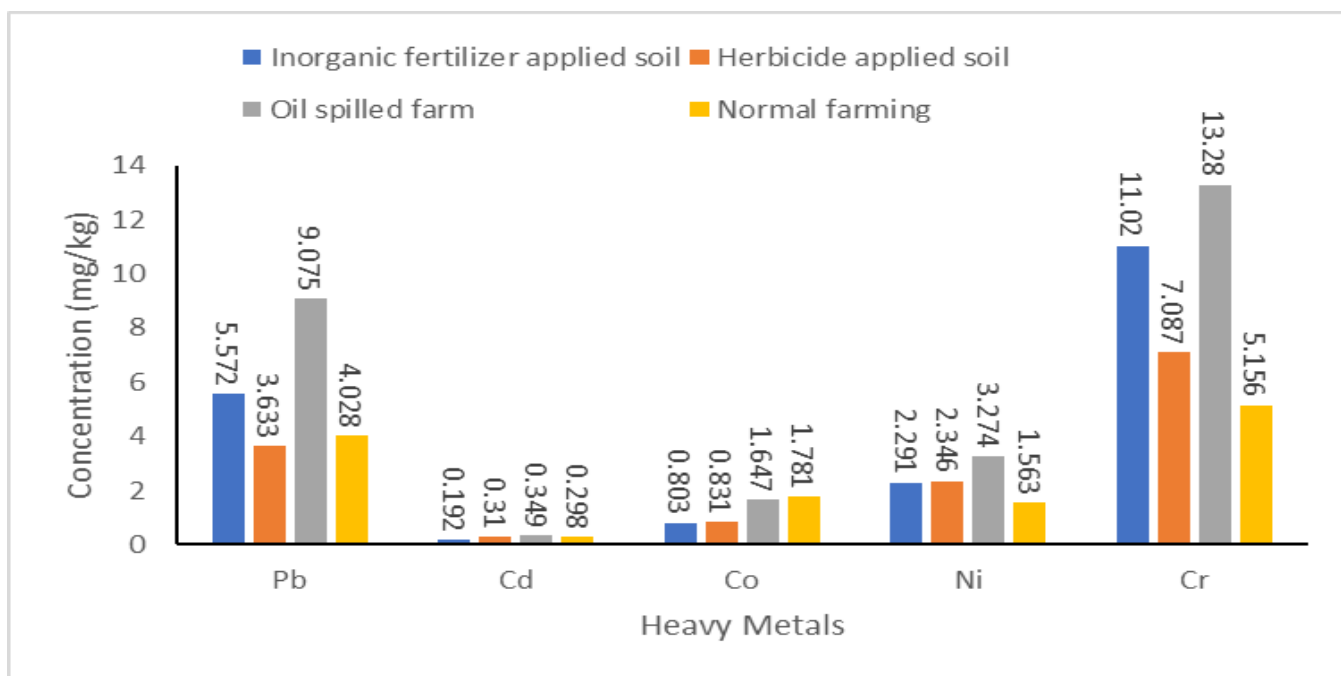
concentrations in samples from different farming conditions.

## 3. RESULTS AND DISCUSSION

### 3.1 Heavy Metals Concentration of Soil Obtained from Sampled Location

The result revealed that the concentrations of heavy metals, Lead (Pb), Cadmium (Cd), Cobalt (Co), Nickel (Ni), and Chromium (Cr) in the soil samples varied with farming conditions in the following decreasing order: oil spilled farm > inorganic fertilizer applied soil > herbicide applied soil > normal farming (Figure 1). This trend is likely attributed to anthropogenic inputs from crude oil pollution, fertilizer residues, and agrochemicals, which significantly influence the bioavailability and accumulation of heavy metals in agricultural soils [16, 24].

Soils contaminated by crude oil typically exhibited increased concentrations of toxic metals due to the association of hydrocarbons with metal complexes and the disruption of soil physicochemical properties [25]. The elevated metal content in the inorganic fertilizer-treated soils may be due to the cumulative input of trace elements commonly found in phosphate fertilizers, especially cadmium and lead [26]. Similarly, herbicide-treated soils, though lower in concentration, may exhibit metal accumulation due to the persistence and degradation products of certain herbicides, which interact with soil particles and nutrients [27]. In contrast, soils under normal farming conditions; that is without chemical treatment, had the lowest metal concentrations, indicating minimal anthropogenic interference.

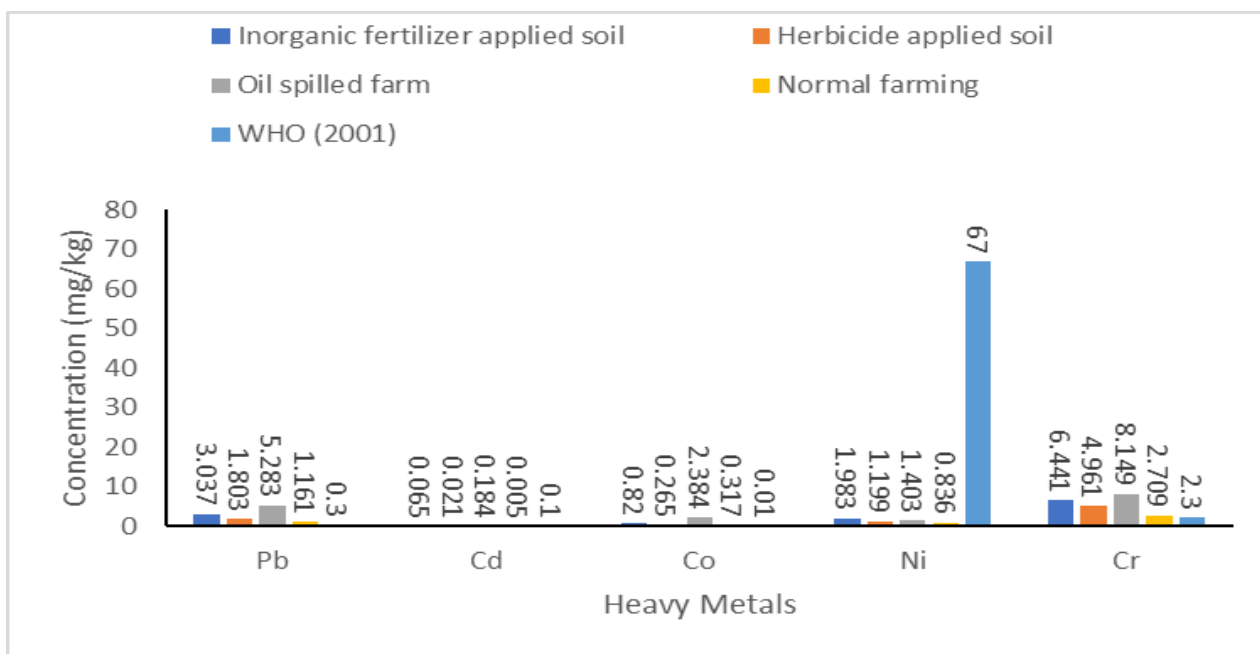


**Figure 1: Heavy Metal Concentration of Soil Obtained from Sampled Location**

These results confirm the environmental burden associated with soil contamination under oil and agrochemical influence. Chromium (Cr) was the most prevalent metal, followed by Pb, Ni, Co, and Cd, which corroborates previous studies that reported high Cr and Pb in petroleum-impacted areas [28, 29]. The soil metal distribution observed may also reflect both direct contamination and long-term bioaccumulation dynamics [30]. Although the work of Hariyadi *et al.*, [31] emphasized that increasing the concentration of fertilizers enhances crop yield and moisture retention, this benefit comes with the trade-off of increased heavy metal uptake in edible plants,

especially in root crops like cassava, which act as metal bioaccumulators. This aligns with the findings of Whalley *et al.* [32], who linked soil chemical interference with increased water uptake and heavy metal mobility in plant roots.

These findings highlight the need for sustainable farming practices, regular soil monitoring, and phytoremediation strategies in regions prone to oil spillage and agrochemical overuse. Heavy metal contamination in agricultural soils is a growing public health concern due to its potential entry into the food chain and its cumulative toxic effects [33].



**Figure 2: Concentration (mg/kg) of heavy metals in dried cassava across the sampling points and WHO permissible limits**

### 3.2 Heavy metal concentration of cassava root tuber obtained from Sampled Location

The concentrations of heavy metals in sun-dried cassava samples varied significantly across the different farming conditions in the following decreasing order: oil-spilled farm > inorganic fertilizer-applied soil > herbicide-applied soil > normal farming soil (Figure 2). This trend suggests that soil contamination due to anthropogenic activities directly influences the bioaccumulation of heavy metals in edible root crops [34].

The overall trend in the mean concentrations of the heavy metals followed the order: Chromium (Cr) > Lead (Pb) > Nickel (Ni) > Cobalt (Co) > Cadmium (Cd). Chromium, being the most abundant in the sun-dried cassava samples, may originate from both natural and anthropogenic inputs such as agrochemicals and industrial effluents [35]. Cadmium had the least concentration across all samples, yet even trace levels of Cd are concerning due to its cumulative toxicity in biological systems [36].

The mean concentration of Pb in cassava ranged from  $1.16 \pm 0.07$  mg/kg in normal farming soil to  $5.28 \pm 0.07$  mg/kg in sun-dried cassava cultivated

on oil-spilled soil (Figure 2). The elevated Pb levels in oil-impacted farms may be attributed to the increased availability and mobility of heavy metals resulting from altered soil physicochemical properties [37]. Pb is non-essential and toxic even at low concentrations, and its bioaccumulation in food crops poses significant health risks. The mean concentration of Cd ranged from  $0.01 \pm 0.00$  mg/kg in normal soil to  $0.18 \pm 0.01$  mg/kg in oil-spilled soil (Figure 2). Though levels were relatively low, cassava from oil-contaminated sites still showed significantly higher Cd concentration. This observation aligns with findings from Agah *et al.* [38], who reported increased Cd uptake in crops grown on petroleum-contaminated soils. Cobalt (Co) levels ranged from  $0.27 \pm 0.12$  mg/kg in herbicide-applied soil to  $2.38 \pm 0.22$  mg/kg in oil-spilled soil (Figure 2). Elevated Co in oil-contaminated soils may result from the decomposition of hydrocarbon fractions and the subsequent release of trace metals [39]. The concentration of Ni ranged from  $0.84 \pm 0.00$  mg/kg in normal farming soil to  $1.98 \pm 0.02$  mg/kg in sun-dried cassava from inorganic fertilizer-applied soil (Figure 2). The observed high Ni levels under

fertilizer application support earlier findings by Hariyadi *et al.* [40], who reported that inorganic fertilizer enhances the solubility of trace metals, thus facilitating their uptake by plants. The concentration of Cr ranged from  $2.709 \pm 0.04$  mg/kg in normal farming soil to  $8.15 \pm 0.06$  mg/kg in sun-dried cassava cultivated on oil-spilled soil (Figure 2). This could be due to its inherent mobility in polluted soils and affinity for plant root accumulation [41].

The observed differences in heavy metal levels among farming conditions may be attributed to the disruption of soil microbial communities and changes in cation exchange capacity caused by agrochemical usage and crude oil pollution [32]. These disruptions impair the soil's ability to bind heavy metals, thereby increasing their bioavailability for plant uptake. The effect was most pronounced in the oil-spilled farm, followed by inorganic fertilizer-applied soil, herbicide-applied soil, and least in the normal farming condition.

### **3.3 Bioaccumulation Factor (BAF) of Sun-dried Cassava Obtained from Sampled Location**

Bioaccumulation factor (BAF) of metals in sun-dried cassava samples varied significantly with the farming conditions in the following increasing order: Normal farming < Inorganic fertilizer-applied soil < Herbicide-applied soil < Oil spilled farm (Table 1). This variation may be attributed to the destruction of soil microbial communities and soil macrofauna due to the presence of herbicides, inorganic fertilizers, and petroleum contaminants. These disturbances reduce the soil's natural capacity to immobilize heavy metals, increasing their mobility and subsequent uptake by the cassava root tubers [42, 43]. The effect is most pronounced with the oil-spilled farm, where the highest BAF values were recorded across most metals, followed by herbicide-applied soil, inorganic fertilizer-applied soil, and finally normal farming soil. The elevated BAFs in polluted soils highlight the environmental risk associated with cultivating root crops in contaminated environments, especially given the dietary significance of cassava in the Niger Delta and broader sub-Saharan Africa [34]. The BAF values

for Lead (Pb) ranged from 0.288 to 0.582 mg/kg (Table 1), with the highest value observed in cassava from the oil-spilled farm and the lowest from the normal farming soil. The increased Pb bioaccumulation in petroleum-contaminated soils may result from the alteration of soil pH and organic matter degradation, which reduces Pb adsorption to soil particles [37, 38]. Cadmium (Cd) BAF values ranged from 0.017 to 0.527 mg/kg (Table 1), following a similar pattern of higher accumulation in oil-polluted soils. Cadmium is known for its high mobility in the soil-plant system and can be readily absorbed by tuberous crops, especially under stressed soil conditions [36]. Cobalt (Co) had BAF values between 0.178 and 1.447 mg/kg (Table 1), with the highest uptake again recorded in cassava from oil-contaminated soil. The degradation of hydrocarbons in oil-polluted soils likely disrupts root zone chemistry, increasing the solubility and plant availability of trace metals such as Co [40]. Interestingly, Nickel (Ni) exhibited a different trend, with BAF values ranging from 0.429 to 0.867 mg/kg (Table 1). The highest Ni BAF was recorded in cassava from inorganic fertilizer-applied soil, while the lowest was found in the oil-spilled farm. This supports previous findings that inorganic fertilizers enhance the solubility of nickel compounds, facilitating their uptake by plants [31, 41]. Chromium (Cr) BAF values ranged from 0.525 to 0.700 mg/kg (Table 1), with the highest recorded in cassava from herbicide-applied soils. Chromium accumulation may be influenced by herbicide-induced stress in the rhizosphere, which alters root membrane permeability and transport proteins, increasing metal uptake [44]. These findings reveal that agrochemical applications and crude oil pollution significantly impact the bioaccumulation potential of cassava plants, raising concerns about food safety and long-term health risks. According to Whalley *et al.* [32], the destruction of beneficial soil organisms and the alteration of soil structure by pollutants reduce soil water and nutrient regulation, thus enhancing the uptake of solutes, including heavy metals. Moreover, Hariyadi *et al.*, [31] emphasized that increasing fertilizer concentration correlates not only with higher yields but also with increased metal accumulation

in edible parts of crops, further compounding the risk in contaminated environments. Table 1 also illustrates that the concentration of heavy metal contamination in crops is sourced from the nature of farming conditions, among all substances

introduced to the soil; petroleum contains the highest amount of lead, cadmium and cobalt; while inorganic fertilizers and herbicides contained the highest amounts of nickel and chromium respectively.

**Table 1: Bioaccumulation Factor (BAF) of Heavy Metals in Sun-dried Cassava Obtained from Sampled Location**

Samples	Pb	Cd	Co	Ni	Cr
Inorganic fertilizer-applied soil	0.545	0.339	1.021	0.867	0.584
Herbicide-applied soil	0.496	0.068	0.319	0.511	0.700
Oil spilled farm	0.582	0.527	1.447	0.429	0.614
Normal farming	0.288	0.017	0.178	0.535	0.525

### 3.4 Estimated Daily Intake (EDI) of Heavy Metals in Adults and Children Population via Consumption of Sun-dried Cassava from Sampled Location

The Estimated Daily Intake (EDI) of heavy metals via consumption of sun-dried cassava varied with the farming conditions in the following increasing order: Normal farming < Inorganic fertilizer applied soil < Herbicide applied soil < Oil spilled farm (Table 2). This could be due to the fact that soil microorganisms and other soil-boring insects have been destroyed by the presence of herbicides, inorganic fertilizers, and spilled petroleum in the soil, thereby reducing the soil's natural buffering capacity and increasing metal mobility and solubility. This promotes the translocation of metals from contaminated soil to the edible portions of cassava [32]. The effect is most severe with the oil spilled farm, where the highest EDI values for Lead (Pb), Cadmium (Cd), Cobalt (Co), Nickel (Ni), and Chromium (Cr) were observed, followed by herbicide-applied soil, inorganic fertilizer-applied soil, and least in the normal farming condition. This pattern may be attributed to the enhanced bioavailability of toxic metals in soils impacted by petroleum hydrocarbons, which alter soil pH, degrade organic matter, and impair microbial diversity, thereby

facilitating metal uptake and accumulation in tuber crops [44]. EDI value of Pb ranged from  $6.88 \times 10^{-4}$  to  $3.13 \times 10^{-3}$  mg/kg/day in adults and  $6.31 \times 10^{-4}$  to  $2.87 \times 10^{-3}$  mg/kg/day in children (Table 2), with the highest values recorded in sun-dried cassava from the oil spilled farm and the lowest from normal farming. This is of public health concern since Pb is non-essential and accumulates in soft tissues, potentially leading to neurological, renal, and developmental disorders, especially in children [36]. EDI of Cd ranged from  $2.96 \times 10^{-6}$  to  $1.09 \times 10^{-4}$  mg/kg/day in adults and  $2.72 \times 10^{-6}$  to  $1.00 \times 10^{-4}$  mg/kg/day in children (Table 2). Again, the highest values were from the oil spilled farm. Cd is a highly toxic element even at trace levels and has been linked to kidney dysfunction, bone demineralization, and carcinogenic risks [37]. Co EDI values ranged between  $1.57 \times 10^{-4}$  and  $1.41 \times 10^{-3}$  mg/kg/day for adults and  $1.44 \times 10^{-4}$  to  $1.30 \times 10^{-3}$  mg/kg/day for children (Table 2). The highest EDI was also observed in the oil spilled farm while the lowest was recorded in sun-dried cassava from herbicide-applied soil. Though Co is essential in trace amounts, elevated intake may interfere with thyroid function and cause cardiotoxicity [41]. EDI for Ni ranged from  $4.95 \times 10^{-4}$  to  $8.31 \times 10^{-4}$  mg/kg/day in adults and  $4.54 \times 10^{-4}$  to  $7.62 \times 10^{-4}$  mg/kg/day in children (Table

2). Ni value of Sun-dried cassava from the inorganic fertilizer farm showed the highest values. Excessive Ni exposure has been linked to dermatitis, respiratory tract effects, and potential carcinogenicity [33]. Cr showed the highest EDI values among the studied metals, ranging from  $1.60 \times 10^{-3}$  to  $4.83 \times 10^{-3}$  mg/kg/day in adults and  $1.47 \times 10^{-3}$  to  $4.43 \times 10^{-3}$  mg/kg/day in children (Table 2). The highest values were recorded in sun-dried

cassava grown on oil spilled soil, while the lowest occurred in normal farming soil. While Cr(III) is essential for glucose metabolism, Cr(VI), which is common in polluted soils, is toxic and potentially

carcinogenic [44]. This might have caused increased transfer of metals into the food chain, particularly for vulnerable populations such as children whose metal absorption rates are higher. The findings corroborate the work of Hariyadi *et al.*, [31], which revealed that increasing fertilizer concentration in soil leads to a corresponding increase in crop yield and nutrient uptake; increased EDI values can therefore also be observed under such intensified soil management conditions.

**Table 2: Estimated Daily Intake (EDI) of Heavy Metals in Adults and Children Population via Consumption of Cassava (Sun-dried) from Sampled Locations**

	Pb		Cd		Co		Ni		Cr	
	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child
Inorganic fertilizer-applied soil	1.80E-03	1.65E-03	3.85E-05	3.53E-05	4.86E-04	4.45E-04	1.18E-03	1.08E-03	3.81E-03	3.50E-03
Herbicide-applied soil	1.07E-03	9.80E-04	1.24E-05	1.14E-05	1.57E-04	1.44E-04	7.10E-04	6.51E-04	2.94E-03	2.70E-03
Oil spilled farm	3.13E-03	2.87E-03	1.09E-04	1.00E-04	1.41E-03	1.30E-03	8.31E-04	7.62E-04	4.83E-03	4.43E-03
Normal farming	6.88E-04	6.31E-04	2.96E-06	2.72E-06	1.88E-04	1.72E-04	4.95E-04	4.54E-04	1.60E-03	1.47E-03
RfD	0.0035		0.05		0.003		0.008		1.5	

### 3.5 Target Hazard Index (THQ) and Hazard Index (HI) of Heavy Metals in Adults and Children Population via Consumption of Cassava from Sampled Location

Target Hazard Quotient (THQ) and Hazard Index (HI) of heavy metals via ingestion of sun-dried cassava varied with the farming conditions in the following increasing order: Normal farming < Inorganic fertilizer applied soil < Herbicide applied soil < Oil spilled farm (Table 3). This

could be due to the fact that soil microorganisms and other soil-boring insects have been destroyed by the presence of herbicides, inorganic fertilizers, and spilled petroleum in the soil, thereby increasing the bioavailability of heavy metals. These contaminants alter the soil's cation exchange capacity and organic matter composition, ultimately facilitating the transfer of toxic metals to the edible portions of cassava [42]. The effect is most severe with the oil spilled farm, followed by the herbicide-applied soil, then the inorganic

fertilizer-applied soil, and finally the normal farming condition. This finding highlights the significant influence of anthropogenic disturbances on heavy metal mobility and their potential health risk when cassava cultivated under these conditions is consumed. THQ for lead (Pb) was highest in cassava from the oil spilled farm, with values of  $8.94 \times 10^{-1}$  for adults and  $8.20 \times 10^{-1}$  for children (Table 3), suggesting a high level of exposure. The lowest Pb THQ was recorded in cassava from normal farming conditions, with values of  $1.96 \times 10^{-1}$  for adults and  $1.80 \times 10^{-1}$  for children (Table 3). These values are particularly

concerning given that Pb is a non-threshold toxicant that can affect neurological development in children even at low exposure levels [36]. For cadmium (Cd), the THQ values ranged from  $2.96 \times 10^{-3}$  to  $1.09 \times 10^{-1}$  in adults and  $2.72 \times 10^{-3}$  to  $1.00 \times 10^{-1}$  in children (Table 3), with the highest observed in the oil spilled farm and the lowest in normal farming conditions. Cd exposure is associated with kidney dysfunction, skeletal damage, and carcinogenic outcomes, even at chronic low-dose exposure [38].

**Table 3: Target Hazard Quotient (THQ) and Hazard Index (HI) of Heavy Metals in Adults and Children Population via Consumption of Cassava Root Tuber from Sampled Location**

Locations	Pb		Cd		Co		Ni		Cr		HI	
	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child
Inorganic fertilizer-applied soil	5.14E-01	4.71E-01	3.85E-02	3.53E-02	2.43E-02	2.23E-02	5.88E-02	5.40E-02	1.27E+00	1.17E+00	1.91E+00	1.75E+00
Herbicide-applied soil	3.05E-01	2.80E-01	1.24E-02	1.14E-02	7.85E-03	7.20E-03	3.55E-02	3.26E-02	9.79E-01	8.98E-01	1.34E+00	1.23E+00
Oil spilled farm	8.94E-01	8.20E-01	1.09E-01	1.00E-01	7.06E-02	6.48E-02	4.15E-02	3.81E-02	1.61E+00	1.48E+00	2.72E+00	2.50E+00
Normal farming	1.96E-01	1.80E-01	2.96E-03	2.72E-03	9.39E-03	8.61E-03	2.48E-02	2.27E-02	5.35E-01	4.91E-01	7.68E-01	7.05E-01
Reference	1		1		1		1		1		1	

THQ of Co via ingestion of sun-dried cassava was also highest in the oil spilled farm at  $7.06 \times 10^{-2}$  for adults and  $6.48 \times 10^{-2}$  for children (Table 3). The lowest values were recorded in cassava from herbicide-applied soil, at  $7.85 \times 10^{-3}$  and  $7.20 \times 10^{-3}$  for adults and children respectively (Table 3). While Co is an essential trace element, excessive intake has been linked to thyroid disruption and cardiomyopathy [41]. Interestingly, nickel (Ni) THQ was highest in cassava from inorganic fertilizer-applied soil, at  $5.88 \times 10^{-2}$  for adults and  $5.40 \times 10^{-2}$  for children (Table 3), and lowest in normal farming soil. The elevated levels under fertilizer application align with previous findings showing that mineral fertilizers may

increase the solubility and uptake of nickel in root crops [31]. THQ values for Cr ranged from  $5.35 \times 10^{-1}$  to  $1.61 \times 10^0$  in adults and  $4.91 \times 10^{-1}$  to  $1.48 \times 10^0$  in children (Table 3). Again, the oil spilled farm recorded the highest values, indicating potential exposure to hexavalent chromium, a known human carcinogen [44].

Hazard Index (HI), which reflects the cumulative non-carcinogenic risk from simultaneous exposure to multiple heavy metals,

exceeded the safety threshold of 1.0 set by USEPA for Inorganic fertilizer-applied soil, Herbicide-applied soil, and Oil spilled farm. The highest value was from the oil spilled farm, whose values

are; 2.72 for adults and 2.50 for children (Table 3), indicating significant potential health [45]. HI value for cassava from the normal farming condition was below the threshold of 1 for both adult and children population (Table 3), indicating no possible health risk. This might have caused increased translocation of heavy metals into the food chain, particularly for children who are more vulnerable due to higher intake-to-body-mass ratio and developing physiological systems. These findings are consistent with the work of Whalley *et al.* [32], who emphasized that pollutants such as petroleum and agrochemicals reduce soil buffering systems, increase root permeability, and promote metal uptake. Similarly, Hariyadi *et al.*, [40] reported that increasing fertilizer concentrations in soil could enhance not only crop yield but also nutrient and heavy metal absorption, hence influencing the THQ and HI values in edible tubers like cassava.

**Table 4: Lifetime Cancer Risk (LCR) and Total Lifetime Cancer Risk (LCR) of Heavy Metals in Adults and Children Population via Consumption of Sun-dried Cassava from Sampled Location**

Locations	Pb		Cd		Ni		Cr		TLCR		
	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child	
Inorganic fertilizer-applied soil	1.53E-05	1.40E-05	1.46E-05	1.34E-05	2.00E-03	1.84E-03	1.91E-03	1.75E-03	3.94E-03	3.61E-03	
Herbicide-applied soil	9.08E-06	8.33E-06	4.73E-06	4.34E-06	1.21E-03	1.11E-03	1.47E-03	1.35E-03	2.69E-03	2.47E-03	
Oil spilled farm	2.66E-05	2.44E-05	4.14E-05	3.80E-05	1.41E-03	1.30E-03	2.41E-03	2.21E-03	3.89E-03	3.57E-03	
Normal farming	5.84E-06	5.36E-06	1.13E-06	1.03E-06	8.42E-04	7.72E-04	8.02E-04	7.36E-04	1.65E-03	1.51E-03	
USEPA (2011)	10 <sup>-6</sup> – 10 <sup>-4</sup>		10 <sup>-6</sup> – 10 <sup>-4</sup>		-	10 <sup>-6</sup> – 10 <sup>-4</sup>		10 <sup>-6</sup> – 10 <sup>-4</sup>		10 <sup>-6</sup> – 10 <sup>-4</sup>	

The effect is most severe with the inorganic fertilizer applied soil, where the highest total lifetime cancer risk (TLCR) values were observed, followed by oil spilled farm, then herbicide applied soil, and least in the normal farming condition. The increased cancer risk under intensive soil treatment and contamination indicates a pressing need for sustainable agricultural practices in these areas. The LCR for Pb in adults ranged from  $5.84 \times 10^{-6}$  (normal farming) to  $2.66 \times 10^{-5}$  (oil spilled farm),

### 3.6 Lifetime Cancer Risk (LCR) and Total Lifetime Cancer Risk (TLCR) of Heavy Metals in Adults and Children Population via Consumption of Sun-dried Cassava from Sampled Location

Lifetime cancer risk (LCR) and total lifetime cancer risk (TLCR) of heavy metals via cassava consumption varied with the farming conditions in the following increasing order: Normal farming < Herbicide applied soil < Oil spilled farm < Inorganic fertilizer applied soil (Table 4). This could be due to the fact that soil microorganisms and other soil boring insects have been destroyed by the presence of herbicides, inorganic fertilizers, and spilled petroleum in the soil, thereby increasing the bioavailability and mobility of toxic heavy metals. This condition facilitates translocation from the soil into the edible parts of cassava tubers [32].

and from  $5.36 \times 10^{-6}$  to  $2.44 \times 10^{-5}$  in children (Table 4), following the same trend. Lead is classified as a probable human carcinogen by the International Agency for Research on Cancer (IARC), and chronic exposure through contaminated foods poses long-term risks [36, 45]. Cd LCR values in adults ranged from  $1.13 \times 10^{-6}$  (normal farming) to  $4.14 \times 10^{-5}$  (oil spilled farm), and in children from  $1.03 \times 10^{-6}$  to  $3.80 \times 10^{-5}$  (Table 4). Cd is a well-established human

carcinogen linked to lung and prostate cancers upon long-term dietary exposure [38]. The elevated values observed in sun-dried cassava from polluted sites reinforce earlier reports of metal mobilization under stressed soil conditions [43]. The LCR for Ni was highest in cassava from inorganic fertilizer applied soil, with values of  $2.00 \times 10^{-3}$  for adults and  $1.84 \times 10^{-3}$  for children. The lowest values were recorded in cassava from normal farming, at  $8.42 \times 10^{-4}$  and  $7.72 \times 10^{-4}$  for adults and children respectively (Table 4). Nickel compounds, particularly soluble salts, are classified as Group 1 carcinogens and pose significant risks when ingested chronically [45]. For Cr, the LCR ranged from  $8.02 \times 10^{-4}$  to  $2.41 \times 10^{-3}$  in adults and  $7.36 \times 10^{-4}$  to  $2.21 \times 10^{-3}$  in children (Table 4), with the highest values observed in cassava from the oil spilled farm. These values suggest possible contamination with hexavalent chromium ( $\text{Cr}^{6+}$ ), which is highly carcinogenic and poses a severe health risk through ingestion [44].

The Total Lifetime Cancer Risk (TLCR), representing the cumulative cancer risk from all metals analyzed, was highest in cassava from inorganic fertilizer applied soil, with values of  $3.94 \times 10^{-3}$  for adults and  $3.61 \times 10^{-3}$  for children. The lowest TLCR was observed in sun-dried cassava from normal farming, at  $1.65 \times 10^{-3}$  for adults and  $1.51 \times 10^{-3}$  for children. These findings are concerning, as values above  $1.0 \times 10^{-4}$  are considered unacceptable by international health and environmental agencies, indicating potential cancer risk over a lifetime [45, 36]. This might have caused increased potential carcinogenic exposure in populations dependent on cassava cultivated under chemically treated or polluted conditions. The work of Hariyadi *et al.*, [40] supported these findings by showing that increasing fertilizer application can intensify metal accumulation in crops, while Whalley *et al.* [32] highlighted that soil health degradation alters metal mobility and uptake. These cumulative effects elevate dietary exposure and long-term health risk, particularly among children, who are more sensitive to toxicants due to their developing physiological systems and higher consumption rates relative to body weight.

#### 4. CONCLUSION

This research evaluates the impact of crude oil pollution and agrochemical use on heavy metal accumulation in cassava. Four farm types; normal, fertilizer-treated, herbicide-treated, and oil-contaminated were assessed across four states in the Niger Delta. The study employed standard analytical procedures to determine heavy metal concentrations and applied established human health risk models (EDI, THQ, HI, LCR, TLCR) for adult and child consumers. Cr and Pb were dominant toxicants in cassava across all impacted sites. Oil-polluted farms exhibited the highest health risk indices. HI values  $>1.0$  were observed in oil-polluted and herbicide-treated soils, particularly in children. LCR and TLCR values exceeded the U.S. EPA safe limit ( $1\text{E-}04$ ) in oil-polluted and fertilizer-treated soils. Normal (control) farm samples had the lowest risk across all indices. Furthermore, it is recommended that immediate regulatory intervention on farming in oil-impacted and agro-chemically saturated lands be put in place. Also, contaminated soils should be remediated using phytoremediation or bioremediation strategies, and food safety monitoring of cassava and similar tubers in industrial regions be done.

#### Conflict of Interest Declaration

The author(s) declare no conflict of interest

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