Communication in Physical Sciences, 2026, 13(9): 1483-1503

Toxic Metals in Farmland Soils of Three Communities in Yenogoa Local Government Area: Concentrations and Impacts Assessment

Augustine Avwerosuo Chokor
Received: 19 May 2026/Accepted: 20 August 2026/Published: 27 August 2026
https://doi.org/10.4314/cps.v13i9.6

Abstract: *sustainable agriculture is closely associated with farmland soils quality which is necessary for crops growth, and adequate supply of healthy foods. In this study, some toxic metals (Zn, Cu, Pb, Cd, Ni, & Cr) contents of soils in farmlands of three communities in Yenagoa LGA were evaluated. Analyses of soils samples were performed with Atomic Absorption Spectroscopy (AAS) after digestions with (5:1) mixtures of nitric and perchloric acids. The result reveals large variations in concentrations of metals in soils within and among the communities. However, the mean concentrations (mg/kg) of metals in the communities' farm soils were: Zn (126.19±55.87), Cu (61.73±29.37), Pb (11.09±6.9), Cd (1.85±0.86), Ni (11.24±4.83), and Cr (2.56±1.53). The average sum of the six determined metals (∑6Metals) in the three communities in decreasing order was: Kpansia (244.71±54.05), Ikarama (205.61±48.28), Amarata (193.37±46.48). The overall average ∑6Metals for the communities was 214.66±50.21mg/kg. Evaluations using various indices reveals overall slight pollution by these metals with cadmium been the major driver of the pollution as reflected by its very high contamination factor. Zinc (Zn) and Cu showed moderate contamination factors, and their contributions to the overall pollutions were secondary. The other trio (Pb, Ni, & Cr) exhibited negligible impact on the overall pollutions due to their low contamination factors. The sequence of metals pollutions in the soils was: Cd > Cu ~ Zn > Pb > Ni > Cr. While the order of pollution in the communities was: Kpansia (KP)> Ikarama (IK) > Amarata (AM).The potential ecological risk index for individual metal (ER) were all low in all communities except for cadmium (Cd) which was very high in AM, extremely high in both KP and IK and thus impacting high risks values on the comprehensive potential ecological risk index (RI). These high levels of cadmium and the tendency of the metals to geo-accumulate in these soils overtime calls for measures to be put in place that will maintain levels that pose negligible human and ecological health risk.*

Keywords: *contamination factor, pollution load, degree of contamination, geo-accumulation, potential ecological risk.*

Augustine Avwerosuo Chokor
Department of Chemistry, Faculty of Science, Federal University Otuoke, P.M.B 126, Yenagoa,
Bayelsa State, Nigeria
Email: chokoraa@fuotuoke.edu.ng
https://orcid.org/0000-0001-5090-7071

1.0 Introduction

Agriculture plays a major role in global food security and economic development. It supports the livelihoods of millions of people and contributes substantially to socioeconomic development. However, sustainable agriculture is fundamentally dependent on healthy and productive soils, which are essential for crop growth and development and the production of safe and nutritious food. Thus, elevated concentrations of potentially toxic metals in agricultural soils pose significant threats to crop productivity, food safety and human health. Heavy metals are generally described as metallic elements and metalloids with relatively high atomic mass and density, although there is no universally accepted definition of the term. These elements occur naturally in the environment and, unlike organic contaminants, cannot be degraded into harmless substances, although they can undergo transformations into different chemical species as soil conditions change or metal-binding organic matter decomposes (Ndema Mbongué et al., 2024; Drall et al., 2025). Heavy metals occur naturally in rock formations and ore minerals; consequently, natural background concentrations of these elements exist in environmental media such as soils, sediments, water and biological tissues. Their generally low background concentrations in environmental media, together with their biological roles, have led to their classification as trace or micronutrient elements (Chokor, 2019; Ramasimong et al., 2025).

Soil contamination by heavy metals occurs when their concentrations increase to levels capable of causing harmful effects on vegetation and other components of the environment (Chokor and Ekanem, 2016). Metal-containing leachates may contaminate groundwater, while humans may be exposed to toxic metals through direct contact with or ingestion of contaminated soil. Human exposure may also occur through the consumption of contaminated groundwater and food products through the food chain (Igwe and Abia, 2006; Chokor, 2019; 2021a). Some metals, including Cu and Zn, are essential micronutrients required for normal physiological and biological functions in living organisms. However, at elevated concentrations, these metals may accumulate in biological tissues and pose adverse health and ecological effects (Al-Anbari et al., 2015; Chokor, 2016; Kowalska et al., 2018). Other metals, such as Pb, Hg and Cd have no known essential biological functions in humans and may produce toxic effects even at relatively low concentrations (Chokor, 2017a; 2019; 2020).

Metal contamination of farmland soils originates from both natural and anthropogenic sources. Natural sources include the weathering of parent rocks, volcanic emissions and atmospheric deposition of mineral particles. Anthropogenic activities are major contributors to heavy-metal contamination and include industrial effluents from mining operations, oil exploration and refining, metal smelting and manufacturing processes (Zhou and Haynes, 2010; He *et al.*, 2015; Chokor, 2020). Other sources include the application of agrochemicals, including phosphate fertilizers contaminated with cadmium and arsenic, copper-based fungicides and zinc-containing pesticides (Zhang et al., 2025). The use of sewage sludge as biosolids, application of animal manure containing elevated metal concentrations from supplemented feeds, and irrigation with untreated industrial wastewater also represent important anthropogenic sources of metal contamination in soils (Wuana and Okieimen, 2011; Kumar et al., 2017). Unlike organic contaminants, microbial and chemical processes in the soil environment generally do not degrade metals. Consequently, metals and their associated ecotoxicological effects may persist in soils for extended periods after their introduction (Zhou and Haynes, 2010).

Elevated metal concentrations in soil may inhibit plant growth, reduce biomass accumulation and decrease crop yield (Scoccianti et al., 2006; Sutapa and Bhattacharyya, 2008). Significant negative correlations between crop yield and concentrations of Cd, Cu, Pb, Zn and Cr in plant roots and shoots have also been reported (Sutapa and Bhattacharyya, 2008). Nickel (Ni) is an essential micronutrient and a component of the urease enzyme required for nitrogen metabolism in higher plants. However, at toxic concentrations, Ni can inhibit plant growth, photosynthesis, seed germination and sugar transport and induce chlorosis, necrosis and wilting (Sreekanth et al., 2013; Bhalerao et al., 2015). Metals in soils can enter food chains, resulting in contamination of forage and food products and potentially causing adverse effects on human health (Bazzi *et al.*, 2020). Exposure to elevated concentrations of toxic metals can cause a range of adverse effects, including gastrointestinal, neurological, renal, hepatic and reproductive disorders (Chokor, 2020; 2021b). Lead, a systemic toxicant, can adversely affect several organs and physiological systems, including the kidneys, liver, hematopoietic system, central nervous system, endocrine system and reproductive system (Ibrahim *et al.*, 2006; Sharma *et al.*, 2014; Singh *et al.*, 2018; Chokor, 2018). Long-term accumulation of cadmium in body tissues and organs can result in kidney dysfunction, hepatic damage and hypertension (Klassen, 2001; Manahan, 2003). Although zinc is essential for normal physiological functions, excessive exposure can cause systemic dysfunction and impair growth and development (Chokor, 2020; 2021a). Similarly, although copper is an essential element, excessive exposure can cause anaemia, hepatic and renal damage and gastrointestinal irritation (Spee *et al.*, 2005). Chromium contamination is of particular concern because certain chromium species, especially hexavalent chromium [Cr(VI)], exhibit toxic, mutagenic and carcinogenic properties (Zhitkovich, 2011; Remy *et al.*, 2017). Exposure to soluble nickel compounds has been associated with respiratory, reproductive and developmental effects (ATSDR, 2000; IARC, 2017; Buxton *et al.*, 2019).

Several indices have been developed to assess the extent of heavy-metal contamination and its potential environmental implications (Kowalska et al., 2018; Chokor, 2019). The contamination/pollution index (C/P) is used to assess the degree of contamination or pollution associated with metal concentrations, while the geoaccumulation index (Igeo) compares current metal concentrations with background or pre-industrial concentrations to determine the severity of metal accumulation and pollution. The contamination factor (CF) evaluates the contamination level of an individual metal relative to its background concentration. Additionally, the potential ecological risk index (PERI) integrates the contamination levels and toxicological responses of individual metals to estimate their potential ecological risks (Abrahim and Parker, 2008; Likuku et al., 2013; Kowalska et al., 2018; Chokor, 2019). The combined application of these indices provides a more comprehensive assessment of the contamination status and potential ecological implications of metals in agricultural soils than concentration data alone.

Bayelsa State, located in Nigeria's Niger Delta region, has experienced prolonged environmental contamination associated with crude-oil exploration and production, gas flaring, pipeline leakages, illegal refining, bunkering activities and industrial waste discharge. Crude oil and petroleum-related wastes may contain trace metals such as vanadium, nickel, lead and chromium. Consequently, oil spills may pose risks not only from hydrocarbon contamination but also from associated metal contaminants. Oil spills, together with other anthropogenic activities, may therefore contribute to the contamination of farmland soils by potentially toxic metals in the region. The occurrence of petroleum-related environmental pollution in the Niger Delta has consequently generated concerns about the quality of agricultural soils and the safety of crops cultivated in affected areas.

Although heavy-metal contamination has been investigated in different environmental compartments of the Niger Delta, information on the current concentrations and contamination status of multiple potentially toxic metals in farmland soils across communities in Yenagoa Local Government Area remains limited. In particular, comparative information on Zn, Cu, Pb, Cd, Ni and Cr in agricultural soils of the selected communities and their potential ecological implications is insufficient. Addressing this gap is important for understanding the present quality of agricultural soils and for supporting appropriate environmental monitoring and soil-management strategies in the study area.

The assessment of toxic metals in farmland soils is therefore important for identifying metals that may constitute particular environmental concerns, establishing the degree of soil contamination, and determining the potential ecological implications of metal accumulation. The findings can provide useful baseline information for environmental monitoring, agricultural soil management, food-safety assessment and the development of appropriate pollution-control strategies in Yenagoa Local Government Area.

Therefore, this study aimed to determine the concentrations of Zn, Cu, Pb, Cd, Ni and Cr in farmland soils from three selected communities in Yenagoa Local Government Area of Bayelsa State, Nigeria, and to assess their contamination and potential ecological risks using relevant pollution and ecological-risk indices.

2.0 Methodology

2.1 Study Area and Site Locations

The study investigated farmland soils in Yenagoa Local Government Area, Bayelsa State, located in Nigeria's Niger Delta region. The study area lies within the broader Niger Delta environment, which extends towards the Gulf of Guinea. The geographical location of Yenagoa LGA within Bayelsa State, its regional context in the Niger Delta and Gulf of Guinea, and the distribution of the selected sampling communities are shown in Figure 1.

Three communities, namely Ikarama (IK; 05°09′17.45″ N, 06°27′08.13″ E), Amarata (AM; 04°55′43.91″ N, 06°17′11.90″ E), and Kpansia (KP; 04°55′47.47″ N, 06°18′49.86″ E), were selected for the investigation (Fig. 1). The communities were selected based on their extensive farming activities, proximity to oil-related infrastructure, and reported history of pollution events. These characteristics provide a relevant setting for investigating the occurrence and distribution of potentially toxic metals in agricultural soils.

Ikarama is a rural community that has experienced several crude-oil spills, making it an important location for investigating the potential influence of petroleum-related pollution on farmland soils. In contrast, Amarata and Kpansia are peri-urban communities that may be exposed to pollution pressures associated with urban and industrial waste disposal, automobile workshops, and domestic wastewater. These differences in settlement characteristics and potential pollution sources provide a basis for examining variations in metal concentrations and contamination status among the selected communities.

The sampling locations are represented by red triangles on the map, while the abbreviations IK, AM and KP identify Ikarama, Amarata and Kpansia, respectively. The map includes a scale bar and north arrow to indicate distance and geographic orientation, while inset location maps show the position of the study area within Bayelsa State and Nigeria. These cartographic features facilitate the identification of the sampling communities and provide geographical context for interpreting the results of the farmland soil investigation.

Figure 1. Map showing the location of Yenagoa Local Government Area in Bayelsa State, Nigeria, and the selected farmland soil sampling communities: Ikarama (IK), Amarata (AM) and Kpansia (KP). Red triangles indicate sampling locations; the map also shows the Niger Delta and Gulf of Guinea context, scale bar, north arrow and inset location maps.

Fig. 1: Map of the study area showing sample sites

2.2 Sample Collection

A standard hand auger was used to collect soil samples from the 0–20 cm surface layer of farmland soils in the three communities. At each sampling location, surface litter was removed before soil collection, and the sampling equipment was cleaned between sampling points to minimize cross-contamination. A total of 135 individual soil samples were collected and combined to obtain 27 composite samples, comprising nine composite samples from each community. Five individual soil samples were combined and thoroughly homogenized to form each composite sample. The composite samples were collected from geographically separated farmlands to improve spatial representation of the study area. The geographical coordinates of the sampling locations were recorded using a handheld GPS device.

The composite soil samples were placed in clean, labeled polyethylene bags and transported to the laboratory for preparation and analysis (Chokor and Ekanem, 2016). The sampling was conducted during the rainy and dry seasons.

2.3 Sample Preparation and Analysis

The soil samples were air-dried in a clean, well-ventilated laboratory environment for approximately two weeks (Chokor, 2017b). Representative portions of the dried samples were obtained using the quartering method. The dried representative soil samples were gently disaggregated using a porcelain mortar and pestle and passed through a 2-mm stainless-steel sieve. A known mass of the sieved soil sample was digested using a 5:1 (v/v) mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$), following the procedure of Tessier *et al.* (1979).

Briefly, 5mL of nitric acid and 1mL of perchloric acid were added to 1g of soil sample in a 150mL digestion tube and digested on a heating digester until white fumes of perchloric acid appeared. The tube was cooled and the sides rinsed with deionized water. The content was filtered through a Whatman No 41 filter paper into a 100mL volumetric flask, and made up to volume with deionized water before instrumental analysis.

The total concentrations of Zn, Cu, Pb, Cd, Ni and Cr in the digested soil samples were determined using an atomic absorption spectrophotometer (Buck Scientific Model 210 VGP). The instrument settings and operational conditions were in accordance with the manufacturer's specifications. Analytical grade standard metal solutions (1mg/L) were used in the calibration of the instrument.

2.4 Quality Control and Quality Assurance

Analytical-grade reagents obtained from BDH and Sigma were used throughout the analysis. Buck Scientific certified standard solutions were used to prepare calibration standards for the atomic absorption spectrophotometer. Calibration curves were prepared for each metal before sample analysis, and instrument response was checked throughout the analytical procedure.

Reagent blanks were subjected to the same digestion procedure using the same quantities of reagents as the samples to account for potential contamination arising from the analytical procedure. Matrix-spike analyses were performed to assess analytical recovery, precision and potential matrix effects. All analytical determinations were performed in triplicate, and the results were expressed as mean ± standard deviation (SD). Recoveries range for the metals were within 92 – 112% connoting the suitability of the method used.

2.5 Contamination and Ecological Risk Assessment

The contamination status and potential ecological risks associated with the measured metal concentrations were evaluated using the contamination/pollution index (C/P), geoaccumulation index (Igeo), contamination factor (CF), modified degree of contamination (mCd), pollution load index (PLI), potential ecological risk factor (ER) and comprehensive potential ecological risk index (RI). The indices were selected to provide complementary information on the contamination status of individual metals, the overall degree of metal accumulation and the potential ecological risks associated with the combined metal concentrations (Abrahim and Parker, 2008; Likuku et al., 2013; Kowalska et al., 2018; Chokor, 2019).

2.5.1 Contamination/Pollution Index (C/P)

The contamination/pollution index (C/P) was used to assess the degree of contamination or pollution associated with the concentration of each investigated metal. The index was calculated according to equation 1

$$C/P = \frac{C_{metal}}{C_{target}} \quad (1)$$

Where, $\boldsymbol{C_{metal}}$ is the measured concentration of the heavy metal in the soil or sample and $\boldsymbol{C_{target}}$ is the target reference/standard limit (e.g., maximum permissible standard, target value, or baseline background concentration).The resulting values were interpreted according to the classification criteria adopted from Lacatusu (1998).

2.5.2 Geoaccumulation Index (Igeo)

The geoaccumulation index (I_{geo}) was used to evaluate the degree of metal accumulation in the farmland soils relative to the selected background concentrations. The index was calculated using equation 2

$$I_{geo} = log_2\left[\frac{C_n}{1.5 \times B_n}\right] \quad (2)$$

where C_n is the measured concentration of the metal in the soil and B_n is its corresponding geochemical background concentration. The factor 1.5 accounts for possible variations in the background concentration caused by lithogenic processes. The Igeo values were classified according to the established categories ranging from unpolluted to extremely polluted (Abrahim and Parker, 2008).

2.5.3 Contamination Factor (CF)

The contamination factor (CF) was used to evaluate the contamination level of an individual metal relative to its background concentration and was calculated using equation 3.

$$CF = \frac{C_n}{B_n} \quad (3)$$

The CF values were interpreted using the standard classification criteria.

2.5.4 Modified Degree of Contamination (mCd)

The modified degree of contamination (mCd) was used to describe the overall degree of contamination resulting from the investigated metals. It was calculated from the contamination factors of the individual metals according to equation 4

$$mC_d = \sum \frac{CF}{n} \quad (4)$$

where, ΣCF represents the sum of the contamination factors for all investigated metals and n is the number of metals evaluated.

2.5.5 Pollution Load Index (PLI)

The pollution load index (PLI) was used to provide an integrated assessment of the overall metal pollution status of the investigated soils. It was calculated as:

$$\mathrm{PLI} = (\mathrm{CF1\ X\ CF2\ X\ CF3} \ldots \mathrm{CFn})1/\mathrm{n} \quad (5)$$

where, CF represents the contamination factor for each metal and n is the number of metals considered. A PLI value of 1 represents baseline levels, whereas values greater than 1 indicate progressive deterioration or pollution relative to the selected background condition.

2.5.6 Potential Ecological Risk Factor (ER)

The potential ecological risk factor (ER) was used to estimate the ecological risk associated with each individual metal by incorporating its contamination level and toxicological response. It was calculated according to equation 6

$$ER = Tr \times CF \quad (6)$$

Where, Tr is the toxic-response coefficient of the metal and CF is its contamination factor. The ER values were interpreted according to the ecological-risk classification.

2.5.7 Comprehensive Potential Ecological Risk Index (RI)

The comprehensive potential ecological risk index (RI) was used to estimate the overall potential ecological risk posed by all investigated metals and was calculated according to equation 7

$$RI = \sum ER \quad (7)$$

where, ER represents the potential ecological risk factor for each individual metal. The RI values were interpreted according to the classification scheme adopted from Hakanson (1980).

2.6 Statistical Analysis

Descriptive statistics were used to summarize the concentrations of the investigated metals in the soil samples from the three communities. Results were expressed as mean ± standard deviation. Correlations between metal's concentrations in the soils were determined with Pearson's correlation; while differences in metal concentrations among communities were evaluated using one-way analysis of variance (ANOVA), with statistical significance established at $p < 0.05$. Statistical analyses were performed using Origin.

3.0 Results and Discussion

3.1 Concentrations of metals in farmland soils

Table 1 presents the mean ± standard deviation and concentration ranges of Zn, Cu, Pb, Cd, Ni and Cr in farmland soils collected from Amarata (AM), Kpansia (KP) and Ikarama

(IK). Considerable spatial variability was observed both within and among the three communities. The overall mean concentrations followed the order Zn > Cu > Ni > Pb > Cd > Cr, with mean concentrations of 126.19 ± 55.87, 61.73 ± 29.37, 11.24 ± 4.83, 11.09 ± 6.90, 1.85 ± 0.86 and 2.56 ± 1.53 mg/kg, respectively. Thus, Zn was the most abundant of the six investigated metals, whereas Cd had a relatively low absolute concentration but was subsequently found to be the most important contaminant when evaluated against background and critical values.

The mean total concentration of the six metals (∑6Metals) was highest in Kpansia (244.71 ± 54.05 mg/kg), followed by Ikarama (205.61 ± 48.28 mg/kg) and Amarata (193.37 ± 46.48 mg/kg). The overall mean ∑6Metals for the three communities was 214.66 ± 50.21 mg/kg.

Table 1: The mean± standard deviation and ranges of metals' concentrations in Farmlands' soils of the different communities

Metals	Mean and range of concentrations (mg/kg)			
	AM	**KP**	**IK**	**Ave**
Zn	118.87±52.40(93.91 - 172.96)	137.46±60.25(107.38 - 190.70)	122.26±54.80(95.30 - 180.17)	126.19±55.87 (118.87 – 137.46)
Cu	53.08±22.32 (41.50 - 77.98)	72.54±37.88 (56.02 - 105.45)	59.58±29.92 (42.63 - 84.56)	61.73±29.37 (53.08 – 72.54)
Pb	8.85±6.10 (2.06 - 15.76)	15.12±7.10 (2.80 - 26.02)	9.29±7.50 (2.21 - 16.30)	11.09±6.9 (8.85 – 15.17)
Cd	1.66±0.75 (0.41 - 2.15)	2.02±1.10 (0.76 - 2.53)	1.88±0.73 (0.59 - 2.23)	1.85±0.86 (1.66 – 2.02)
Ni	9.81±4.73 (7.30 - 15.08)	13.29±5.15 (10.15 - 19.53)	10.62±4.70 (7.90 - 16.33)	11.24±4.83 (9.81 – 13.29)
Cr	1.43±1.00 (0.80 - 2.66)	4.28±2.50 (3.10 - 6.57)	1.98±1.20 (1.31 - 3.37)	2.56±1.53 (1.43 – 4.28)
∑6Metals	193.37±46.48 (168.80 – 281.53)	244.71±54.05 (187.23 – 345,80)	205.61±48.28 (157.93 – 293.95)	214.66±50.21 (193.37 – 244.76)

***range in brackets; AM = Amarata; KP = Kpansia; IK = Ikarama**

The relatively higher total metal concentration observed in Kpansia may reflect its greater exposure to urban, domestic and other anthropogenic inputs, whereas the elevated concentrations observed in Ikarama may be associated with its documented history of petroleum-related pollution. However, these proposed sources should be regarded as possible contributors rather than definitive sources because concentration data alone cannot establish contaminant provenance.

Zinc concentrations ranged from 93.91–172.96 mg/kg in AM, 107.38–190.70 mg/kg in KP, and 95.30–180.17 mg/kg in IK. The corresponding mean concentrations were 118.87 ± 52.40, 137.46 ± 60.25 and 122.26 ± 54.80 mg/kg, respectively. The highest mean Zn concentration occurred in Kpansia. The mean concentrations exceeded the Canadian and Finnish critical values of 50 and 90 mg/kg, respectively, and were also above the 100 mg/kg values reported for Denmark and Eastern Europe. These comparisons indicate that Zn enrichment warrants attention, although the interpretation should acknowledge that guideline values are jurisdiction-specific and may differ in their derivation, land-use assumptions and ecological endpoints.

Copper concentrations were 53.08 ± 22.32 mg/kg in AM, 72.54 ± 37.88 mg/kg in KP and 59.58 ± 29.92 mg/kg in IK. Kpansia therefore recorded the highest mean Cu concentration, whereas Amarata had the lowest. The mean concentrations were above several of the international critical values presented in Table 2. The elevated Cu concentrations may be associated with a combination of agricultural and urban inputs, including copper-containing agrochemicals and wastes; however, additional source-specific evidence would be required to establish the dominant contribution.

Lead concentrations ranged from 2.06–15.76 mg/kg in AM, 2.80–26.02 mg/kg in KP and 2.21–16.30 mg/kg in IK, with mean concentrations of 8.85 ± 6.10, 15.12 ± 7.10 and 9.29 ± 7.50 mg/kg, respectively. Kpansia recorded the highest mean Pb concentration. Although the observed Pb concentrations were generally below most of the critical values presented in Table 2, the considerable spatial variability suggests heterogeneous inputs within the study area. Possible contributors include vehicular activities, waste disposal and petroleum-related activities, but these sources cannot be conclusively established from concentration data alone.

Cadmium recorded mean concentrations of 1.66 ± 0.75, 2.02 ± 1.10 and 1.88 ± 0.73 mg/kg in AM, KP and IK, respectively. These concentrations were above all of the critical values presented in Table 2. In particular, the mean Cd concentrations substantially exceeded the values reported for Canada, Denmark, Finland, the Czech Republic, Ireland, Eastern Europe, Switzerland and the Netherlands. This finding is important because Cd is a non-essential toxic metal and can pose environmental concerns even when its absolute concentration is relatively low. Agricultural inputs, particularly phosphate fertilizers, are recognized potential sources of Cd in cultivated soils. Nevertheless, direct attribution to phosphate fertilizer application requires information on fertilizer type, application rate and historical land-use practices.

Nickel concentrations ranged from 7.30–15.08 mg/kg in AM, 10.15–19.53 mg/kg in KP and 7.90–16.33 mg/kg in IK, with corresponding means of 9.81 ± 4.73, 13.29 ± 5.15 and 10.62 ± 4.70 mg/kg. Kpansia again recorded the highest mean Ni concentration. Except for the comparison with the Canadian critical value, the mean concentrations were generally below the critical limits reported for the countries listed in Table 2. The relatively low Ni concentrations indicate limited enrichment relative to most of the cited guideline values.

Chromium concentrations were 0.80–2.66 mg/kg in AM, 3.10–6.57 mg/kg in KP and 1.31–3.37 mg/kg in IK, with an overall mean concentration of 2.56 ± 1.53 mg/kg. Kpansia had the highest Cr concentration range. The observed concentrations were considerably lower than the critical values presented in Table 2, indicating relatively low Cr enrichment based on the selected guideline comparisons. Nevertheless, the spatial differences in Cr concentration indicate that local variability exists and should be considered when evaluating possible sources.

3.2 Comparison with international critical values

The comparison presented in Table 2 shows that the degree of concern differs considerably among the investigated metals. Zn and Cu showed concentrations exceeding several of the listed critical values, while Pb, Ni and Cr were generally below most of the corresponding limits. Cd showed the most consistent exceedance of the listed critical values. This distinction is important because absolute concentration alone does not adequately describe contamination severity; the interpretation also depends on the selected reference or regulatory value.

Table 2: Critical limits of metals in soil for several countries

Countries	Critical limits (mg/kg)					
	Zn	Cu	Pb	Cd	Ni	Cr
Canada	50	30	25	0.5	20	20
Denmark	100	30	40	0.3	10	50
Finland	90	32	38	0.3	40	80
Czech Republic	150	70	70	0.4	60	130
Netherland	140	36	85	0.8	35	100
Switzerland	200	50	50	0.8	50	75
Ireland	150	50	50	1.0	30	100
Eastern Europe	100	55	32	0.2	85	90

Sources: De Vries and Bakker, 1998; Eastern Europe includes Russia, Ukraine, Moldova and Belarus)

3.3 Contamination/pollution index

The contamination/pollution (C/P) indices calculated using the Canadian critical values are presented in Table 3, while their classification criteria are presented in Table 4. The C/P index represents the ratio between the measured concentration of a metal and its selected critical/reference value. Values greater than one indicate that the measured concentration exceeds the selected reference value.

The mean C/P values for the six metals were 2.53 for Zn, 2.06 for Cu, 0.44 for Pb, 3.71 for Cd, 0.56 for Ni and 0.13 for Cr. Based on the classification presented in Table 4, Zn, Cu and Cd were within the pollution category, whereas Pb, Ni and Cr fell within the contamination category. Cd recorded the highest mean C/P value and was therefore the principal contributor to the overall pollution status.

The mean C/P values for the three communities were 1.40 for AM, 1.78 for KP and 1.53 for IK, with an overall mean of 1.57. These values fall within the slight-pollution category according to the classification adopted in this study. Kpansia had the highest overall C/P value, followed by Ikarama and Amarata. This pattern is broadly consistent with the concentration data and suggests greater overall enrichment in Kpansia. The ranking of the metals based on their mean C/P values was Cd > Zn > Cu > Ni > Pb > Cr. The dominance of Cd is particularly noteworthy because it combines relatively elevated concentrations with a comparatively low critical/reference value. Thus, Cd represents the most important metal requiring attention in the study area.

Table 3: Heavy metal pollution profiles calculate from the range and mean concentrations individual metal C/P index

Samples	Mean and range of C/P values			
	AM	KP	IK	Ave
Zn	2.38 (1.88 – 3.46)	2.75 (2.15 – 3.81)	2.45 (1.91 – 3.60)	2.53 (2.38 – 2.75)
Cu	1.77 (1.38 – 2.60)	2.42 (1.87 – 3.52)	1.99 (1.42 – 2.82)	2.06 (1.77 – 2.42)
Pb	0.35 (0.08 – 0.63)	0.60 (0.11 – 1.04)	0.37 (0.09 – 0.65)	0.44 (0.35 – 0.60)
Cd	3.32 (0.82 – 4.30)	4.04 (1.52 – 5.06)	3.76 (1.18 – 4.46)	3.71 (3.32 – 4.04)
Ni	0.49 (0.37 – 0.75)	0.66 (0.51 – 0.98)	0.53 (0.40 – 0.82)	0.56 0.49 – 0.66)
Cr	0.07 (0.04 – 0.13)	0.21 (0.16 – 0.33)	0.10 (0.07 – 0.17)	0.13 (0.07 – 0.21)
Ave	1.40 (0.07 – 3,32)	1.78 (0.21 – 4.04)	1.53 (0.10 – 3.76)	1.57 (1.40 – 1.78)

***range in brackets; AM = Amarata; KP = Kpansia; IK = Ikarama**

3.4 Geoaccumulation index

The geoaccumulation index (Igeo) values calculated using upper continental crust (UCC) background concentrations are presented in Table 5. The Igeo provides an estimate of the degree to which measured metal concentrations are enriched relative to a selected geochemical background. The index should be interpreted cautiously because UCC values represent generalized background conditions and may not adequately capture the natural geochemical characteristics of the local soils.

Table 4: Significance of intervals of contamination/pollution (C/P) index

C/P	Significance
<0.1	Very slight contamination
0.10 – 0.25	Slight contamination
0.26 – 0.50	Moderate contamination
0.51 – 0.75	Severe contamination
0.76 – 1.0	Very severe contamination
1.1 – 2.0	Slight pollution
2.1 – 4.0	Moderate pollution
4.1 – 8.0	Severe pollution
8.1 – 16.0	Very severe pollution
>16	Excessive pollution

Source: Lacatusu, 1998

The mean Igeo values for Zn were 0.242, 0.452 and 0.283 in AM, KP and IK, respectively, indicating unpolluted to moderately polluted conditions. Copper recorded mean Igeo values of 0.338, 0.788 and 0.504, also corresponding to unpolluted to moderately polluted conditions. The mean Igeo values for Pb, Ni and Cr were negative in all three communities, indicating unpolluted conditions relative to the adopted UCC background values.

Table 5: Ranges and mean Igeo values calculated from Upper continental crust (UCC) background values

Metal	Igeo		
	AM	**KP**	**IK**
Zn	0.242 (-0.098 – 0.783)	0.452 (0.096 – 0.924)	0.283 (-0.077 – 0.842)
Cu	0.338 (-0.017 – 0.893)	0.788 (0.416 – 1.328)	0.504 (0.021 – 1.00)
Pb	-1.2447 (-3.350 - -0.414)	-0.474 (-2.907 – 0.309)	-1.177 (-3.248 - -0.366)
Cd	2.883 (0.866 – 3.256)	3.166 (1.756 – 3.491)	3.063 (1.391 – 3.309)
Ni	-2.845 (-3.272 - -2.225)	-2.407 (-2.796 - -1.852)	-2.731 (-3.158 - -2.110)
Cr	-6.593 (-7.430 - -5.697)	-5.011 (-5.476 - -4.393)	-6.123 (-6.719 - -5.3560)

*range in brackets; UCC values were abstracted from Rudnick and Gao, 2003

Cadmium exhibited a markedly different pattern, with mean Igeo values of 2.883 in AM, 3.166 in KP and 3.063 in IK. These values correspond to; moderately to strongly polluted conditions for AM and strongly polluted conditions for KP and IK, according to the adopted Igeo classification. Cd was therefore the dominant metal responsible for geochemical enrichment in the study soils.

The high Cd Igeo values suggest substantial enrichment relative to the adopted UCC background. Possible sources include phosphate fertilizers, petroleum-related materials, domestic wastes and other anthropogenic inputs. However, because Igeo is dependent on the selected background concentration, the observed enrichment should be interpreted as evidence of relative accumulation rather than definitive proof of a particular source.

3.5 Contamination factor and modified degree of contamination

The contamination factors (CF) and ecological risk factors (ER) presented in Table 6 provide further evidence of differences in metal enrichment among the communities. The mean CF values for Cd were 11.07, 13.47 and 12.53 in AM, KP and IK, respectively. Based on the classification of Hakanson (1980), these values represent very high contamination by Cd in all three communities. Copper and Zn followed Cd in terms of contamination factor, whereas Pb, Ni and Cr generally exhibited lower CF values. The overall order of contamination based on mean CF was Cd > Cu > Zn > Pb > Ni > Cr. This ranking agrees broadly with the C/P and Igeo results and identifies Cd as the principal contaminant of concern.

The modified degree of contamination (mCd) considers the combined contribution of the investigated metals. Mean mCd values were 2.60 for AM, 3.25 for KP and 2.90 for IK, indicating moderate degrees of overall contamination according to the classification adopted in this study. The highest mean mCd occurred in Kpansia, consistent with its higher total metal concentration and C/P value.

However, mCd represents an averaged measure and may obscure the contribution of individual metals. In this study, such masking is particularly important because Cd exhibited very high contamination while several other metals showed comparatively low CF values. Consequently, mCd should be interpreted together with the individual CF values rather than as an independent indication that all six metals pose comparable environmental concerns.

The pollution load index (PLI) provides an integrated measure of the combined contamination factors of the investigated metals. The mean PLI values were 0.65 for AM, 1.00 for KP and 0.73 for IK. These values indicate that the overall pollution burden was greatest in Kpansia. The PLI values for Amarata and Ikarama were below one, while Kpansia was approximately one, suggesting the need for continued monitoring and more detailed investigation of metal accumulation in the agricultural soils.

3.6 Pollution load index and ecological risk

The pollution load index (PLI), modified degree of contamination (mCd), contamination factor (CF), ecological risk factor (ER), and potential ecological risk index (RI) were used to evaluate the degree and ecological implications of heavy-metal contamination in the agricultural soils. The PLI values varied from 0.32 to 1.47, with mean values of 0.65, 1.00, and 0.73 for Amarata (AM), Kpansia (KP), and Ikarama (IK), respectively. Amarata and Ikarama recorded mean PLI values below unity, indicating generally low overall contamination relative to the reference background. In contrast, the mean value for Kpansia was 1.00, suggesting an incipient level of contamination. The maximum PLI of 1.47 occurred in Kpansia, indicating a greater cumulative influence of anthropogenic inputs at this location.

The mean mCd values were 2.60, 3.25, and 2.90 for AM, KP, and IK, respectively. These values indicate moderate overall contamination, with Kpansia showing the highest contamination intensity. The elevated mCd values in Kpansia may reflect the combined influence of agricultural activities, waste deposition, petroleum-related operations, and other local anthropogenic sources. The relatively high value at Ikarama also indicates substantial metal accumulation, although its overall contamination level was lower than that of Kpansia. Amarata exhibited the lowest mean mCd, suggesting comparatively reduced cumulative contamination.

Table 6: lower range (LR), upper range (UR), and mean (M) values for contamination factors (CF), modified degree of contaminations (mCd), Pollution load index (PLI), ecological risk indices (ER), and the comprehensive ecological risk indices (RI) for the different communities

Metal	Amarata (AM)					
	CF			ER		
	LR	UR	M	LR	UR	M

Zn	1.40	2.58	1.77		1.40	2.58	1.77
Cu	1.48	2.79	1.90		7.41	13.93	9.48
Pb	0.15	1.13	0.63		0.74	5.63	3.16
Cd	2.73	14.33	11.07		82.00	430.00	332.00
Ni	0.16	0.32	0.21		0.78	1.60	1.04
Cr	0.012	0.03	0.02		0.02	0.06	0.03
Cd*	5.93	21.18	15.59	RI= ∑ER	92.34	453.80	347.49
mCd	0.99	3.53	2.60				
PLI	0.32	1.01	0.65				
Kpansia (KP)							
Zn	1.60	2.85	2.05		1.60	2.85	2.05
Cu	2.00	3.77	2.59		10.00	18.83	12.95
Pb	0.20	1.86	1.08		1.00	9.29	5.40
Cd	5.07	16.87	13.47		152.00	506.00	404.00
Ni	0.22	0.42	0.28		1.08	2.08	1.41
Cr	0.03	0.07	0.05		0.07	0.14	0.09
Cd*	9.12	25.82	19.52	RI= ∑ER	165.75	539.19	425.91
mCd	1.52	4.30	3.25				
PLI	0.54	1.47	1.00				
Ikarama (IK)							
Zn	1.42	2.69	1.82		1.42	2.69	1.82
Cu	1.52	3.02	2.13		7.61	15.10	10.64
Pb	0.16	1.16	0.66		0.79	5.82	3.32
Cd	3.93	14.87	12.53		118.00	446.00	376.00
Ni	0.17	0.35	0.23		0.84	1.74	1.13
Cr	0.01	0.04	0.02		0.03	0.07	0.04
Cd*	7.22	22.12	14.40	RI= ∑ER	128.69	471.42	392.95
mCd	1.20	3.69	2.90				
PLI	0.54	1.10	0.73				

C_d* refers to degree of contamination

The CF results revealed considerable differences among the investigated metals. Cadmium exhibited the highest contamination factors at all locations, with mean values of 11.07, 13.47, and 12.53 for AM, KP, and IK, respectively. These values indicate very high contamination and identify Cd as the principal contributor to the observed pollution burden. Copper and zinc showed moderate contamination, with mean CF values of 1.90 and 1.77 in Amarata, 2.59 and 2.05 in Kpansia, and 2.13 and 1.82 in Ikarama, respectively. Lead displayed low to moderate contamination, with mean CF values of 0.63, 1.08, and 0.66, while nickel and chromium showed low contamination, with mean CF values of 0.21 and 0.02 in AM, 0.28 and 0.05 in KP, and 0.23 and 0.02 in IK, respectively.

The dominance of Cd may be associated with its persistence, strong affinity for soil organic and mineral phases, and possible inputs from phosphate fertilizers, agrochemicals, petroleum-related activities, and contaminated wastes. Its elevated CF values also suggest that Cd may pose a greater risk of soil–plant transfer and subsequent dietary exposure than the other investigated metals. The relatively elevated Cu and Zn concentrations may reflect both agricultural inputs and localized industrial or petroleum-associated activities. In contrast, the low CF values for Ni and Cr suggest limited enrichment relative to the selected background values.

The ecological risk factors further demonstrated the dominant contribution of Cd to potential ecological risk. Mean ER values for Cd were 332, 404, and 376 in AM, KP, and IK, respectively, whereas the corresponding values for Cu were 9.48, 12.95, and 10.64. The mean ER values for Zn, Pb, Ni, and Cr were comparatively low. Cadmium therefore contributed approximately 95% of the total RI at each location, indicating that ecological risk was strongly controlled by Cd contamination. The high ER values for Cd reflect both its elevated contamination factor and its high toxicity-response coefficient.

The mean RI values were 347.49 for Amarata, 425.91 for Kpansia, and 392.95 for Ikarama. According to the classification presented in Table 7, all three locations fall within the high ecological-risk category. Kpansia recorded the highest RI, followed by Ikarama and Amarata, indicating spatial variation in the magnitude of toxicity-weighted contamination. This pattern agrees with the PLI and mCd results and suggests that Kpansia is the most impacted location. Nevertheless, the high RI values at all sites demonstrate that ecological concern is not restricted to a single area.

The combined indices indicate that Cd is the priority contaminant requiring immediate attention. Although several metals exhibited low or moderate contamination, the high toxicity-weighted contribution of Cd substantially increased the overall ecological risk. Continuous monitoring, source identification, and appropriate soil-management practices are therefore necessary. Further investigations involving metal speciation, sequential extraction, soil physicochemical properties, and plant-uptake studies would improve understanding of Cd bioavailability and its potential transfer into the food chain.

3.7 Correlation analysis and possible sources of metals

The Pearson correlation coefficients among the six metals are presented in Table 8. A very strong positive correlation was observed between Pb and Ni ($r = 0.889$, $p < 0.01$), suggesting that their concentrations varied in a similar manner across the sampled soils. Strong positive relationships were also observed between Zn and Cd ($r = 0.817$) and between Cu and Cd ($r = 0.776$), while Zn and Cu were positively correlated ($r = 0.753$, $p < 0.05$). These relationships may indicate common or partially overlapping sources, similar environmental behaviour or co-transport processes.

In contrast, weak or very weak relationships were observed among several metal pairs, particularly those involving Cr. The relatively weak correlations between Cr and the other metals suggest that its spatial distribution may be influenced by factors different from those controlling the distributions of Zn, Cu and Cd. However, correlation alone cannot establish contaminant sources because similar concentrations can arise from different processes and different metals can behave similarly under common soil conditions.

Principal component analysis (PCA) was therefore used as an additional multivariate approach to investigate patterns of association among the metals. As shown in Table 9, two principal components accounted for approximately 87.0% of the total variance, with PC1 explaining 54.3% and PC2 explaining 32.7%.

PC1 was associated primarily with the group of metals linked broadly with Zn, Cu and Cd. The association of these metals may reflect common contributions from agricultural, urban and industrial activities. PC2 was principally associated with Pb and Ni, which may be consistent with petroleum-related or other anthropogenic inputs in the study area.

However, these interpretations should be considered indicative rather than definitive source assignments, because PCA identifies statistical associations rather than proving specific sources.

The combined correlation and PCA results therefore suggest that the observed metal concentrations may arise from multiple overlapping sources rather than from a single contamination pathway.

Agricultural inputs, urban activities, waste disposal and petroleum-related activities may all contribute to the observed metal distribution. Confirmation of these sources would require additional evidence, such as detailed land-use information, source-specific sampling, soil physicochemical properties, petroleum hydrocarbon measurements and, where appropriate, source-apportionment techniques.

Table 7: Grading standard for single and comprehensive potential ecological risk index

Monomial potential ecological risk factor (ER)	Comprehensive potential ecological risk factor (RI)	Pollution level (ecological hazard)
≤40	≤150	Low
40 – 80	150 – 300	Moderate
80 – 160	300 – 600	High
160 – 320	>600	Very high
>320		Extremely high

(Source: Hakanson, 1980)

Table 8: Correlation matrix showing the relationship between concentrations levels of metals in the soils

	Zn	Cu	Pb	Cd	Ni	Cr
Zn	1.000					
Cu	0.753*	1.000				
Pb	0.431	0.322	1.000			
Cd	0.817**	0.776*	-0.433	1.000		
Ni	-0.217	-0.457	0.889**	-0.314	1.000	
Cr	-0.183	0.305	0.379	0.0953	0.141	1.000

****significant at the 1% level, significant at the 5% level**

Table 9: Summary of Principal component analysis of metals' concentrations in the soils

Test Component	Variable compared	Result	Significance
PCA Component 1	Industrial, Urban& Agricultural activities	54.3%	Dominant
PCA Component 2	Petroleum related activities	32.7%	Secondary

The results demonstrate that Cd represents the principal metal of environmental concern in the investigated farmland soils, despite Zn having the highest absolute concentration. The distinction arises because Cd showed the greatest enrichment relative to its reference values and contributed disproportionately to the ecological risk indices. Kpansia consistently exhibited the highest overall metal burden based on ∑6Metals, C/P, mCd and PLI, while Ikarama also showed substantial enrichment and ecological risk. These findings support the need for continued monitoring of farmland soils, particularly with respect to Cd accumulation and potential transfer into agricultural crops.

4.0 Conclusion

The study assessed the contamination status, ecological risk, and potential environmental implications of six metals (Zn, Cu, Pb, Cd, Ni, and Cr) in farmland soils from Amarata, Kpansia, and Ikarama communities in Yenagoa Local Government Area, Bayelsa State, Nigeria. The overall degree of metal pollution followed the order Kpansia > Ikarama > Amarata, with the comparatively higher contamination at Kpansia plausibly associated with its more urbanized setting and greater exposure to domestic, municipal, industrial, and other anthropogenic wastes. The relatively elevated contamination observed at Ikarama, despite its rural character, is consistent with the documented influence of petroleum-related activities and recurrent oil-pollution events in the area. Statistical analyses further demonstrated substantial variability in metal concentrations among the soils, indicating heterogeneous anthropogenic inputs rather than a uniformly distributed geogenic source.

The mean concentrations of Cd, Zn, and Cu exceeded several international soil critical limits, whereas Pb, Ni, and Cr generally remained below the critical limits reported for most of the countries considered. The C/P index similarly identified Zn, Cu, and Cd as being within the pollution category, while Pb, Ni, and Cr were predominantly within the contamination category. The geoaccumulation index provided further evidence of differential enrichment: Ni, Pb, and Cr were generally classified as unpolluted (Igeo < 0), Zn and Cu as unpolluted to moderately polluted (0 ≤ Igeo < 1), while Cd exhibited moderate to strong pollution, with mean Igeo values of 2.883, 3.166, and 3.063 in Amarata, Kpansia, and Ikarama, respectively.

The contamination factor followed the order Cd > Cu > Zn > Pb > Ni > Cr, demonstrating that Cd was the principal contaminant across the studied farmlands. This finding was reinforced by the ecological risk assessment, in which Cd contributed disproportionately to the potential ecological risk, while the other metals generally presented low individual ecological risk. The mean RI values indicated high potential ecological risk across the three communities, with Cd identified as the dominant contributor to this risk. Principal component analysis further suggested that urban, industrial, and agricultural activities constituted the dominant source group, while petroleum-related activities represented an additional important source, indicating that the observed metal burden is associated with multiple anthropogenic inputs.

Overall, the findings demonstrate that cadmium constitutes the most critical environmental concern in the studied farmland soils, despite the generally lower concentrations of Pb, Ni, and Cr. The PLI values, which ranged from 0.65 in Amarata to 1.00 in Kpansia and 0.73 in Ikarama, indicate that the soils require continued monitoring and more detailed investigation rather than immediate classification as uniformly polluted. The study therefore recommends sustained monitoring of farmland soils, particularly for Cd, Zn, and Cu, together with improved management of agricultural inputs, domestic and industrial wastes, and petroleum-related pollution sources to minimize further accumulation and potential transfer of toxic metals through the agricultural food chain.

5.0 References

Abrahim, G. M. S., & Parker, R. J. (2008). Assessment of heavy metal enrichment factors and the degree of contamination in marine sediments from Tamaki Estuary, Auckland, New Zealand. *Environmental Monitoring and Assessment, 136*, 227–238. https://doi.org/10.1007/s10661-007-9678-2

Ahaneku, I. S., & Sadiq, B. O. (2014). Assessment of heavy metals in Nigerian agricultural soils. *Polish Journal of Environmental Studies, 23*(4), 1091–1100.

Al-Anbari, R., Abdul Hameed, M. J., Obaidy, A. A., & Fatima, H. A. A. (2015). Pollution loads and ecological risk assessment of heavy metals in the urban soil affected by various anthropogenic activities. *International Journal of Advanced Research, 2*, 104–110.

Agency for Toxic Substances and Disease Registry. (2000). *Toxicological profile for nickel (update).* U.S. Department of Health and Human Services, Public Health Service.

Bazzi, I. E. M., Chaouay, A., & others. (2020). Monitoring heavy metal contamination levels and microbiological pollution in seawater of Agadir coastal zones. *Indonesian Journal of Science & Technology, 5*(3), 463–469.

Bhalerao, S. A., Sharma, A. S., & Poojari, A. C. (2015). Toxicity of nickel in plants. *International Journal of Pure and Applied Bioscience, 3*(2), 345–355.

Buxton, S., Garman, E., Heim, K. E., Lyons-Darden, T., Schlekat, C. E., Taylor, M. D., & Oller, A. R. (2019). Concise review of nickel human health toxicology and ecotoxicology. *Inorganics, 7*, 89. https://doi.org/10.3390/inorganics7070089

Chokor, A. A. (2016). Soil profile distribution of heavy metals in automobile workshops in Sapele, Nigeria. *International Journal of Basic Science & Technology, 2*(1), 30–38.

Chokor, A. A. (2017a). The assessment of forms and bioavailability of copper, chromium, and cadmium in soils of automobile workshops using sequential extraction procedure. *Journal of Environmental and Earth Sciences, 7*(5), 67–75.

Chokor, A. A. (2017b). The speciation and potential bioavailability of zinc, manganese, and lead in soils of automobile workshops in Sapele, Nigeria. *Journal of Environmental and Earth Sciences, 7*(3), 98–106.

Chokor, A. A. (2018). Boosting the octane rating of petrol: A review of the trends and impacts on the environment. *American Journal of Environmental Protection, 6*(2), 39–42. https://doi.org/10.12691/env-6-2-2

Chokor, A. A. (2019). Chemical assessment of heavy metals contaminated soil: A review of evaluation indices. *American Journal of Environmental Protection, 7*(2), 34–40. https://doi.org/10.12691/env-7-2-1

Chokor, A. A. (2020). Removal of zinc and lead ions from liquefied natural gas flow station wastewater using modified and unmodified water hyacinths biomass. *Pacific Journal of Science and Technology, 21*(2), 302–309.

Chokor, A. A. (2021a). Metals' content and physicochemical characteristics of well waters in Sapele metropolis, south-southern Nigeria. *Journal of Materials and Environmental Science, 11*(2), 295–307.

Chokor, A. A. (2021b). Impact of urban activities on the physicochemical characteristics and metals content of the Sapele section of the Benin-Ethiope river system, Delta State, Nigeria. *Quest Journal of Research in Environmental and Earth Sciences, 7*(3), 1–8.

Chokor, A. A. (2023). Impact assessment of some toxic phenols and heavy metals in farmlands' soils of Obio-Akpor LGA, Rivers State, Nigeria. *Journal of Materials* *and Environmental Science, 14*(12), 1517–1528.

Chokor, A. A., & Ekanem, E. O. (2016). Heavy metal contamination profile in soil from automobile workshops in Sapele, Nigeria. *World Journal of Analytical Chemistry, 4*(2), 26–28. https://doi.org/10.12691/wjac-4-2-3

De Vries, W., & Bakker, D. J. (1998). *Manual for calculating critical loads of heavy metals for terrestrial ecosystems: Guidelines for critical limits, calculation methods and input data.* TNO Institute of Environmental Sciences, Energy Research and Process Innovation.

De Vries, W., Lofts, S., Tipping, E., Meili, M., Groenenberg, J. E., & Schütze, G. (2007). Impact of soil properties on critical concentrations of cadmium, lead, copper, zinc and mercury in soil and soil solution in view of ecotoxicological effects. *Reviews of Environmental Contamination and Toxicology, 191*, 47–89.

Drall, J. K., Rautela, R., Jambhulkar, R., Kataria, A. K., & Kumar, S. (2025). Effect of heavy metals contamination due to leachate migration from uncontrolled dumpsites: A comprehensive analysis on soil and groundwater. *Journal of Environmental Management, 373*, 123473. https://doi.org/10.1016/j.jenvman.2024.123473

Hakanson, L. (1980). An ecological risk index for aquatic pollution control: A sedimentological approach. *Water Research, 14*, 975–1001.

He, Z., Shentu, J., Yang, X., Baligar, V. C., Zhang, T., & Stoffella, P. J. (2015). Heavy metal contamination of soils: Sources, indicators and assessment. *Journal of Environmental Indicators, 9*, 17–18.

International Agency for Research on Cancer. (2017). *IARC monographs on the evaluation of carcinogenic risks to humans: Nickel and nickel compounds* (Vol. 100C, pp. 169–218). World Health Organization.

Ibrahim, D. B., Wolf, F. A., & Rusyniak, D. L. (2006). Heavy metal poisoning: Clinical presentations and pathophysiology. *Clinics in Laboratory Medicine, 26*, 67–97.

Igwe, J. C., & Abia, A. A. (2006). A bio-separation process for removing heavy metals from wastewater using biosorbents. *African Journal of Biotechnology, 5*(12), 1167–1179.

Klassen, C. D. (2001). Heavy metals and heavy metal antagonists. In L. S. Goodman & A. Gilman (Eds.), *The pharmacological basis of therapeutics* (pp. 1851–1875). McGraw-Hill.

Kowalska, J. B., Mazurek, R., Gąsiorek, M., & Zaleski, T. (2018). Pollution indices as useful tools for the comprehensive evaluation of the degree of soil contamination—A review. *Environmental Geochemistry and Health, 40*, 2395–2420. https://doi.org/10.1007/s10653-018-0106-z

Kumar, V., Chopra, A. K., & Kumar, A. (2017). A review on sewage sludge (biosolids): A resource for sustainable agriculture. *Archives of Agriculture and Environmental Science, 2*(4), 340–347. https://doi.org/10.26832/24566632.2017.020417

Lăcătușu, R. (1998). Appraising levels of soil contamination and pollution with heavy metals. In H. J. Heineke, W. Eckelmann, A. J. Thomasson, R. J. A. Jones, & B. Buckley (Eds.), *Land information systems for planning the sustainable use of land resources* (pp. 393–402). European Soil Bureau, Research Report No. 4, Office for Official Publications of the European Communities.

Lăcătușu, R. (2000). Appraising levels of soil contamination and pollution with heavy metals. *European Soil Bureau Research Report, 4*, 393–402.

Likuku, A. S., Mmolawa, K. B., & Gaboutloeloe, K. G. (2013). Assessment of heavy metal enrichment and degree of contamination around the Copper-Nickel Mine in the Selebi Phikwe region, Eastern Botswana. *Environment and Ecology Research, 1*(2), 32–40.

Manahan, S. E. (2003). *Toxicological chemistry and biochemistry* (3rd ed.). CRC Press.

Müller, G. (1969). Index of geoaccumulation in the sediments of the Rhine River. *Geojournal, 2*, 108–118.

Ndema Mbongué, J. L., Sigué, C., Igor Fulbert, M. N., Nkongho, A. A. O., Yiika, L. P., Nga Essomba, T. P. E., & Eseya Mengu, E. J. (2024). Potentially toxic metals contamination in stream sediments of Mbal area (Pan African Fold Belt, Cameroon). *Discover Geoscience, 2*, 15. https://doi.org/10.1007/s44288-024-00017-1

Ramasimong, K. H., Adeniji, A. O., Itanna, F., Mabaleha, M., Motśoane, M. P., & Qadeer, A. (2025). Assessment of heavy metal pollution at the urban Maputsoe dumpsite, Lesotho and the associated ecological risks. *Discover Toxicology*, 2–20.

Remy, L. L., Byer, V., & Clay, T. (2017). Reproductive outcomes after non-occupational exposure to hexavalent chromium, Willits, California, 1983–2014. *Environmental Health, 16*, 18. https://doi.org/10.1186/s12940-017-0222-8

Rudnick, R. L., & Gao, S. (2003). Composition of the continental crust. In R. L. Rudnick (Ed.), *The crust* (pp. 1–64). Elsevier.

Scoccianti, V., Crinelli, R., Tirillini, B., Mancinelli, V., & Speranza, A. (2006). Uptake and toxicity of Cr(III) in celery seedlings. *Chemosphere, 64*, 1695–1703.

Sharma, R., & Mogra, S. (2014). Lead as a developmental toxicant: A review. *International Journal of Pharmaceutical Sciences and Research, 5*(3), 636–642.

Singh, N., Kumar, A., Gupta, V. K., & Sharma, B. (2018). Biochemical and molecular bases of lead induced toxicity in mammalian systems and possible mitigation. *Chemical Research in Toxicology, 31*(10), 1009–1021.

Spee, B., Mandigers, P. J. J., Arends, B., Bode, P., Vanden-Ingh, T. S. G. A. M., Hoffmann, G., Rothuizen, J., & Penning, L. C. (2005). Differential expression of copper-associated and oxidative stress-related proteins in a new variant of copper toxicosis in Doberman Pinschers. *Comparative Hepatology, 4*, 3. https://doi.org/10.1186/1476-5926-4-3

Sreekanth, T. V. M., Nagajyothi, P. C., Lee, K. D., & Prasad, T. N. V. K. V. (2013). Occurrence, physiological responses and toxicity of nickel in plants. *International Journal of Environmental Science and Technology, 10*, 1129–1140. https://doi.org/10.1007/s13762-013-0245-9

Sutapa, B., & Bhattacharyya, A. K. (2008). Heavy metal accumulation in wheat plant grown in soil amended with industrial sludge. *Chemosphere, 70*(7), 1264–1272.

Tessier, A., Campbell, P. G. C., & Bisson, M. (1979). Sequential extraction procedure for the speciation of particulate trace metals. *Analytical Chemistry, 51*(7), 844–851.

Wuana, R. A., & Okieimen, F. E. (2011). Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation. *ISRN Ecology*, 2011, 402647.

Zhang, L., Liu, X., Sun, Y., Lottermoser, B. G., Boi, R., Windmann, H., Haneklaus, S. H., & Schnug, E. (2025). Risks and governance of heavy metals in European soil-applied phosphate fertilizers. *China Geology, 8*(3), 560–572.

Zhitkovich, A. (2011). Chromium in drinking water: Sources, metabolism, and cancer risks. *Chemical Research in Toxicology, 24*, 1617–1629.

Zhou, Y., & Haynes, R. (2010). Use of inorganic and organic waste for in situ immobilization of Pb and Zn in contaminated soil. In *Proceedings of the 19th World Congress of Soil Science: Soil solutions for a changing world* (pp. 127–130). Brisbane, Australia.

Declaration:

Consent for publication

Not Applicable

Data Availability Statement:

The datasets supporting the findings of this study are available in the manuscripts

Conflict of Interest

Not Applicable

Ethical Considerations

Not applicable

Funding

The author(s) declared no source of funding

Authors' Contributions

All components of the work were carried out by the authors.