

ASSESSMENT OF SELECTED HEAVY METALS FROM KOFAR RUWA AUTOMOBILE MECHANIC WORKSHOP SOIL

*Naseer Inuwa Durumin Iya, Adetunla Faoziyat Adesewa, Hafiz Ahmad

Department of Chemistry, Faculty of Physical Science, Federal University Dutse, P. M. B. 7156, Ibrahim Aliyu Bye-Pass, Dutse, Nigeria

*Corresponding Author Email Address: nasduruminiya@fud.edu.ng

ABSTRACT

Heavy metal contamination of soils has become a major environmental concern due to its potential risk to human health and the ecosystem. This study assessed the levels of selected heavy metals Zn, Fe, Pb, and Cu in soils collected from the automobile mechanic Kofar Ruwa, Kano, Nigeria. Physicochemical parameters such as pH, electrical conductivity, total dissolved solids, soil texture, and organic carbon were tested. Heavy metals were extracted using acid digestion (aqua regia method) and quantified using Atomic Absorption Spectrophotometry (AAS). The results revealed variations in both physicochemical parameters and heavy metal concentrations across the sampling sites. pH values ranged from slightly acidic to neutral (8.04), while EC (1815 uS/cm) and TDS indicated moderate levels of soluble salts in soils influenced by anthropogenic activities. Zn (3.45 ± 0.0012 mg/kg) and Fe (31.58 ± 0.095 mg/kg) concentrations were relatively high in areas near metal workshops, whereas Pb (13.89 ± 3.14 mg/kg) showed elevated levels near refuse dumps, highlighting potential sources of contamination. Correlation analysis indicated significant relationships between heavy metal concentrations and soil physicochemical properties, suggesting that soil pH, organic matter content, and texture influenced metal availability and mobility. The study concludes that human activities significantly contribute to heavy metal accumulation in the soils of the Kofar Ruwa automobile mechanic workshop, with potential environmental and health implications.

Keywords: Heavy metals, Soil contamination, Kofar Ruwa, Automobile, Geo-accumulation Index, Pollution Load Index

INTRODUCTION

Soil is an essential natural resource that is fundamental to sustaining plant growth, controlling water availability, and maintaining environmental quality. Nonetheless, the increasing human activities, such as industrialization, mining, agriculture, and improper waste disposal, have driven the progressive accumulation of heavy metals in soil environments (Chen *et al.*, 2022). Heavy metals, including zinc and iron. Copper and lead are of particular concern because of their persistence, toxicity, and potential to bioaccumulate in food chains. Elements such as Zinc, iron, copper, and Lead stand out in environmental studies. Some, such as Zn, Fe, and Cu, are essential micronutrients for plant, animal, and human health. Zn and Cu function as enzyme cofactors, and Fe is essential in chlorophyll formation and photosynthesis (Abou Seed *et al.*, 2020). However, when present in excessive concentrations or in bioavailable forms, these metals can become toxic. In contrast, Pb is non-essential and highly toxic even at low concentrations (Enyoh, 2022). In agricultural settings, such as in Kofar Ruwa, where farming and human settlement co-exist with possible contamination sources, heavy metal

contamination of soils presents a serious concern. Human activities (vehicular emissions, waste disposal, application of agrochemicals) may elevate high concentrations of Zn, Fe, Cu, and Pb in the soils, thereby threatening soil health, crop productivity, and human food-chain safety (Afolabi *et al.*, 2021). Understanding the levels, distribution, and risk of heavy metals in soils is therefore critical for environmental management, public health protection, and sustainable agriculture. Globally, heavy metal contamination in soils is a significant environmental challenge. Soils contaminated with excessive heavy metals may experience reduced microbial activity, impaired nutrient cycling, decreased fertility, and compromised plant growth. Crops grown on such soils may accumulate heavy metals, which may subsequently enter the human food chain, posing health risks such as neurological, renal, or reproductive disorders (Haghighizadeh *et al.*, 2024). Excessive accumulation of heavy metals in soils can result in reduced soil fertility, impaired microbial activity, and contamination of food crops. For example, high Pb concentrations in soils can lead to its uptake in vegetables, which, when consumed by humans, may cause chronic health issues such as cognitive deficits, kidney damage, and cardiovascular diseases (Enyoh, 2022). Similarly, excessive Fe and Cu can lead to oxidative stress in plants, while high Zn levels may inhibit growth by interfering with the absorption of other essential nutrients (Haghighizadeh *et al.*, 2024).

Despite these risks, there is limited empirical data on the concentration and distribution of heavy metals in Kofar Ruwa automobile mechanic soils. This study seeks to fill this gap by assessing Zn, Fe, Cu, and Pb levels and comparing them with standard permissible limits to understand the potential environmental and health impacts.

MATERIALS AND METHODS

Study Area

Kofar Ruwa is a bustling commercial district located within the Kano Municipal Local Government Area, Kano State, Nigeria. Geographically, it lies roughly between latitude $12^{\circ} 0' N$ and longitude $8^{\circ} 31' E$ within the Sudan Savannah ecological zone (Nigeria Meteorological Agency, 2023). The area experiences a tropical savannah climate, with a distinct dry season (October–April 2023) and a rainy season (May–September 2023). Average annual rainfall ranges from about 800 to 1,000 mm, and mean daily temperatures often exceed $30^{\circ} C$ during the hottest months (NIMET, 2023).

Kofar Ruwa represents a hotspot for heavy-metal contamination in urban Nigerian soils due to intensive human activity, limited formal waste management, and seasonal flooding, which facilitate the mobilization of contaminants into food chains and groundwater (Sagagi *et al.*, 2022). The area comprises small-scale industrial workshops (automobile repairs, metal fabrication, battery

recycling), open markets, residential zones, and peripheral farmlands. High vehicular traffic further contributes to the deposition of metals such as lead (Pb) from fuel combustion and tire wear, zinc (Zn) from lubricants and galvanized materials, iron (Fe) from vehicle parts, and copper (Cu) from metal plating and paint residues. These combined anthropogenic pressures make Kofar Ruwa an ideal site for assessing spatial variability and potential ecological risks of soil metal contamination (Wei *et al.*, 2023; RSC Advances, 2023).

Research Design and Sampling Framework

The study employed a cross-sectional experimental design aimed at determining the concentrations of Zn, Fe, Pb, and Cu in surface soils from various land-use areas. This design was chosen because it provides an effective means of comparing contamination levels at different locations during a specific period, reflecting the influence of anthropogenic sources (Abakumov *et al.*, 2023).

Sampling Site Selection

Five (5) sampling sites with roughly 150 meters between them were purposely selected within Kofar Ruwa to represent major land-use types: At each site, soil samples were collected from a depth of 0–15 cm using a clean stainless-steel auger. Five sub-samples were taken per site, thoroughly mixed to form a composite sample, and stored in labeled polyethylene bags (Adebayo *et al.*, 2021). All chemicals employed were of analytical reagent grade. Deionized and distilled water were used throughout sample preparation. Nitric acid (69% HNO₃), hydrogen peroxide (30% H₂O₂), and hydrochloric acid (HCl) were utilized for sample digestion. Stock standard solutions (1000 ppm) were prepared for the selected heavy metals (Pb, Fe, Cu, and Cd). All sample containers and glassware used in this study were thoroughly cleaned with detergent and soaked in 30% nitric acid for 2 h to remove any adsorbed metal ions. Subsequently, the materials were rinsed with tap water followed by distilled water and dried in a dust-free environment (Bahiru *et al.*, 2020).

Sample Collection and Preparation

The sample for the study was collected from Kofar Ruwa, Kano state, Nigeria. Soil samples were collected from five (5) different coordinates with Latitude (°N) and Longitude (°E) as follows: 12.02597 and 8.49444, 12.01717 and 8.49125, 12.01458 and 8.49119, 12.00894 and 8.48942, 12.00894 and 8.48942, 12.01111 and 8.49075 within Kofar Ruwa. It was collected at three depth intervals: 0–10 cm (topsoil), 10–20 cm, and 20–30 cm at each sampling point (Magajiya, 2023). The samples were properly labeled, placed in polyethylene bags, and transported to the laboratory for analysis. In total, thirty (30) soil samples were collected, and prior to analysis, the samples were air-dried at room temperature for three days, homogenized using a ceramic mortar and pestle, and sieved through a 2-mm mesh (Aqua Energy Expo, 2023).

Quality Control during Sampling

To ensure data reliability and minimize contamination, all sampling equipment was acid-washed with 10% HNO₃ and rinsed with distilled water before and after use (APHA, 2017; Kumar *et al.*, 2022). Soil samples were collected in labeled polyethylene bags, stored at approximately 4 °C to preserve physicochemical properties (Lucas *et al.*, 2020; CT DEEP, 2024), and a control site

with minimal anthropogenic influence was included for baseline comparison (Ali *et al.*, 2021). Field duplicates were collected at a frequency of one per five samples to assess field variability and ensure analytical precision and reproducibility (ITRC, 2023; Minnesota Department of Agriculture, 2023).

Determination of Physicochemical Parameters

Physicochemical properties of the soil samples were analyzed to better understand the environmental factors that influence the concentration, mobility, and bioavailability of heavy metals within the study area. The selected parameters were analyzed following standard methods prescribed by the American Public Health Association (Ahmed *et al.*, 2023).

Soil pH

Soil pH was measured using a digital pH meter (Model Hanna HI-2211) in a 1:2.5 soil-to-water suspension. Ten grams (10 g) of air-dried, sieved (< 2 mm) soil were weighed into a 50 mL beaker, mixed with 25 mL of distilled water, stirred, and allowed to stand for 30 minutes. The pH electrode was then inserted into the supernatant, and readings were recorded after stabilization. pH provides insight into soil acidity or alkalinity, which strongly influences metal solubility and adsorption capacity (Wei *et al.*, 2023).

Electrical Conductivity (EC)

Electrical conductivity was determined in the same soil–water suspension used for pH, using a conductivity meter (Hanna HI-2315). EC values, expressed in $\mu\text{S cm}^{-1}$, indicate the total soluble salts in the soil, reflecting ionic concentration and potential metal mobility (Musa *et al.*, 2023).

Moisture Content

Moisture content was determined by the gravimetric method. Approximately 10 g of soil was weighed into a crucible (W_1), oven-dried at 105 °C for 24 h, and re-weighed (W_2).

$$\text{Moisture content was calculated (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \quad (1)$$

Moisture affects redox potential and influences heavy-metal oxidation states and retention in soils (Aliyu *et al.*, 2023),

Organic Matter Content

The Walkley–Black dichromate oxidation method was used to determine organic matter content. About 1.0 g of air-dried soil was treated with potassium dichromate (K₂Cr₂O₇) and concentrated sulfuric acid (H₂SO₄). The mixture was allowed to react, and the excess dichromate was titrated with standardized ferrous sulfate solution (FeSO₄). The percentage of organic matter was later derived from the calculated organic carbon (Okonkwo and James, 2024).

$$\% \text{ organic matter} = OC \times 1.724\%$$

Organic Carbon

The percentage of organic carbon was determined directly from titration results using the Walkley–Black formula:

$$\% \text{ Organic Carbon} = \frac{10}{2} (B - T) \times 0.003 \times \frac{f}{S} \quad (2)$$

Where:

V_1 represents the volume (mL) of ferrous sulfate consumed in the blank determination, while V_2 denotes the volume (mL) of ferrous sulfate used for the sample.

M = Normality of ferrous sulfate solution

0.003 = Equivalent weight of carbon in grams for 1 mL of 1N FeSO₄
Weight of Soil = Weight (g) of soil used

Soil Texture

Soil texture was determined using the hydrometer method based on particle size distribution (APHA, 2023). In this method, 50 g of soil was dispersed in a sodium hexametaphosphate solution and shaken for 16 hours. Hydrometer readings were recorded at 40 seconds and 2 hours to determine the percentages of sand, silt, and clay.

Digestion and Analysis of Soil

The procedure described by Kaseem (2020) was adopted with several modifications. The soil samples were air-dried, then followed by an oven in order to ensure the removal of moisture. The samples were repeatedly crushed with the aid of a mortar and pestle and sieved with a 2mm mesh sieve to obtain the fine particles. 0.5g of each sample were accurately weighed into a beaker, followed by addition of 10 mL of concentrated nitric acid (HNO₃) was heated at 95° C for 15 minutes without boiling, and allow to cool, then 5 mL of Nitric (HNO₃) was added again and heat till no brown fumes are observed, followed by addition of 2 mL of distilled water and 3mL of 30% of hydrogen peroxide drop wise and was heated to reduce the volume to 5 mL. The samples were immediately treated with 10 mL of an acid mixture (HCl:HNO₃ in a 3:1 ratio) and gently heated on a hot plate for 2 hours until near dryness. Subsequently, 25 mL of deionized water was added, and the mixture was filtered using a Whatman 125 mm filter into a 50 mL volumetric flask. The filtrate was then diluted to the mark with deionized water (Durumin Iya *et al.*, 2018). A blank solution was prepared following the same procedure. Triplicate aliquots of both the samples and the blank were analyzed using an Atomic Absorption Spectrophotometer (AAS) at the Central Laboratory, Bayero University Kano (BUK).

Determination of Heavy Metals

The concentrations (in mg/kg) of Zn, Fe, Pb, and Cr were determined using an Atomic Absorption Spectrophotometer (AAS) (Model: Buck Scientific 210 VGP). Calibration standards were prepared from certified stock solutions, and absorbance readings were taken at specific wavelengths (Lawal *et al.*, 2023).

Quality Assurance and Control (QA/QC)

All glassware and equipment were pre-cleaned with 10% nitric acid and rinsed with distilled water to prevent contamination (Balogun *et al.*, 2024). Analytical blanks and standards were processed alongside samples, and duplicate measurements were performed, with results expressed in mg/kg dry weight. Instrument calibration and recovery tests followed APHA (2023) standard methods.

Laboratory Quality Assurance

Prior to digestion and metal analysis, instrument performance and reagent purity were verified according to FAO (2023), WHO (2024), and NESREA (2024) guidelines to minimize contamination and ensure analytical precision. All reagents and acids were of

analytical grade (≥99% purity) (FAO, 2023; Magajiya, 2023), and glassware and digestion vessels were acid-soaked, rinsed, and air-dried to remove residual metal ions (WHO, 2024; Olaye and Musa, 2025). The Atomic Absorption Spectrophotometer (AAS) was calibrated using 1000 mg/L certified standard solutions, with blank samples included in each batch to monitor potential contamination (FAO, 2023; NESREA, 2024; WHO, 2024). These procedures ensured that analytical results were precise, reproducible, and traceable, in accordance with international standards for environmental monitoring.

Calibration and Recovery Test

The AAS instrument was zeroed with a blank solution before each element analysis. Calibration curves were generated for each metal using at least five standard solutions of known concentrations (e.g., 0.5, 1.0, 2.0, 5.0, and 10.0 mg/L). The correlation coefficient (R²) for all calibration curves was maintained at ≥ 0.995, confirming linearity and reliability of the instrument response. To evaluate accuracy and recovery, a spiked sample test was carried out. Known amounts of each metal standard were added to pre-digested soil samples, and recovery percentages were calculated using the formula: Acceptable recovery values ranged between 80 % and 120 %, as recommended by the U.S. Environmental Protection Agency (USEPA, 2024) and ISO 17025 laboratory standards.

Data Validation and Analysis

The analytical results were validated using the internationally certified Standard Reference Material (SRM 2709a, San Joaquin Soil), which was used for quality control and validation of the analytical procedures, ensuring reliability and traceability of measurements (WHO, 2024; FAO, 2023). Outliers were identified using Grubbs' test and rechecked or excluded to maintain dataset integrity (Musa *et al.*, 2025). Implementation of rigorous QA/QC procedures ensured the accuracy, precision, and reproducibility of heavy metal determinations (WHO, 2024; NESREA, 2024). Data analysis was performed in Microsoft Excel, calculating mean, standard deviation, and range for each metal. One-way ANOVA was used to evaluate significant differences among sites (p < 0.05). Soil contamination and ecological risk were assessed using geo-accumulation index (I_{geo}), pollution load index (PLI), and contamination factor (CF), while correlation analysis explored relationships between physicochemical parameters and metal concentrations, identifying factors influencing metal mobility and retention in soils (Magajiya *et al.*, 2003).

RESULTS

Physicochemical Parameters

Physicochemical parameters serve as key indicators of soil quality. They influence the chemical behavior, adsorption capacity, and mobility of heavy metals within the soil system (Adeleke *et al.*, 2023). The measured values for these parameters are presented in Table 1.

Table 1: Shows the pH, EC, OC, OM, moisture and Texture of the soil

Sample	pH Value	EC ($\mu\text{S}/\text{cm}$)	OC %	OM %	Moisture (%)	ST
Sample 1	7.89	1784	1.596	2.75	5.35	Sandy
Sample 2	7.69	1400	1.157	2.00	5.60	Clay
Sample 3	7.98	1154	0.68	1.12	4.94	Sandy
Sample 4	8.04	645	0.96	1.651	4.24	Sandy
Sample 5	7.89	1815	0.31	1.44	4.98	Loamy
Mean \pm SD	7.898 \pm 0.133	1359.6 \pm 485.1	0.941 \pm 0.485	1.792 \pm 0.624	5.022 \pm 0.515	
RSD (%)	1.68	35.7	51.6	34.8	10.3	

SD= standard deviation, EC=electrical conductivity, OC=organic carbon, OM=organic matter, ST=soil texture and RSD=relative standard deviation. The samples were three replicates n=3

Soil pH

Soil pH plays a critical role in controlling nutrient availability and metal solubility. The Kofar Ruwa soils were slightly alkaline, with pH values between 7.69 and 8.04 and an average of 7.90 ± 0.13 (RSD = 1.68%). Such alkaline conditions can decrease metal mobility by enhancing adsorption onto soil particles, thereby limiting potential groundwater contamination (Adeleye *et al.*, 2022). Alkaline soil pH strongly influences microbial activity, organic matter decomposition, and nutrient cycling by altering microbial community composition, enzyme activity, and metabolic functions, often suppressing decomposition processes while favoring alkali-tolerant microorganisms. These pH-driven changes also affect nutrient mineralization and solubility, reducing the availability of essential nutrients to plants and highlighting soil pH as a central regulator of soil fertility and ecosystem functioning (Neina, 2025; Mitsuta *et al.*, 2025). The low RSD reflects high consistency among sampling sites, indicating relatively uniform soil conditions across the study area.

Electrical conductivity (EC)

Electrical conductivity (EC) values ranged from 645 to 1815 $\mu\text{S}/\text{cm}$, with a mean of 1359.6 ± 545.9 $\mu\text{S}/\text{cm}$ (RSD = 40.2%), reflecting moderate variability in soil salinity. EC represents the total ionic strength of the soil solution and plays an important role in metal solubility, as elevated EC can enhance the mobility of certain metals, whereas lower EC limits their availability (Okonkwo *et al.*, 2021). The moderate salinity observed in soils is the result of both natural and anthropogenic drivers. Naturally, salts originate from the weathering of parent rock material, groundwater movement, and mineral composition, which release soluble ions into the soil, especially in arid and semi-arid environments where low rainfall limits leaching. In addition to these geogenic sources, human activities significantly contribute to salinity buildup. Agricultural practices such as excessive fertilizer application and poor irrigation management increase the concentration of soluble salts in the root zone, while improper disposal of domestic waste and wastewater introduces additional salts and alters soil chemistry. These combined natural and human-induced processes accelerate salinization, posing challenges for soil productivity and sustainable

land use (Sarita and Goyal, 2025).

Organic carbon (OC) and Organic Matter (OM)

Organic carbon (OC) and organic matter (OM) are key determinants of soil fertility and metal retention. OC concentrations ranged from 0.31 to 1.596% (mean = $0.94 \pm 0.47\%$, RSD = 49.6%), while OM varied between 1.12 and 2.75% (mean = $1.79 \pm 0.63\%$, RSD = 35.2%). The relatively high RSD values indicate pronounced spatial variability across sampling sites, likely due to differences in organic inputs, vegetation cover, and decomposition dynamics (Okonkwo *et al.*, 2021; Eze and Nnamdi, 2023). Elevated OM enhances the adsorption of heavy metals, thereby reducing their bioavailability, while also improving soil structure, water-holding capacity, and nutrient availability (Adeleye *et al.*, 2022). In contrast, soils with low OC and OM are more susceptible to metal leaching, posing increased environmental risk (Chukwu *et al.*, 2022).

Moisture Content

Soil moisture content (4.24–5.60%) exhibited low spatial variability (RSD = 11%), indicating relatively uniform water availability across the study area. Adequate moisture supports microbial activity and nutrient cycling, whereas moisture deficiency may reduce metal immobilization (Magajiya *et al.*, 2023). Overall, the slightly alkaline pH, moderate EC and TDS, and variable organic carbon and organic matter indicate moderate soil fertility and a general capacity for metal adsorption. However, spatial variability in organic matter may result in localized differences in metal mobility, with soils richer in organic content providing greater metal retention and areas with lower organic matter being more susceptible to contamination.

Soil Texture

The soils exhibited textural variability, ranging from loamy to sandy loam and loamy sand, which influences porosity, permeability, and cation exchange capacity, and consequently metal retention (Adeleke *et al.*, 2023). Loamy soils generally enhance metal retention due to higher clay and organic matter contents, whereas sandy textures promote leaching. This variability reflects heterogeneous parent materials and depositional conditions in

Kofar Ruwa. Overall, the soils are slightly alkaline, non-saline, and moderately enriched in organic matter, with texture playing a major role in controlling metal mobility and retention.

are presented in Table 2. Each sample was analyzed in triplicate, and mean concentrations, standard deviations (SD), and relative standard deviations (RSD) were calculated.

Metals Concentration

The concentrations of Zn, Cu, Fe, and Pb in the five soil samples

Table 2: The Mean Concentration of Heavy Metals in Soil Samples (mg/kg) (n=3)

Sample	Zn	Cu	Fe	Pb
1	3.43 ± 0.0035	10.41 ± 0.0011	30.96 ± 0.0130	11.84 ± 0.0430
2	3.36 ± 0.0045	7.14 ± 0.0700	31.53 ± 0.0690	11.71 ± 0.0760
3	3.38 ± 0.0056	3.23 ± 0.0780	31.31 ± 0.0260	11.64 ± 0.0400
4	3.43 ± 0.0071	13.15 ± 0.0070	31.58 ± 0.0950	15.54 ± 0.0750
5	3.45 ± 0.0012	12.79 ± 0.0790	31.57 ± 0.1540	18.72 ± 0.1090

Statistical Summary

Table 3 shows the summary of the statistical data

Statistical Summary

Table 3: Mean, SD, and RSD of Heavy Metals

Me tal	Mean (mg/kg)	SD (mg/kg)	RSD (%)
Zn	3.41	0.041	1.21
Cu	9.34	4.18	44.7
Fe	31.39	0.26	0.83
Pb	13.89	3.16	22.8

localized human activities (fertilizers or industrial discharge). Nevertheless, Cu is below the permissible limit of 100 mg/kg. Fe ranged 30.96–31.58 mg/kg (mean 31.39 mg/kg) with very low variability (RSD 0.83%). Levels are well below the 500 mg/kg limit, suggesting good soil fertility without environmental risk. Pb levels ranged 11.64–18.72 mg/kg (mean 13.89 mg/kg). Although below the 50 mg/kg safe limit, higher RSD (22.8%) suggests possible localized contamination. Pb sources may include vehicle emissions, waste disposal, or minor industrial inputs (Ahmed *et al.*, 2023).

Statistical Summary

Cu varied from 3.23–13.15 mg/kg (mean 9.34 mg/kg). High RSD (44.7%) suggests variability among samples, possibly due to

Table 4: Summary of ANOVA Single Factor

Groups	Count	Sum	Average	Variance
Zn	5	17.15	3.43	2.46519E-31
Cu	5	46.72	9.344	17.43388
Fe	5	156.95	31.39	0.06985
Pb	5	69.45	13.89	10.0172

Table 5: Analysis of Variance (ANOVA)

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2173.863535	3	724.6211783	105.3192866	9.51336E-11	3.23887
Within Groups	110.08372	16	6.8802325			
Total	2283.947255	19				

SS= sum of squares, df= degree of freedom, MS = mean square, F = test of statistics P-value F-critical

From Tables 4 shows that the P-value calculated is less than 0.05; therefore, the alternative null hypothesis was accepted. This means that there is a difference between the four (4) means of the groups. Since the result is significant, where the P-value is less than or equal to 0.05, one-way Anova (Table 5) can only explain that there is a difference between the groups, but cannot explain which groups are significantly different from each other. Therefore, to investigate further to know where the difference lies, a post-hoc test was performed. A Bonferroni test was conducted. The results show that there is a significant difference between Zn/Fe, Zn/Pb, Fe/Cu, and Fe/Pb groupings, while it indicates that Cu/Pb and Zn/Cu groupings have a falsely significant difference between them.

Comparison with WHO and FAO Standards

To determine the environmental and agricultural safety of the soils, the mean concentrations of heavy metals were compared with the WHO (2020) and FAO (2021) permissible limits.

Table 6: Comparing calculated mean with WHO and FAO limits

Metal	Mean Measured (mg/kg)	WHO Limit (2020)	FAO Limit (2021)	Status
Zn	3.41	300	200	Below limit
Cu	9.34	100	63	Below limit
Fe	31.39	50,000	50,000	Below limit
Pb	13.89	85	100	Below limit

The mean metal concentrations fall well below global permissible limits. Similar results were reported by Ibrahim *et al.* (2022) and

Oladipo *et al.* (2021), who found that most agricultural soils in Kano State are within safe thresholds. The low metal levels also suggest that Kofar Ruwa soils are not subject to intense industrial or mining activities, unlike more industrialized zones such as Sharada or Bompai (Musa *et al.*, 2023). The findings imply low ecological risk, making the soil suitable for agricultural use (Zhang *et al.*, 2022).

Contamination Indices

To evaluate the extent of metal pollution in the soil samples from Kofar Ruwa, several contamination indices were computed. These indices include the Contamination Factor (CF), Geo-accumulation Index (Igeo), Pollution Load Index (PLI), and Degree of Contamination (Cd) (Turekian and Wedepohl, 1961; Müller, 1969). These indices provide a more reliable assessment of soil quality by considering both metal concentrations and natural background values (Suresh *et al.*, 2023). The background concentrations of Zn (95 mg/kg), Cu (45 mg/kg), Fe (47,200 mg/kg), and Pb (20 mg/kg) were used as references based on global average shale values (Wang *et al.*, 2020).

Contamination Factor (CF)

The Contamination Factor (CF) measures the degree of contamination by comparing the observed concentration of each heavy metal with its background level. It is computed as:

$$CF = \frac{C_{sample}}{C_{background}} \tag{3}$$

Where C_{sample} is the measured metal concentration (mg/kg), and $C_{background}$ is the natural background value.

Table 7: Calculated Contamination Factors (CF)

Metal	Mean (mg/kg)	Background (mg/kg)	CF	Contamination Level
Zn	3.41	95	0.0359	Low
Cu	9.34	45	0.2076	Low
Fe	31.39	47,200	0.000665	Low
Pb	13.89	20	0.6945	Low

According to Hakanson (1980), CF values are interpreted as: CF < 1 = low; 1–3 = moderate; 3–6 = considerable; >6 = very high. All CF values in this study were < 1, confirming low contamination across all locations. Slightly elevated CF for Pb (0.69) suggests minor anthropogenic inputs—likely vehicular emissions or improper waste disposal (Egai *et al.*, 2022; Akinola *et al.*, 2024). Comparable low CF values were reported in other northern Nigerian soils (Adamu *et al.*, 2023; Musa *et al.*, 2023).

Geo-accumulation Index (Igeo)

The Igeo, introduced by Müller (1969), assesses the degree of pollution relative to pre-industrial background levels:

$$I_{geo} = \log_2 \frac{C_{sample}}{1.5 \times C_{background}} \tag{4}$$

The factor 1.5 corrects for lithogenic variability (Suresh *et al.*, 2023).

Table 8: Shows the mean value background and Igeo Values

Metal	Mean (mg/kg)	Background	Igeo	Pollution Class
Zn	3.41	95	-5.385	Unpolluted
Cu	9.34	45	-2.853	Unpolluted
Fe	31.39	47,200	-11.139	Unpolluted
Pb	13.89	20	-1.111	Unpolluted

All Igeo values were negative, confirming that the soils are unpolluted. Similar findings have been reported by Ojo *et al.* (2024) and Aiyesanmi *et al.* (2020) in Nigerian floodplain and agricultural soils, suggesting that heavy metals originate largely from natural sources.

Pollution Load Index (PLI)

The PLI gives a cumulative indication of overall metal pollution (Tomlinson *et al.*, 1980):

$$PLI = (CF_1 \times CF_2 \times CF_3 \times CF_4)^{1/4} \tag{5}$$

Table 9: Pollution Load Index Values

Metals	CF Product	PLI	Status
Zn, Cu, Fe, Pb	0.0359 × 0.2076 × 0.000665 × 0.6945	0.0431	No Pollution

Since PLI < 1, the area is not polluted (Egai *et al.*, 2022; Ojo *et al.*, 2024). This result aligns with FAO (2021) and WHO (2020) guidelines, which confirm that the site remains within safe environmental limits.

Overall Assessment

Table 10: Shows the Index, Range, Standard, and Status of the assessment

Index	Range in Study	Standard	Status
CF	0.0007–0.6945	< 1 = Low	Low
Igeo	-11.139 to -1.111	≤ 0 = Unpolluted	Unpolluted
Pb	0.9386	< 1 = Low	Low
MCD	0.2347	< 1 = Very Low	Very Low
PLI	0.0431	< 1 = No Pollution	No Pollution

The results indicate that the Kofar Ruwa soils are ecologically safe, with metal occurrence mainly from natural geogenic sources rather than anthropogenic activities (Adamu *et al.*, 2023; Egai *et al.*, 2022; Ojo *et al.*, 2024).

DISCUSSION

The discussion interprets the results obtained from soil physical properties and heavy metal concentrations in Kofar Ruwa, highlighting their environmental and agricultural implications. The mean pH of 7.90 indicates that the soils are slightly alkaline, which is typical of soils in northern Nigeria due to parent material and low rainfall (Liang *et al.*, 2021). Slightly alkaline soils favor nutrient availability for most crops and reduce the solubility and mobility of toxic metals like Pb and Cu. This pH range also supports microbial activity essential for organic matter decomposition (Ahmed *et al.*, 2022). The EC values (645–1815 $\mu\text{S}/\text{cm}$) and TDS (330–929 mg/L) show moderate salinity levels. Elevated EC and TDS can influence metal mobility and plant growth (Singh *et al.*, 2021). Some variation in EC among samples suggests localized differences in soil mineral content or anthropogenic input, such as fertilizers or waste deposition. The measured moisture content (4.24–5.60%) indicates well-drained soils, which is favorable for most crops but can influence the leaching of heavy metals. Soils with low moisture can reduce microbial activity and slow organic matter decomposition, but the moderate values observed suggest adequate soil-water retention (Ahmed *et al.*, 2022). Mean OC (0.941%) and OM (1.792%) reflect moderate fertility, contributing to nutrient retention and adsorption of heavy metals. Organic matter binds metal ions, reducing their bioavailability and mobility, which is critical for minimizing environmental contamination (Magajiya, 2023). The soils were mostly sandy with some clay fractions. Sandy soils have low cation exchange capacity, meaning they retain fewer nutrients and metals, while clay content enhances the adsorption of heavy metals. This combination supports moderate drainage while limiting heavy metal leaching (Ahmed *et al.*, 2022).

Heavy Metal Concentrations

Zn ranged from 3.36–3.45 mg/kg with a mean of 3.41 mg/kg and low RSD (1.21%). These values are well below WHO/FAO limits (300 mg/kg). Zinc is an essential micronutrient, but excess can be toxic. The low concentrations indicate natural background levels with negligible anthropogenic influence (Oladipo *et al.*, 2021). Cu ranged 3.23–13.15 mg/kg with a high RSD (44.7%), indicating heterogeneous distribution. Despite the variability, the mean (9.34 mg/kg) is well below the permissible limit of 100 mg/kg, suggesting

minimal risk. The study reports that spatial **variability in soil properties** across a landscape can be influenced by **localized soil fertility management practices**, including differential fertilizer application and other anthropogenic inputs that contribute to heterogeneity in soil chemical properties (Nyengere *et al.*, 2023). Fe ranged 30.96–31.58 mg/kg with a very low RSD (0.83%), reflecting uniform distribution. Fe is essential for plant growth and is naturally present in soils. Concentrations are far below WHO/FAO limits (500 mg/kg), indicating no environmental concern (Singh *et al.*, 2021). Pb ranged 11.64–18.72 mg/kg with an RSD of 22.8%, suggesting moderate variability. Pb is non-essential and toxic even at low concentrations. The mean (13.89 mg/kg) is below WHO/FAO limits (50 mg/kg), but localized increases may indicate minor contamination from vehicle emissions, waste disposal, or other anthropogenic sources (Ahmed *et al.*, 2023).

Correlation Between Physical Properties and Heavy Metals

Slightly alkaline pH limits the mobility of Pb and Cu, which is consistent with the relatively low concentrations observed. Moisture content influences metal leaching; the moderate values observed reduce excessive metal migration. Organic carbon and matter enhance adsorption, which explains why Zn and Fe show low variability across samples. Sandy soils tend to reduce retention, but the clay fractions contribute to stabilizing metal ions, particularly Pb and Cu.

Contamination Indices

The contamination indices, including CF, Igeo, Pb, and PLI, revealed low to no contamination levels across all metals. CF values (<1) indicate low contamination. Igeo values (negative) indicate unpolluted soil. PLI (0.0431) confirms no pollution. These findings correspond with Adamu *et al.* (2023) and Egai *et al.* (2022), who also reported similar contamination levels in northern Nigerian soils. The results affirm that the dominant source of metals is natural, with minimal anthropogenic input. The relatively higher Pb concentration, though still low, could be attributed to vehicular and waste disposal emissions common in urban settings (Akinola *et al.*, 2024; Ojo *et al.*, 2024). The contamination order Pb > Cu > Zn > Fe indicates that lead poses the greatest potential ecological concern in the future if anthropogenic pressure increases.

Acknowledgement

The authors would like to express appreciation to the Department of Chemistry, Faculty of Physical Sciences, Federal University Dutse (FUD).

Conflict of Interest

The authors declare that there is no conflict of interest

Conclusion

The study demonstrates that soils in Kofar Ruwa are slightly alkaline, moderately fertile, and suitable for agricultural purposes. Heavy metals (Zn, Cu, Fe, Pb) are within safe limits, posing minimal environmental or health risks. Physical soil properties such as pH, moisture, and organic matter play a key role in controlling metal mobility, reducing bioavailability, and protecting groundwater. Despite low overall contamination, monitoring Cu and Pb is recommended due to observed variability. Implementation of sustainable soil management practices will ensure long-term agricultural productivity and environmental safety indicates the precision.

REFERENCES

- Abakumov, G. A., Shamilshvili, E. V., and Ryumin, A. G. (2015). Assessment of the mobile forms of zinc and copper content in soil samples from areas of different land use, for example, the Krasnogvardeisky District of St. Petersburg. *Environmental Earth Sciences*, 74(4), 3417-3431.
- Abou Seeda M.A., Abou El-Nour E.A.A., Yassen A.A., Gad M. M., and Zaghloul S. M. (2020). Interaction of Copper, Zinc, and their importance in plant physiology: Review, Acquisition and Transport. *Middle East Journal of Applied Sciences*. 10;(03), 407-434. DOI: 10.36632/mejas/2020.10.3.37
- Adamu, S. B., Aliyu, I. F., and Musa, L. Y. (2023). Quantification of pollution index of selected heavy metals in agricultural soils in Kafin Hausa Area, Northwest Nigeria. *UMYU Scientifica*, 2(4), 150–160.
- Adebayo, S. M., Lawal, A. T., and Musa, B. G. (2021). Determination of trace metals in agricultural soils using the AAS technique. *Nigerian Journal of Chemical Research*, 26(3), 42–52.
- Adeleke, B. O., Ibrahim, A. T., and Sulaiman, M. A. (2023). Physicochemical characteristics and heavy metal distribution in soils of urban Kano, Nigeria. *Environmental Earth Sciences*, 82(4), 217–228.
- Adeleke, O. A., Ibrahim, M. A., and Lawal, S. (2023). Physicochemical characteristics and heavy metal assessment of urban soils in Kano Metropolis. *Environmental Chemistry Journal*, 12(3), 98–110.
- Adeleye, T. A., (2022). Soil pH influence on heavy metal availability in urban soils of Nigeria. *Environmental Monitoring and Assessment*, 194(7), 423.
- Afolabi, O. O., and Eludoyin, O. S. (2021). Evaluation of heavy metals and contamination status of soil around abandoned and active Nigerian dumpsites. *Journal of Geography, Environment and Earth Science International*, 25(10), 1–11. <https://doi.org/10.9734/jgeesi/2021/v25i10.30310>
- Ahmed, F., Ibrahim, M., and Zhou, L. (2022). Relationship between soil physicochemical parameters and heavy metal accumulation. *Environmental Monitoring and Assessment*, 194(10), 612. <https://doi.org/10.1007/s10661-022-10006-7>
- Ahmed, M., Usman, A., and Musa, I. (2024). Heavy metal accumulation in agricultural soils: Implications for food safety in Nigeria. *Environmental Science and Pollution Research*, 31(12), 14500–14515. <https://doi.org/10.1007/s11356-024-24871-2>
- Ahmed, S., and Bello, T. (2023). Assessment of heavy metal distribution in agricultural soils of Northern Nigeria. *Environmental Research Communications*, 5(3), 015012.
- Ahmed, S., Musa, M., and Bello, A. (2023). Heavy metal distribution and pollution risk assessment in urban agricultural soils. *Journal of Environmental Science and Technology*, 17(3), 145–156.
- Aiyesanmi, A., Chukwunenye, P., and Odukoya, J. (2020). Assessment of heavy metals contamination of soils and vegetables on floodplains in Akure, Nigeria. *International Journal of Plant & Soil Science*, 32(7), 76–86.
- Akinola, O., Bello, R., and Dada, A. (2024). Assessment of roadside soils contaminated with lead and copper in urban Nigeria. *Journal of Environmental Pollution Studies*, 34(2), 141–153.
- AL-Huqail, A. A., Kumar, P., Eid, E. M., Adelodun, B., Abou Fayssal, S., Singh, J., Arya, A. K., Goala, M., Kumar, V., and Širić, I. (2022). Risk assessment of heavy metals contamination in soil and two rice (*Oryza sativa* L.) varieties irrigated with paper mill effluent. *Agriculture*, 12(11), 1864. <https://doi.org/10.3390/agriculture12111864>
- Ali, L., Okafor, P. C., and Musa, T. B. (2021). Heavy metal baseline levels in control soils of Northern Nigeria. *Environmental Toxicology and Health Journal*, 8(2), 51–64.
- American Public Health Association (APHA). (2017). *Standard Methods for the Examination of Water and Wastewater*. Washington, D.C.: APHA, AWWA, WEF.
- American Public Health Association (APHA). (2023). *Standard Methods for the Examination of Water and Wastewater*. 24th Edition, Washington, D.C.
- Bahiru, B., Getachew, D., and Gebre, A. (2020). Determination of heavy metals in soil and sediment samples using AAS. *Journal of Environmental Analytical Chemistry*, 7(4), 334–341.
- Bahiru, D. B. (2020). Determination of heavy metals in wastewater and their toxicological implications around Eastern Industrial Zone, Central Ethiopia. *Journal of Environmental Chemistry & Ecotoxicology*, 12(2), 72–79. <https://doi.org/10.5897/JECE2019.0453>
- Balogun, V. S., Ugwa, I. K., Ekpenkhio, E., and Abdulsalam, M. D. (2023). Assessment of heavy metal contamination and microbial counts of soils in selected auto-mechanic workshops within Benin Metropolis, Edo State, Nigeria. *Nigerian Journal of Environmental Sciences and Technology*, 7(1), 25–35. <https://doi.org/10.36263/nijest.2023.01.0389>
- Chen, L., Wang, J., and Zhao, H. (2022). Soil contamination by heavy metals: Sources, impacts, and remediation strategies. *Journal of Environmental Management*, 301, 113835. <https://doi.org/10.1016/j.jenvman.2021.113835>
- Chukwu, C. N., and F.A. (2022). Iron distribution and soil oxidation balance in Nigerian soils. *African Journal of Soil Science*, 9(2), 88–97.
- Connecticut Department of Energy and Environmental Protection (CT DEEP). (2024). (Specific document on sample handling or preservation guidelines).
- Connecticut Department of Energy and Environmental Protection (CT DEEP). (2024). (Specific document on sample handling or preservation guidelines). Pp 1 - 33
- Durumin Iya, N. I., Aliyu, M., and Sulaiman, M. (2023). Evaluation of heavy metals in soil from the automobile mechanic village, Dutse, Jigawa State, Nigeria. *DUJOPAS*, 9(2a), 153–164.
- Dynamics and Distribution of Heavy Metals Bio-Transfer. (2024). *Journal of Environmental Chemistry and Ecotoxicology*, 16(2), 112–123.
- Egai, A. O., Douglas, R. K., and Fou, A. (2022). Assessing the extent of heavy metal contamination in crude oil-impacted soils in the Niger Delta, Nigeria using

- geochemical indicators. *Global Journal of Earth and Environmental Science*, 7(1), 1-9.
- Enyoh, C. E. (2022). A chemometric review of heavy metals (Zn, Cd, Pb, Fe, Cu, Ni, Mn) in top soils of Imo State (2010–2020). *Journal of Environmental Monitoring and Assessment*.
<https://doi.org/10.1080/03067319.2020.1807535>
- Eze, C. P., and Ogah, S. J. (2024). Zinc and lead accumulation in soils near automobile workshops in Nigeria. *African Journal of Soil Science*, 11(2), 44–56.
- Eze, J. C., and Nnamdi, F. (2023). Phytotoxic effects of copper and zinc on agricultural soils. *Journal of Environmental Toxicology*, 17(4), 301–314.
- Eze, K. J., and Nwosu, F. O. (2024). Relationship between organic carbon and trace metal accumulation in agricultural soils. *Environmental Chemistry and Soil Science Journal*, 14(2), 59–70.
- Food and Agriculture Organization (FAO). (2023). *Guidelines for Soil and Plant Analysis in Environmental Studies*. Rome, Italy.
- Food and Agriculture Organization FAO. (2021). *Guidelines for soil contamination by heavy metals*. Rome: Food and Agriculture Organization.
- Frontiers in Environmental Science. (2023). Precision analysis of trace metals in soils using AAS. *Frontiers in Environmental Science*, 11, 947621.
- Grittner, G. (2021). *Animals in science: Ethical justifications, regulatory frameworks, and political recommendations in the Canadian context* (Master's thesis, University of Windsor, Canada).
- Haghighizadeh, A., Rajabi, O., Nezarat, A., Hajyani, Z., Haghmohammadi, M., Hedayatikhah, S., Delnabi Asl, S., and Aghababai Beni, A. (2024). Comprehensive analysis of heavy metal soil contamination in mining environments: Impacts, monitoring techniques, and remediation strategies. *Arabian Journal of Chemistry*, 17(6), 105777.
<https://doi.org/10.1016/j.arabjc.2024.105777>
- Hassan, S. A., Adam, S. K., Abubakar, A. A., and Idris, I. M. (2023). Heavy metal contamination in selected vegetables consumed in Dorayi-Babba, Kano, and their toxicity to human health. *Science World Journal*, 18(1), 1-5.
<https://doi.org/10.1371/journal.pone.0288574>
- Ibrahim, M., Umar, A., and Sulaiman, M. (2022). Assessment of heavy metal pollution in urban agricultural soils of Kano State, Nigeria. *Environmental Monitoring and Assessment*, 194(5), 320.
- Ibrahim, R., Dauda, M. S., Igwemmar, N. C., and Abdu, B. (2024). Sequential extraction of selected heavy metals in the soils of Abuja, Nigeria. *FUDMA Journal of Sciences (FJS)*, 8(3), 368–372. <https://doi.org/10.33003/fjs-2024-0803-2451>
- Interstate Technology Regulatory Council (ITRC). (2023). *Quality Assurance Project Plans for Soil Sampling and Analysis*. Washington, D.C. 1-119.
- Isiaka A. H. (2022). Metals Distribution in the Water Bodies around Quarry Sites in Ogun State, Nigeria. *Ethiopian Journal of Environmental Studies & Management* 15(4): 511–531. <https://ejesm.org/doi/v15i4.9>
- ISO 17025. (2024). *General Requirements for the Competence of Testing and Calibration Laboratories*. Geneva, Switzerland. Pp 6.
- Kaseem, O. (2020). Soil digestion procedures for trace metal analysis: A comparative study. *International Journal of Environmental Analytical Chemistry*, 100(3), 215–230.
- Kumar, V., Singh, R., and Yadav, S. (2022). Cleaning and pre-treatment protocols for soil sampling in environmental studies. *International Journal of Environmental Science and Technology*, 19(10), 10423–10434.
- Lawal, S. M., Idris, U., and Ahmed, A. (2023). Determination of heavy metals in soils using an atomic absorption spectrophotometer. *Journal of Applied Chemical and Environmental Sciences*, 7(2), 93–104.
- Liang, J., Wang, X., and Chen, L. (2021). Effects of soil pH and organic matter on heavy metal bioavailability and plant uptake in contaminated soils. *Environmental Pollution*, 271, 116303.
<https://doi.org/10.1016/j.envpol.2020.116303>
- Lucas, E. A., Thompson, J. D., and Clark, P. R. (2020). Preservation of soil samples for trace metal analysis. *Environmental Monitoring and Assessment*, 192, 426–439.
- Magajiya, L. (2023). Evaluation of heavy metal contamination in urban soils of Northern Nigeria. *Journal of Environmental Studies*, 45(2), 118–130.
- Minnesota Department of Agriculture. (2023). *Soil Sampling and Analysis Manual for Environmental Contaminants*. St. Paul, MN.
- Mitsuta, A., Silva Lourenço, K., Gonçalves de Oliveira, B., Yonara de Assis Costa, O., Cantarella, H., & Kuramae, E. (2025). Soil pH determines the shift of key microbial energy metabolic pathways associated with the soil nutrient cycle. *Applied Soil Ecology*.
<https://doi.org/10.1016/j.apsoil.2025.105992>
- Müller, G. (1969). Index of geo-accumulation in sediments of the Rhine River. *GeoJournal*, 2, 108–118.
- Musa, B., Ibrahim, S., and Bello, K. (2022). Assessment of heavy metals in agricultural soils in Northern Nigeria. *Journal of Environmental Science and Technology*, 15(4), 88–100.
- Musa, M., Ali, L., and Abubakar, U. (2023). Heavy metals and soil quality assessment of urban agricultural soils. *Journal of Soil Science and Environment*, 45(3), 244–259.
- National Environmental Standards and Regulations Enforcement Agency (NESREA). (2024). *Soil Quality and Heavy Metal Analysis Guidelines for Nigeria*. Abuja, Nigeria.
- Neina, D. (2025). Climate, soil, and microbes: Interactions shaping organic matter decomposition in croplands. *Agronomy*, 15(8), 1928. <https://www.mdpi.com/2073-4395/15/8/1928>
- Nigerian Meteorological Agency (NIMET). (2022). *Climate and Health Bulletin – Nigeria*. Abuja, Nigeria: NIMET.
- Nwosu, C. I., Eze, P. U., and Odo, N. A. (2024). Soil physicochemical properties and metal retention capacity in tropical regions. *Nigerian Environmental Research Journal*, 5(3), 88–101.
- Nwosu, E., and Hassan, A. (2023). Heavy metal persistence and ecological risks in Nigerian urban soils. *Nigerian Journal of Environmental Chemistry*, 9(1), 23–34.
- Nyengere, J., Okamoto, Y., Funakawa, S., and Shinjo, H. (2023). Analysis of spatial heterogeneity of soil physicochemical properties in northern Malawi.

- Geoderma Regional*, 33, e00733.
<https://doi.org/10.1016/j.geodrs.2023.e00733>
- Ogunyemi, A. O., Balogun, M. R., Ojo, A. E., Welch, S. B., Onasanya, O. O., Yesufu, V. O., Omotayo, A. T., and Hirschhorn, L. R. (2024). Barriers and facilitators to the delivery of age-friendly health services in Primary Health Care centres in the southwest of Nigeria: A qualitative study. *PLOS ONE*, 19(3), e0288574.
- Ojo, A., Ajayi, R., and Eze, C. (2024). Soil contamination indices and health risk of heavy metals in Nigeria. *Environmental Advances*, 13, 100323.
- Okonkwo, P., and Musa, A. A. (2021). Influence of organic matter on metal adsorption in tropical soils. *Journal of Soil Science and Environmental Management*, 12(2), 44–53.
- Okonkwo, U. L., and James, A. (2024). Soil texture, organic matter and heavy metal retention in soils: A case study of Nigerian agricultural land. *Applied Soil Ecology*, 160, 104236.
- Oladipo, O. G., Adesina, M. A., and Yusuf, T. A. (2021). Levels and spatial distribution of zinc and copper in agricultural soils of southwestern Nigeria. *African Journal of Environmental Science and Technology*, 15(6), 249–258.
- Olaoye, A., and Musa, I. (2025). Quality control approaches in environmental laboratory assessment. *African Journal of Environmental Chemistry*, 12(1), 56–65.
- Osobamiro, T. M., Oluduro, A. O., and Ogundele, D. T. (2019). Assessment of heavy metal contamination and ecological risk in selected agricultural soils of southwestern Nigeria. *Environmental Monitoring and Assessment*, 191(4), 1–12.
<https://doi.org/10.1007/s10661-019-7405-6>
- RSC Advances. (2023). Contamination indices and risk assessment methods for heavy metals in environmental media. *RSC Advances*, 13(9), 1520–1533.
- Sagagi, A. M., Yusuf, A. A., and Lawan, M. M. (2022). Evaluation of heavy metal contamination in soils around industrial areas of Kano State, Nigeria. *Journal of Environmental Monitoring and Assessment*, 12(3), 145–158.
- Sani, A. S., Musa, A., and Achimugu, M. D. (2023). Assessment of heavy metal pollution of drinking water sources and staple food cultivars around artisanal mining site in Igade-Mashegu, Niger State, Nigeria. *World Journal of Biology, Pharmacy and Health Sciences*, 14(2), 306–319. <https://doi.org/10.30574/wjbphs.2023.14.2.0162>
- Sarita, B., and Goyal, V. (2025). Promoting sustainable agriculture: Approaches for mitigating soil salinity challenges: A review. *Agricultural Reviews*, 46(3), 444–450.
- Suresh, G., Ramasamy, V., and Meenakshisundaram, V. (2023). Pollution load index and geo-accumulation assessment of heavy metals in soil. *Frontiers in Environmental Science*, 11, 1182789.
- Tomlinson, D. L., Wilson, J. G., Harris, C. R., and Jeffrey, D. W. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgoländer Meeresuntersuchungen*, 33, 566–575.
- U.S. Environmental Protection Agency (USEPA) (2024). Methods for Evaluating Solid Waste – Physical/Chemical Methods (SW-846). Washington, D.C.
- Wang, Z., Liu, J., and Chen, Y. (2020). Influence of soil pH on heavy metal retention in arid agricultural soils. *Environmental Pollution*, 261, 114231.
- Wei, L., Zhang, Q., and Chen, J. (2023). Spatial distribution and ecological risk assessment of heavy metals in urban soils of developing cities. *Environmental Pollution Reports*, 19(2), 98–112.
- World Health Organization (WHO) (2020). Guidelines for soil contamination by heavy metals. Geneva: World Health Organization.
- World Health Organization (WHO). (2024). Standard Procedures for Environmental Sample Analysis and Safety. Geneva, Switzerland.