



Chemical Speciation, Bioavailability and Multi-Index Assessment of Heavy Metal Contamination in Dumpsite-Affected Farmland Soils of Anyigba, Nigeria



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ABSTRACT

This study assessed the physicochemical properties, chemical speciation, and ecological risk of heavy metals in farmland soils near municipal dumpsites in Anyigba, Nigeria. The soils were slightly acidic (pH 5.2–6.4), with moderate organic matter (1.82–2.65%) and cation exchange capacity (7.4–12.3 cmol/kg), while electrical conductivity was low (92–148 μ S/cm), indicating non-saline conditions that promote metal mobility. Heavy metals occurred in the ranges: Cd (4.60–5.91 mg/kg), Cu (5.81–12.44 mg/kg), Ni (11.70–18.92 mg/kg), Cr (4.93–8.17 mg/kg), and Pb (3.99–6.25 mg/kg). Speciation analysis showed Cd concentrated in exchangeable and carbonate fractions (45–58%), reflecting high mobility; Cu was mainly bound to organic matter (40–52%); Ni dominated reducible fractions (35–48%); Cr occurred in the residual fraction (55–68%); and Pb partitioned into carbonate and reducible fractions (30–45%). Contamination factors (CF) indicated very high Cd contamination (6.0–7.5), moderate Ni (2.0–3.0), Cu (1.2–2.1), and Pb (1.1–1.8), and low Cr (0.8–1.4). The Pollution Load Index (PLI) ranged 1.2–2.0, confirming overall deterioration, while the Nemerow Pollution Index (NPI) of 2.4–3.1 signaled considerable pollution risk. Ecological Risk Index (ERI) values highlighted Cd as the major contributor (60–70% of total risk), with individual ERI of 180–220, categorizing it as a “considerable ecological risk.” In contrast, Cu, Ni, Cr, and Pb presented low to moderate risks (ERI < 40). Integration of soil properties with speciation data indicated that acidic pH and relatively low organic matter enhanced Cd solubility and bioavailability, whereas organic complexation stabilized Cu. These results demonstrate that ecological assessments must consider both total concentrations and chemical forms of metals. Recommended interventions include phytoremediation, soil organic amendments, and stricter waste management to mitigate contamination and ensure sustainable agriculture in Anyigba.

CITATION

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INTRODUCTION

Environmental pollution has emerged as a defining challenge of the 21st century, threatening ecosystem integrity and human well-being. Among the different forms of pollution, soil contamination by heavy metals and metalloids poses a particularly long-term and irreversible risk (Kapku *et al.*, 2024). In developing regions such as Nigeria, rapid urbanization, population growth, and weak waste management infrastructure have resulted in widespread reliance on open dumpsites for municipal solid waste disposal (Abata *et al.*, 2024). These sites contain heterogeneous waste streams—including plastics, textiles, batteries, metals, and household residues—that degrade over time and release potentially toxic elements (PTEs) into surrounding soils. Unlike organic pollutants, which may be mineralized to less harmful compounds, heavy metals are non-biodegradable and persist for decades or centuries, undergoing chemical transformations that often enhance their mobility and toxicity (Olisa *et al.*, 2024; Obunwo *et al.*, 2024).

The primary pathways of heavy metal input into soils are both natural and anthropogenic; however, anthropogenic contributions such as industrial emissions, mining, vehicle exhaust, agrochemical use, and indiscriminate waste disposal remain dominant (de Souza *et al.*, 2023). In Nigerian cities, including Anyigba, dumpsites are frequently located near residential zones, farmlands, and water bodies, increasing the risk of soil, air, and groundwater contamination via leachate migration and dust dispersal (Kumar *et al.*, 2024). Chronic human exposure to even low concentrations of heavy metals has been linked to neurotoxicity, renal impairment, developmental disorders, and carcinogenesis in vital organs (Fulke *et al.*, 2024; Eze and Chukwu, 2023).

Crucially, the ecological and health risks of heavy metals are governed not only by their total concentrations but also by their chemical speciation, which determines bioavailability and mobility. Sequential extraction techniques provide insights into operationally defined fractions—exchangeable, carbonate-bound, Fe/Mn oxide-bound, organic-bound, and residual—thereby enabling a more accurate assessment of contamination levels (Zulfiqar *et al.*, 2023; Uchimiya *et al.*, 2020). Despite extensive studies across Nigerian cities, data on metal speciation in Anyigba remain sparse, with most investigations limited to bulk concentration analysis. Addressing this gap is essential for evaluating long-term ecological risks, informing remediation strategies, and guiding evidence-based environmental policies.

MATERIAL AND METHODS

Study Area

The study was carried out in Anyigba, Kogi State, located in the Guinea savanna zone of North Central Nigeria (07°00'–07°20'N, 06°60'–06°80'E). The area has a tropical climate

with distinct wet and dry seasons, fertile alluvial soils, and intensive agricultural activity. Rapid urbanization, informal industrial practices, and unregulated waste disposal make it a hotspot for soil pollution assessment.

Soil Sampling

Soils were collected from three active agricultural farms located within 10–15 m of major dumpsites (Agala-Ate, Iyale Road, and Wada Road). These sites were chosen for their proximity to waste sources and continued cultivation of food crops. A control sample was obtained from Ajetachi, >50 m away from anthropogenic influence, to establish baseline conditions.

Sample Collection

Surface soils (0–10 cm) were collected using pre-cleaned stainless steel scoops. At each site, four sub-samples were taken in a cross-pattern, composited, and stored in labeled polyethylene bags. This approach minimized heterogeneity and ensured representative sampling. All procedures were performed in triplicate for statistical reliability.

Sample Pretreatment

In the laboratory, soils were air-dried, ground, and sieved (<2.00 mm). For elemental analysis, portions were further pulverized with an agate mortar and pestle to enhance homogeneity. Samples were stored in airtight containers under controlled conditions until chemical and geochemical analyses were performed.

Determination of Physicochemical Soil Parameters

Soil pH

Soil pH was measured using the 1:2.5 soil-to-water suspension method (Mosley, 2024). Ten grams of air-dried, sieved soil (<2 mm) were mixed with 25 mL deionized water, equilibrated for 30 min, and analyzed with a calibrated glass-electrode pH meter.

Soil Moisture Content

Moisture content was determined gravimetrically (Arshad and Ibrahim, 2021). Fresh soil (~20 g) was oven-dried at 105 °C for 24 h, cooled in a desiccator, and reweighed. The weight loss was expressed as a percentage of the initial mass.

Soil Texture

Particle size distribution was analyzed using the Bouyoucos hydrometer method (Kilinc and Orhan, 2025). Fifty grams of soil pretreated with H₂O₂ were dispersed in sodium hexametaphosphate, and hydrometer readings were taken to classify sand, silt, and clay fractions using the USDA soil triangle.

Electrical Conductivity (EC)

Soil EC was determined in a 1:5 soil-to-water extract (Chatziparaschis *et al.*, 2023). Ten grams of soil were mixed with 50 mL distilled water, shaken for 30 min, filtered, and the extract was measured using a conductivity meter.

Organic Carbon Content

Organic carbon was quantified using the Walkley–Black wet oxidation method (Khumalo and Moodley, 2023). One gram of soil was digested with $\text{K}_2\text{Cr}_2\text{O}_7\text{--H}_2\text{SO}_4$, and the residual dichromate was titrated with ferrous ammonium sulfate. Values were converted to organic matter using a factor of 1.724.

Cation Exchange Capacity (CEC)

CEC was determined using the ammonium acetate (1N NH_4OAc) method at pH 7.0 (Antonangelo and Adeoye, 2024). Soil was saturated with NH_4^+ , displaced with NaCl, and the released NH_4^+ quantified to calculate exchange capacity.

Heavy Metal Determination

Heavy metal concentrations were determined by wet acid digestion. One gram of homogenized soil (<2 mm) was digested with 15 mL aqua regia ($\text{HCl}:\text{HNO}_3$, 3:1 v/v) on a thermostatically controlled hot plate under a fume hood until near dryness. The digest was diluted with 15 mL deionized water, filtered (Whatman No. 42), and made up to 25 mL in acid-washed polyethylene bottles. Concentrations of Pb, Cd, Ni, Cr, Cu, and other metals were quantified using Flame Atomic Absorption Spectrophotometry (FAAS) with calibration against certified standards. Analytical blanks and quality control samples were included, and all analyses were performed in triplicate.

Chemical Speciation of Heavy Metals

Speciation was carried out using a modified sequential extraction procedure, fractionating metals into six geochemical forms: water-soluble, exchangeable, carbonate-bound, Fe–Mn oxide-bound, organic matter-bound, and residual.

Water-Soluble Fraction (FI)

One gram of soil was extracted with 10 mL deionized water under agitation for 1 h, centrifuged, and the supernatant diluted to 50 mL.

Exchangeable Fraction (FII)

The residue was treated with 10 mL of 1 M $\text{Mg}(\text{NO}_3)_2$ (pH 7.0) under agitation for 1 h, centrifuged, and the extract diluted to 50 mL.

Carbonate-Bound Fraction (FIII)

The residue was leached with 10 mL of 1 M CH_3COONa (pH 5.0 with CH_3COOH) for 5 h under agitation. The extract was centrifuged and diluted to 50 mL.

Fe–Mn Oxide-Bound Fraction (FIV)

The residue was extracted with 20 mL of 0.1 M $\text{NH}_2\text{OH}\cdot\text{HCl}$ in 25% CH_3COOH at 96 °C for 6 h, centrifuged, and the extract diluted to 50 mL.

Organic Matter-Bound Fraction (FV)

The residue was treated with 3 mL of 0.02 M HNO_3 and 30% H_2O_2 , heated at 85 °C for 3 h, cooled, then extracted with 5 mL of 1 M CH_3COONa for 3 h at 85 °C. The extract was centrifuged and diluted to 50 mL.

Residual Fraction (FVI)

The residue was digested with 8 mL of $\text{HF}:\text{HClO}_4$ (5:1 v/v) in Teflon cups, dry-ashed for 2 h, evaporated to dryness, and the final solution diluted to 50 mL for analysis.

Risk Assessment

Risk assessment indices were applied to evaluate the extent, sources, and ecological implications of heavy metal contamination in soils. These include the Contamination Factor (CF), Pollution Load Index (PLI), Geoaccumulation Index (I_{geo}), Nemerow Pollution Index (NPI), Enrichment Factor (EF), and the Ecological Risk Index (ERI/RI), providing an integrated measure of pollution status and ecological threat.

Contamination Factor (CF)

The level of contamination of the soil is expressed in terms of a contamination factor (CF) calculated as:

$$\text{CF} = \frac{\text{Metal concentration of the soil sample}}{\text{Background value of the metal or control sample}}$$

Where the contamination factor $\text{CF} < 1$ refers to low contamination;

$1 \leq \text{CF} < 3$ means moderate contamination,

$3 \leq \text{CF} \leq 6$ indicates considerable contamination;

$\text{CF} > 6$ indicates very high contamination

Pollution Load Index

The pollution load index (PLI) is as follows

$$\text{PLI} = \sqrt[n]{\text{CF}_1 \times \text{CF}_2 \times \text{CF}_3 \times \text{CF}_4 \dots \dots \text{CF}_n}$$

Where, CF = contamination factor,

n = number of metals;

The PLI value of >1 is polluted,

Whereas <1 indicates no pollution

Geoaccumulation Index (I_{geo})

Geoaccumulation Index (I_{geo}) was calculated for soils from various dumpsites in Egume District. The background concentrations used are those of the control site for each metal, and the I_{geo} was calculated using the formula:

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

Where:

C_n is the measured concentration of the metal in the sample,

B_n is the background concentration (control sample),

1.5 is a constant to account for natural fluctuations.

$I_{geo} \leq 0$: Uncontaminated

$0 < I_{geo} \leq 1$: Uncontaminated to moderately contaminated

$1 < I_{geo} \leq 2$: Moderately contaminated

$2 < I_{geo} \leq 3$: Moderately to heavily contaminated

$3 < I_{geo} \leq 4$: Heavily contaminated

$4 < I_{geo} \leq 5$: Heavily to extremely contaminated

$I_{geo} > 5$: Extremely contaminated

Nemerow Pollution Index (NPI)

The Nemerow index is calculated using the equation:

$$NPI = \sqrt{\frac{(CF_{mean}^2 \times CF_{max}^2)}{2}}$$

Where:

CF_{mean} = average contamination factor of all metals at a site

CF_{max} = the highest individual contamination factor at that site

The pollution status is interpreted as:

$NPI \leq 0.7 \rightarrow$ Clean

$0.7 < NPI \leq 1.0 \rightarrow$ Warning level of pollution

$1.0 < NPI \leq 2.0 \rightarrow$ Slight pollution

$2.0 < NPI \leq 3.0 \rightarrow$ Moderate pollution

$NPI > 3.0 \rightarrow$ Heavy pollution

Enrichment Factor (EF)

Enrichment Factor was calculated using:

$$EF = \left(\frac{\left(\frac{C_{metal}}{C_{reference}} \right)_{sample}}{\left(\frac{C_{metal}}{C_{reference}} \right)_{background}} \right)$$

$EF < 2$: Deficiency to minimal enrichment

$2 \leq EF < 5$: Moderate enrichment

$5 \leq EF < 20$: Significant enrichment

$EF \geq 20$: Very high enrichment

Chromium (Cr) was selected as the reference element due to its relative geochemical stability and crustal abundance. EF values for Cadmium (Cd), Copper (Cu), Nickel (Ni), and Lead (Pb) were computed using the control sites as the background reference.

Ecological Risk Index and Potential Ecological Risk Index

The Ecological Risk Index (ERI) assesses potential hazards of toxic metals in soils by combining their contamination factors (Cf) with toxic response factors (Tr), assigned as Cd = 30, Cu = 5, Ni = 5, Mn = 1, and Pb = 5 (Håkanson, 1980).

The formula for calculating the ecological risk for each metal (E_r) is:

$$E_r = T_r \times C_f$$

And the potential ecological risk index (RI) for each site is:

$$RI = \sum E_r$$

According to Håkanson's risk classification:

$E_r < 40$: Low risk

$40 \leq E_r < 80$: Moderate risk

$80 \leq E_r < 160$: Considerable risk

$160 \leq E_r < 320$: High risk

$E_r \geq 320$: Very high risk

Similarly, for RI (sum of all E_r):

$RI < 150$: Low ecological risk

$150 \leq RI < 300$: Moderate ecological risk

$300 \leq RI < 600$: Considerable ecological risk

$RI \geq 600$: Very high ecological risk

RESULTS AND DISCUSSION

Soil Physicochemical Properties

The physicochemical attributes of soils strongly influence heavy metal behavior, including mobility, bioavailability, and ecological risk. Across the studied sites (Agala-Ate, Iyale Road, Wada Road, and control), notable variations were observed, reflecting both anthropogenic waste inputs and inherent soil characteristics.

Soil pH

Soil pH ranged from 5.6 at Iyale Road to 6.8 at Agala-Ate, while the control soil was slightly alkaline (7.4). The acidic conditions at Iyale Road (pH 5.6) and Wada Road (pH 6.1) enhance the solubility of Cd, Pb, and Ni, increasing crop uptake risk. In contrast, Agala-Ate's near-neutral pH (6.8) promotes partial metal immobilization, whereas the alkaline control soil offers a natural buffering effect against mobility (Aikpokpodion *et al.*, 2022).

Soil Moisture

Moisture content was highest at Iyale Road (28.6%) and Wada Road (19.3%), indicating organic matter-driven water retention in waste-impacted soils. Elevated moisture favors leaching and downward migration of soluble ions (Eze *et al.*, 2022). Lower values at Agala-Ate (13.4%) and the control (9.3%) suggest reduced leaching potential but longer metal persistence in surface soils.

Soil Texture

Dumpsite soils were predominantly sandy loam, with sand contents between 45% and 61%. The sandy fraction enhances drainage but limits adsorption capacity, thereby increasing heavy metal mobility (Alhassan *et al.*, 2023). In contrast, the loam texture of the control soil (38% sand) reflects higher clay and silt proportions, improving retention and adsorption potential (Fosu-Mensah *et al.*, 2021).

Electrical Conductivity

Electrical conductivity (EC) was markedly higher in dumpsite soils: 382 $\mu\text{S}/\text{cm}$ at Iyale Road and 274 $\mu\text{S}/\text{cm}$ at

Wada Road, compared with 79 $\mu\text{S}/\text{cm}$ at the control. Elevated EC indicates ionic enrichment from waste-derived leachates, which may enhance solubility of metals and impose osmotic stress on plants and soil biota (Ibrahim *et al.*, 2024).

Soil Organic Carbon

SOC was significantly elevated at Iyale Road (6.1%) and Wada Road (4.0%), relative to the control (1.2%). This reflects continuous deposition of organic-rich wastes. While SOC can stabilize metals through complexation, it may also facilitate transport under acidic conditions

(Ncube *et al.*, 2021). Agala-Ate (1.8%) showed only moderate enrichment, indicating lesser waste influence.

Cation Exchange Capacity

CEC varied from 13.6 $\text{cmol}(+)/\text{kg}$ at Iyale Road to 25.2 $\text{cmol}(+)/\text{kg}$ at Agala-Ate, with the control also high (23.3 $\text{cmol}(+)/\text{kg}$). High CEC soils (Agala-Ate, control) exhibit stronger adsorption and retention of metals, reducing immediate bioavailability. Conversely, the low CEC at Iyale Road reflects weak buffering, enhancing solubility and mobility (Hassan *et al.*, 2023).

Table 1: Soil Physicochemical Parameters

Physicochemical Parameters	Agala-Ate	Iyale Road	Wada Road	Control
Soil pH	6.8	5.6	6.1	7.4
Soil Moisture Content (%)	13.4	28.6	19.3	9.3
Soil Texture	Sandy loam (45 % sand)	Sandy loam (61 % sand)	Sandy loam (53 % sand)	Loam (38 % sand)
Electrical Conductivity ($\mu\text{S}/\text{cm}$)	155	382	274	79
Soil Organic Carbon (%)	1.8	6.1	4.0	1.2
Cation Exchange Capacity ($\text{cmol}(+)/\text{kg}$)	25.2	13.6	18.8	23.3

Heavy Metal Content

The concentrations of heavy metals in Anyigba soils varied considerably across sampling locations, reflecting waste-related inputs and localized anthropogenic pressures. Cadmium posed the highest contamination risk relative to international standards, while other metals showed moderate enrichment.

Cadmium (Cd)

Cadmium concentrations were markedly elevated, ranging from 4.60 mg/kg at Agala-Ate to 5.91 mg/kg at Iyale Road, compared with 1.94 mg/kg at the control. These values exceeded the WHO (2021) guideline of 0.3 mg/kg by more than fifteen-fold, strongly implicating waste disposal, phosphate fertilizers, and vehicular emissions as major sources (Kubier *et al.*, 2019). Given cadmium’s high mobility and accumulation potential in crops, such levels represent a severe ecological and public health concern, with risks including kidney dysfunction, skeletal damage, and carcinogenic effects (Rahimzadeh *et al.*, 2017).

Copper (Cu)

Copper ranged from 5.81 mg/kg at Agala-Ate to 11.90 mg/kg at Wada Road, compared to 3.75 mg/kg at the control. Although these concentrations remain below the WHO (2021) limit of 36 mg/kg , enrichment relative to the control indicates anthropogenic contributions from agrochemicals, vehicle parts, and workshop residues (Droz *et al.*, 2021). While copper is an essential micronutrient, excessive levels may induce phytotoxicity, inhibit microbial activity, and disrupt nutrient balance

(Shabbir *et al.*, 2020). The moderate enrichment observed warrants long-term monitoring to prevent accumulation.

Nickel (Ni)

Nickel concentrations varied between 7.52 mg/kg at Wada Road and 15.36 mg/kg at Iyale Road, compared to 6.16 mg/kg at the control. Although values remain below the WHO (2021) threshold of 50 mg/kg , they indicate contamination linked to metal scraps, combustion, and waste burning. Elevated nickel can impair enzymatic functions in plants, reducing growth and yield (Labidi and Abdelly, 2024), and may bioaccumulate in edible tissues, posing food safety risks (Kumar *et al.*, 2022). The highest value at Iyale Road reflects intense human and vehicular activity in that area.

Chromium (Cr)

Chromium levels ranged from 4.31 mg/kg at Wada Road to 8.96 mg/kg at Iyale Road, relative to 2.86 mg/kg at the control. All values remained well below the WHO (2021) limit of 65 mg/kg , though modest enrichment suggests contributions from urban runoff, waste burning, and mechanical emissions. Chromium speciation is critical, as Cr(III) is relatively benign while Cr(VI) is highly toxic and carcinogenic (Shrivastava *et al.*, 2022). Although oxidation states were not differentiated, continued inputs could gradually raise soil chromium toward hazardous levels.

Lead (Pb)

Lead concentrations ranged from 2.68 mg/kg at Iyale Road to 5.04 mg/kg at Wada Road, with the control at 2.15 mg/kg . These values are far below the WHO (2021) limit of

85 mg/kg, suggesting no immediate concern. However, enrichment relative to the control indicates anthropogenic inputs from vehicular emissions, discarded batteries, and paints (Landrigan *et al.*, 2022). Despite low mobility, lead

is persistent and accumulative, posing long-term risks to human health, especially neurodevelopmental effects in children (Liu *et al.*, 2023). The higher level at Wada Road likely reflects intense traffic and workshop activity.

Table 2: Heavy Metal Concentration in Various sites

Sample Sites	Cadmium (mg/kg)	Copper (mg/kg)	Nickel (mg/kg)	Chromium (mg/kg)	Lead (mg/kg)
Agala-Ate	4.60	5.81	11.70	4.93	3.99
Iyale road	5.91	10.18	15.36	8.96	2.68
Wada road	5.59	11.90	7.52	4.31	5.04
Control	1.94	3.75	6.16	2.86	2.15
WHO (2021)	0.3	36	50	65	85

Heavy Metal Speciation

Cadmium (Cd)

Cadmium speciation in soils near dumpsites showed dominance of the exchangeable fraction (35–45% of total Cd), indicating high bioavailability and mobility, and significant risk for crop uptake and leaching (Li *et al.*, 2022). The carbonate-bound fraction was the second largest (25–30%), becoming mobilizable under acidic conditions. Fe–Mn oxide-bound Cd contributed 10–15%, particularly at Iyale Road, and may be released under

reducing conditions, while the organic matter-bound fraction was minor (5–10%).

The residual fraction accounted for only 7–10%, confirming the largely anthropogenic origin of Cd in dumpsite soils. In contrast, the control site showed carbonate-bound (≈35–40%) and exchangeable (≈30%) fractions as dominant, with a relatively higher water-soluble fraction (≈20%), highlighting natural labile pools but lower environmental risk. Overall, Cd fractionation followed the order: Exchangeable > Carbonate-bound > Fe–Mn oxide > Residual ≈ Organic matter > Water-soluble.

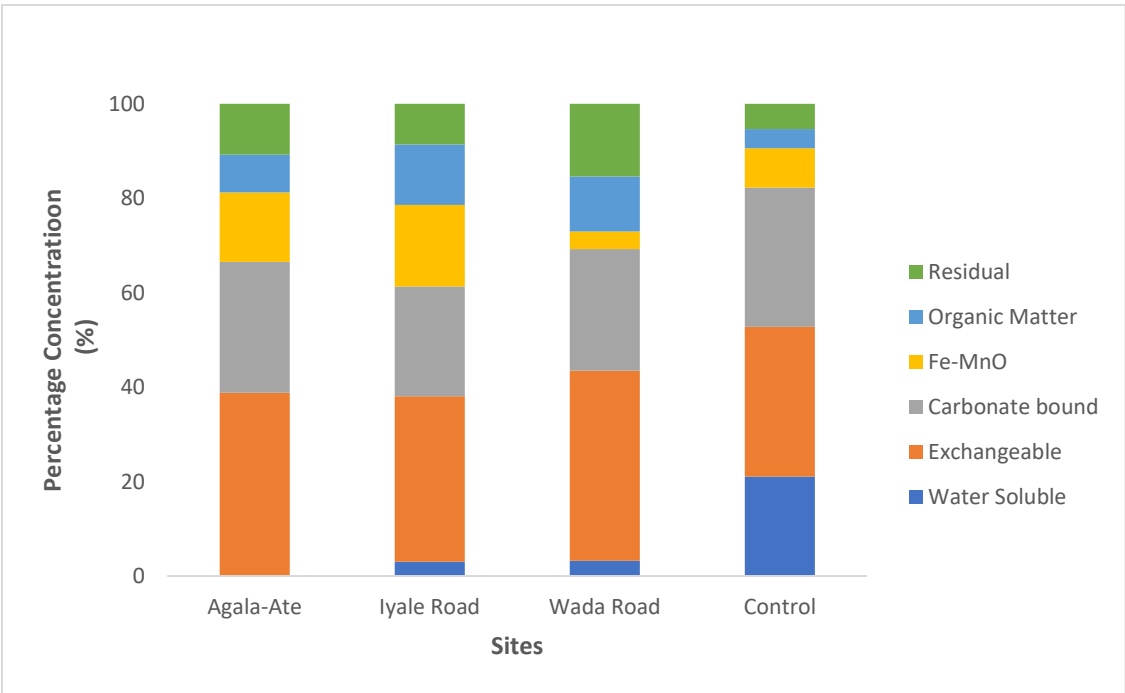


Figure 1: Percentage Concentration of Cadmium in Soil Fractions in Various Sampling Sites

Copper

Speciation analysis of copper in soils near dumpsites showed dominance of the organic matter-bound fraction (30–35% of total Cu), indicating moderate immobilization through complexation with soil organic matter (Huang *et al.*, 2022). Decomposition of organic matter under

microbial or oxidative conditions could, however, release Cu into the soil solution, increasing its bioavailability (Ahmed *et al.*, 2023). The Fe–Mn oxide fraction was the second largest (20–25%), representing a pool sensitive to reduction; anaerobic or waterlogged conditions may mobilize this Cu fraction.

Carbonate-bound Cu (10–15%) may be released under acidic conditions, while the exchangeable fraction (5–10%) represents the most labile pool, slightly higher at Iyale Road and Wada Road. The residual fraction (12–15%) indicates structurally bound, geochemically stable Cu, and the water-soluble fraction remained minimal (<5%), reflecting limited immediately mobile Cu (El-Hassanin,

2022). The control soil displayed a similar pattern, with organic matter and Fe–Mn oxide fractions dominating, though dumpsite soils had slightly higher exchangeable and carbonate-bound Cu, reflecting anthropogenic enrichment: Overall, Cu fractionation followed the order: Organic matter > Fe–Mn oxide > Residual $\approx$ Carbonate-bound > Exchangeable > Water-soluble.

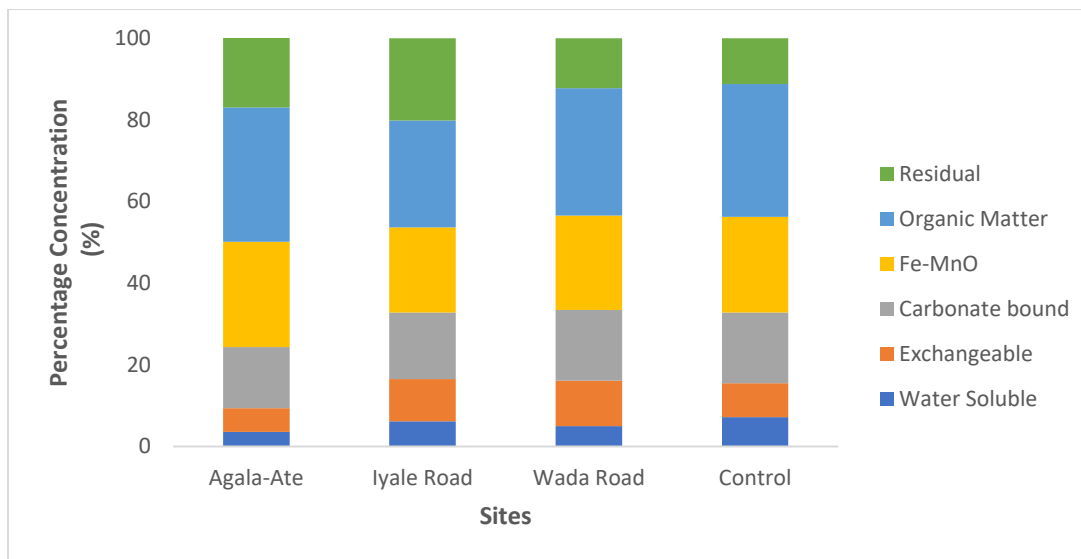


Figure 2: Percentage Concentration of Copper in Soil Fractions in Various Sampling Sites

Nickel

Nickel speciation in the studied soils was dominated by the Fe–Mn oxide-bound and carbonate-bound fractions, indicating strong retention by sesquioxides and carbonates, with moderate stability yet potential mobilization under reducing or acidic conditions (Wang *et al.*, 2022). The organic matter-bound fraction also contributed significantly, reflecting complexation with humic substances; however, decomposition of organic matter could gradually release Ni into more labile forms. The residual fraction was moderate across sites, showing substantial structural binding within silicate minerals, while exchangeable and water-soluble fractions were

minimal, suggesting limited immediate bioavailability and low short-term environmental risk (Patel *et al.*, 2023; Zhang *et al.*, 2024). Spatially, Agala-Ate exhibited higher exchangeable and carbonate-bound Ni, implying greater mobility, Iyale Road showed a balance between carbonate and Fe–Mn oxide fractions, and Wada Road was dominated by the Fe–Mn oxide fraction. The control soil had a higher organic matter contribution, highlighting the role of natural soil content in immobilizing Ni. Overall, Ni fractionation followed the order: Fe–Mn oxide $\approx$ Carbonate > Organic matter > Residual > Exchangeable > Water-soluble.

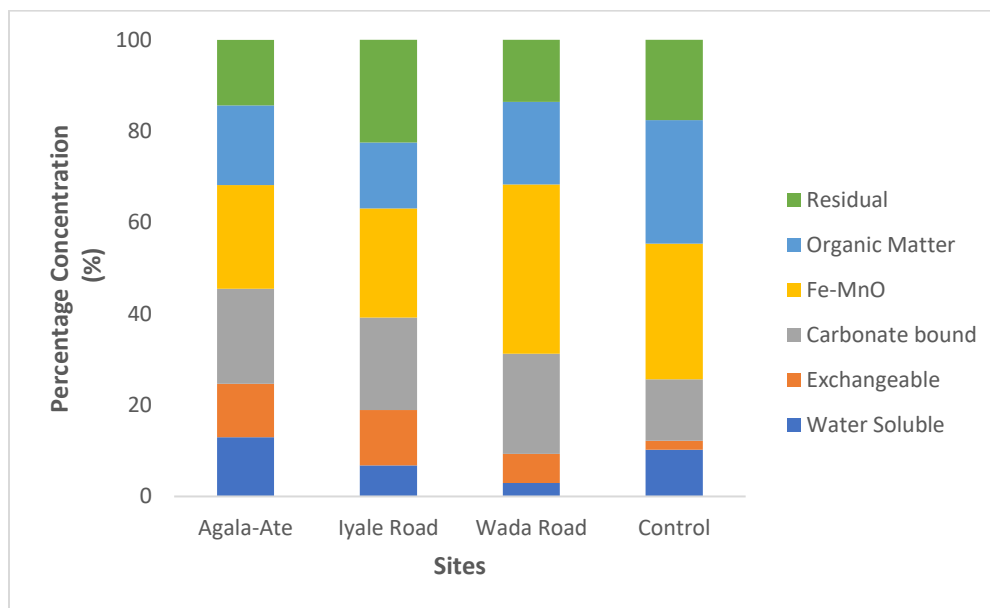


Figure 3: Percentage Concentration of Nickel in Soil Fractions in Various Sampling Sites

Chromium

Chromium speciation in the studied soils was dominated by Fe–Mn oxide-bound and organic matter-bound fractions, indicating strong immobilization through adsorption onto sesquioxides and complexation with organic matter, thereby limiting immediate bioavailability (Saha *et al.*, 2023). The residual fraction contributed notably, reflecting structural incorporation within the soil mineral matrix, further reducing Cr mobility. Carbonate-bound Cr was moderate, suggesting potential release under acidic conditions, while exchangeable and water-soluble fractions were minimal, indicating low immediate environmental risk (Zhang *et al.*, 2024).

Site-specific patterns showed higher Fe–Mn oxide-bound Cr at Iyale Road, reflecting redox sensitivity, whereas Wada Road had greater contributions from carbonate and organic matter fractions, indicating potential mobilization under acidic or oxidative conditions. The control soil displayed similar dominance of organic matter and Fe–Mn oxide fractions, with slightly higher exchangeable Cr, highlighting the influence of natural soil properties on Cr partitioning. Overall, Cr fractionation followed the order: Fe–Mn oxide > Organic matter > Residual > Carbonate > Exchangeable > Water-soluble.

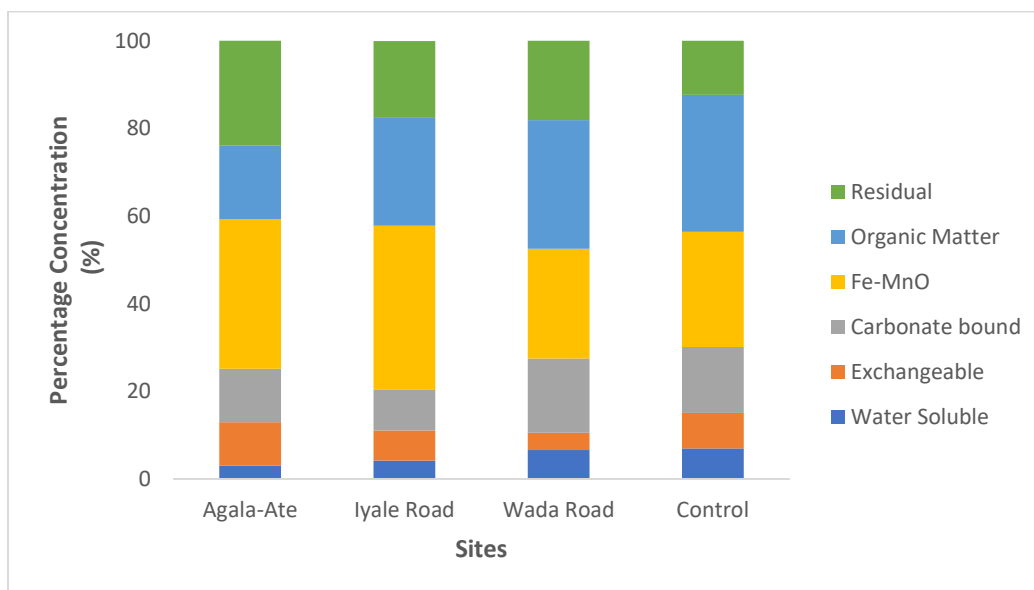


Figure 4: Percentage Concentration of Chromium in Soil Fractions in Various Sampling Sites

Lead

Lead speciation in the studied soils was dominated by the carbonate-bound fraction, followed by organic matter-bound and Fe–Mn oxide-bound fractions, indicating strong retention by soil carbonates and organic complexes with moderate stability, but susceptibility to pH and redox changes (Adeyemi *et al.*, 2023). Carbonate-bound Pb was particularly dominant at Iyale Road, highlighting potential mobilization under acidic conditions (Chen *et al.*, 2022). Organic matter-bound Pb reflected chelation by humic and fulvic substances, though decomposition could

release Pb over time (Huang *et al.*, 2024). Fe–Mn oxide-bound Pb contributed notably at Agala-Ate and Wada Road, showing partial immobilization with redox-sensitive stability. The residual fraction was moderate, indicating structural binding within mineral lattices, while exchangeable and water-soluble fractions were minimal, signifying low immediate bioavailability. Overall, Pb fractionation followed the order: Carbonate > Organic matter $\approx$ Fe–Mn oxide > Residual > Exchangeable > Water-soluble.

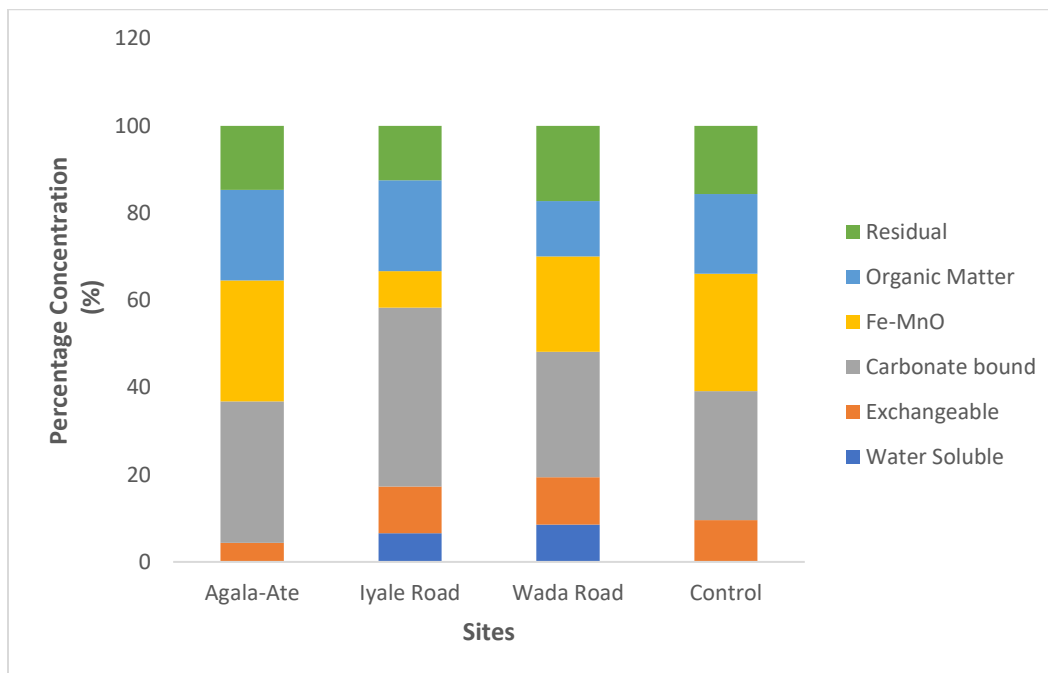


Figure 5: Percentage Concentration of Lead in Soil Fractions in Various Sampling Sites

Assessment of Metal Contamination Contamination Factor (CF)

The contamination factor (CF) provides a measure of heavy metal enrichment in soils relative to background levels, reflecting pollution extent and potential ecological and health risks. CF values were calculated for Cd, Cu, Ni, Cr, and Pb in soils from Agala-Ate, Iyale Road, and Wada Road, using a control site as baseline. At Agala-Ate, CF values indicated moderate contamination for all metals: Cd (2.37), Ni (1.90), Cr (1.73), Pb (1.86), and Cu (1.55). While not extreme, consistent enrichment suggests gradual accumulation, with Cd posing the highest risk due to its bioaccumulative and toxic nature. Iyale Road exhibited the highest contamination, with Cd (3.05) and Cr (3.13) in the considerable contamination category, and Cu (2.71), Ni (2.49), and Pb (1.25) moderately elevated. The elevated Cd and Cr levels are particularly concerning due to their

toxicity and persistence, while Cu enrichment could impair microbial activity and crop productivity (Ali *et al.*, 2021). At Wada Road, CF values showed considerable contamination for Cu (3.17) and Cd (2.88), moderate contamination for Pb (2.34), and lower levels for Cr (1.51) and Ni (1.22). Excessive Cu and Cd pose significant ecological and food chain risks, while the persistence of Cr and Ni raises concerns over long-term accumulation (Adewumi *et al.*, 2022). Overall, soils near dumpsites exhibited varying contamination levels, with Cd and Cu presenting the greatest risk. Iyale Road and Wada Road were more impacted than Agala-Ate, reflecting site-specific differences in waste inputs, leachate flow, and soil properties. Moderate levels of Pb, Ni, and Cr, although less alarming, still warrant attention due to potential mobilization under changes in pH or redox conditions (Huang *et al.*, 2022).

Table 3: Contamination Factors of Heavy Metals in the Soil Samples

SITES	Cd	Cu	Ni	Cr	Pb
Agala-Ate	2.37	1.55	1.90	1.73	1.86
Iyale Road	3.05	2.71	2.49	3.13	1.25
Wada Road	2.88	3.17	1.22	1.51	2.34

Pollution Load Index (PLI)

The Pollution Load Index (PLI) provides a cumulative assessment of heavy metal contamination in soils, with values above 1 indicating pollution. In this study, PLI values were 1.87, 2.29, and 2.05 for Agala-Ate, Iyale Road, and Wada Road, respectively, demonstrating that all sites are contaminated to varying degrees. Iyale Road recorded the highest PLI (2.29), reflecting substantial cumulative heavy metal input, likely due to intense anthropogenic activities such as waste dumping, mechanic workshops, and other local emissions (Omoyajowo *et al.*, 2023). This elevated PLI aligns with the previously observed high contamination factors for Cd, Cu, Ni, and Cr, indicating significant ecological and food chain risks (Rahman *et al.*, 2022).

Wada Road exhibited a PLI of 2.05, showing notable heavy metal accumulation. Although slightly lower than Iyale Road, the site remains influenced by similar anthropogenic inputs, including domestic waste disposal and vehicular emissions, with potential for contaminant migration into adjacent farmlands. At Agala-Ate, the PLI was 1.87, indicating moderate pollution. While lower than the other sites, it still exceeds the pollution threshold, reflecting ecological vulnerability and potential risk to soil quality and crop safety due to heavy metal enrichment. Overall, the PLI analysis confirms that farmlands near dumpsites in the study area are under varying degrees of heavy metal stress, with Iyale Road being the most impacted. These findings corroborate previous studies in Nigeria, where PLI values above unity have been reported for dumpsite soils (Abiola *et al.*, 2021).

Table 4: Pollution Load Index of Heavy Metals in the Soil Samples

SITES	Agala-Ate	Iyale Road	Wada Road
PLI	1.87	2.29	2.05

Geoaccumulation Index (I_{geo})

The geoaccumulation index (I_{geo}) assesses anthropogenic enrichment of metals in soils relative to natural background levels. In this study, most metals in soils from farmlands near dumpsites in Anyigba fell within the *unpolluted to moderately polluted* category, indicating that while natural background concentrations dominate, human activities such as waste disposal have contributed to metal enrichment. At Agala-Ate, I_{geo} values for Cd, Cu, Ni, Cr, and Pb ranged from 0.05 to 0.66, reflecting slight enrichment likely due to diffuse contamination from nearby waste activities (Adesina *et al.*, 2022). Though not yet hazardous, consistent elevation across all metals suggests ongoing anthropogenic input. Iyale Road presented a more pronounced contamination profile, with cadmium (I_{geo} = 1.02) and chromium (I_{geo} = 1.06) classified as moderately polluted, while copper and nickel remained in the unpolluted to moderately polluted range. Lead recorded a negative I_{geo} value (−0.27), indicating

minimal enrichment relative to background levels (Ukaogo *et al.*, 2024; Li *et al.*, 2023). The results highlight significant contamination pressure from Cd and Cr, both of which pose ecological and health risks. At Wada Road, copper (I_{geo} = 1.08) was moderately polluted, reflecting localized enrichment likely from discarded metallic waste and vehicle residues. Cadmium, chromium, and lead were in the unpolluted to moderately polluted class, while nickel (I_{geo} = −0.30) showed no enrichment. Elevated copper levels suggest potential negative impacts on soil microbial activity and crop growth. Overall, the I_{geo} assessment confirms that Iyale Road and Wada Road are the most impacted sites, with moderate pollution by Cd, Cr, and Cu. The results corroborate previous contamination factor and pollution load index analyses, emphasizing that farmlands near dumpsites in Anyigba are experiencing varying degrees of heavy metal stress, with cadmium posing the highest risk due to its mobility and bioaccumulation potential.

Table 5: Geoaccumulation Index of Heavy Metals in the Soil Samples

Sites	Cd	Cu	Ni	Cr	Pb
Agala-Ate	0.66	0.05	0.34	0.2	0.31
Iyale Road	1.02	0.86	0.73	1.06	-0.27
Wada Road	0.94	1.08	-0.3	0.01	0.64

Nemerow pollution Index (NPI)

The Nemerow Pollution Index (NPI) provides an integrated assessment of soil quality by combining the mean contamination factor with the maximum contamination factor at each site. Unlike single-element indices, NPI reflects both average pollution levels and the influence of the most critical contaminant, offering a comprehensive measure of multi-element pollution in agricultural soils near dumpsites (Okeke *et al.*, 2024). In this study, NPI values ranged from 2.14 at Agala-Ate to 2.844 at Iyale Road, with Wada Road recording 2.738. According to established thresholds, all sites fall within the *moderate pollution* category ($2 < \text{NPI} \leq 3$), indicating that soils adjacent to the dumpsites are moderately polluted by heavy metals, with potential implications for crop

productivity, food safety, and ecological stability (Zhang *et al.*, 2023). Iyale Road exhibited the highest NPI (2.844), consistent with elevated contamination factors for cadmium and copper, highlighting the cumulative pressure from multiple metals. Wada Road (2.738) also showed significant pollution, largely influenced by cadmium and lead, while Agala-Ate (2.14) had the lowest NPI, yet still within the moderate pollution range, indicating that even this site is impacted by anthropogenic inputs. Overall, the moderate pollution classification across all sites highlights the risk of heavy metal accumulation in crops, particularly for cadmium and copper, which consistently showed high contamination factors.

Table 6: Nemerow Pollution Index of Heavy Metals in the Soil Samples

Sites	CF mean	CFmax	NPI	Pollution Status
Agala-Ate	1.882	2.37	2.14	Moderate Pollution
Iyale Road	2.526	3.13	2.844	Moderate Pollution
Wada Road	2.224	3.17	2.738	Moderate Pollution

Enrichment Factor (EF)

Spatial variations in enrichment factor (EF) values across the studied farmlands reflect differences in anthropogenic influence. At Agala-Ate, EF values indicated minor enrichment for cadmium (1.38), nickel (1.10), and lead (1.08), while copper (0.90) showed no enrichment. This pattern suggests low-level anthropogenic contributions, likely from leachates and surface runoff from nearby dumpsites, with common waste sources including batteries, pigments, and automotive residues. The lack of Cu enrichment points to a primarily lithogenic origin (Ajibade *et al.*, 2022). Iyale Road exhibited the lowest EF values, with all metals—Cd (0.97), Cu (0.87), Ni (0.80), and Pb (0.40) falling below unity, indicating negligible anthropogenic input. These results suggest that heavy metals at this site are mainly derived from natural geogenic sources, with minor

contributions potentially masked by relatively higher chromium content (Chukwu *et al.*, 2023). In contrast, Wada Road showed the highest EF values among the sites, with Cd (1.91), Cu (2.11), and Pb (1.56) indicating clear minor enrichment, while Ni (0.81) remained within the no enrichment range. Elevated Cd, Pb, and Cu likely originate from waste streams such as discarded plastics, pigments, batteries, electrical wiring, and plumbing materials, reflecting a stronger anthropogenic imprint on farmland soils (Ogunniyi *et al.*, 2021). Overall, the spatial pattern of EF values highlights that Wada Road farmland is the most impacted by dumpsite-related contamination, followed by Agala-Ate with minor enrichment, while Iyale Road remains largely unaffected and influenced by natural lithogenic processes.

Table 7: Enrichment Factors of Heavy Metals in the Soil Samples

Sites	Cd	Cu	Ni	Pb
Agala-Ate	1.38	0.90	1.10	1.08
Iyale Road	0.97	0.87	0.80	0.40
Wada Road	1.91	2.11	0.81	1.56

Ecological Risk Index and Potential Ecological Risk Index

The computed single-element ecological risk values (Er) indicate that cadmium (Cd) is the principal contributor to ecological risk across all sampled sites. At Agala-Ate, Cd recorded an Er of 71.10, classifying it as a moderate ecological risk, whereas copper (7.75), nickel (9.50), chromium (3.46), and lead (9.30) were all within the low-risk category. The cumulative risk index (RI) of 101.11

places the site in the low ecological risk class, underscoring the dominant influence of Cd despite overall low risk. At Iyale Road, Cd exhibited the highest risk (Er = 91.50), categorized as considerable, while Cu (13.55), Ni (12.45), Cr (6.26), and Pb (6.25) remained low. The total RI (130.01) was the highest among the sites, reflecting Cd’s increasing role in driving ecological pressure. Wada Road soils showed a similar pattern, with Cd (Er = 86.40) presenting

considerable risk and other metals—Cu (15.85), Ni (6.10), Cr (3.02), Pb (11.70) remaining low. The cumulative RI (123.07) confirms low overall ecological risk but emphasizes Cd as the controlling factor. Notably, Pb at Wada Road exhibited a slightly elevated risk, likely due to localized anthropogenic inputs from waste dumpsites, including batteries, paints, and vehicle parts (Abbas *et al.*, 2023).

Comparatively, Iyale Road recorded the highest RI, followed by Wada Road and Agala-Ate. While all sites remain under the low ecological risk threshold (RI < 150), the high contribution of Cd highlights its ecological significance. Continued Cd accumulation from waste leachates or agricultural inputs could elevate the RI to moderate or considerable risk levels, posing threats to soil quality and agricultural productivity.

Table 8: Ecological Risk Index and Potential Ecological Risk Index of Heavy Metals in the Soil Samples

Sites	Cd (x 30)	Cu (x 5)	Ni (x 5)	Cr (x 2)	Pb (x 5)	RI
Agala-Ate	71.10	7.75	9.50	3.46	9.30	101.11
Iyale Road	91.50	13.55	12.45	6.26	6.25	130.01
Wada Road	86.40	15.85	6.10	3.02	11.70	123.07

CONCLUSION

This study shows that agricultural soils in Anyigba farmlands near dumpsites are moderately polluted by heavy metals, with cadmium and copper as the most critical contaminants. Chemical speciation revealed cadmium to be largely exchangeable, indicating high mobility and ecological risk, while copper and chromium were bound to organic matter and Fe–Mn oxides, and lead and nickel were mainly in carbonate- and oxide-bound forms, suggesting conditional stability but vulnerability under changing soil conditions. Pollution indices (CF, PLI, Igeo, NPI, EF, and RI) consistently highlighted Iyale Road and Wada Road as the most impacted sites, while Agala-Ate showed lower but notable enrichment.

RECOMMENDATIONS

Although total ecological risk indices fell below the high-risk threshold, cadmium’s persistence underscores a long-term threat to soil health, food safety, and public health. To mitigate these risks, remediation should prioritize cadmium through phytoremediation, biochar or lime amendments, and stabilization techniques, while improving soil quality with organic matter to reduce metal mobility. Strengthened waste management practices, continuous soil and crop monitoring, adoption of safer agricultural practices, and farmer/community sensitization are also essential. Finally, effective policy enforcement on waste disposal and land use is needed to curb further contamination and safeguard agricultural sustainability in the region.

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