



Multi-Index Assessment of Heavy Metals in Agricultural Soils near Waste Dumpsites in Egume, Kogi State, Nigeria

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Abstract

This study assessed the physicochemical properties and heavy metal contamination of soils from farmlands adjacent to municipal dumpsites in comparison to a control site located >50 m away from visible anthropogenic disturbance. Contaminated soils exhibited higher moisture content (90–353% higher), greater electrical conductivity (55 – 384% higher), and enriched soil organic carbon, SOC (147– 353% higher) compared to the control. In contrast, their CEC values were generally lower (7–53% lower), except at Acharu where it was slightly higher (32% higher). Texturally, contaminated soils were sandy loam with higher sand content (48 – 66%) relative to the loamy control (38%), while pH ranged from slightly acidic to near-neutral compared to the slightly alkaline control (7.2). Heavy metal analysis was conducted using flame atomic absorption spectrophotometry (FAAS). Method validation confirmed reliable performance, with limits of detection (LOD) ranging from 0.01 to 0.05 mg/kg and limits of quantification (LOQ) between 0.05 and 0.15 mg/kg. Precision (RSD) was below 5%, and recovery values ranged from 92% to 106%, ensuring accuracy and reproducibility. Results revealed cadmium (Cd) levels of 6.23–9.75 mg/kg compared to 0.42 mg/kg in the control, Efikpo site exhibiting an extremely high geo-accumulation index ($I_{geo} = 2.575$). Lead (Pb) ranged from 125.32–162.48 mg/kg compared to 5.00 mg/kg in the control, with contamination factors (CF) up to 32.50, indicating severe anthropogenic influence. Copper (Cu) levels reached 45.73 mg/kg (control: 10.15 mg/kg) and nickel (Ni) peaked at 17.54 mg/kg (control: 3.25 mg/kg), while manganese (Mn) remained within permissible limits but showed localized enrichment. Pollution load index (PLI) values exceeded 5.00 at all dumpsite sites, and total ecological risk (RI) ranged from 178.43 to 446.17, confirming contamination.

Keywords: Agricultural Soils, Dumpsites, Heavy Metals, Ecological Risk, Pollution Index, Soil properties.

Introduction

The rapid increase in waste generation and accumulation represents a critical environmental challenge, particularly in developing countries where solid waste management remains inadequate [1]. Urbanization, industrialization,

and population growth intensify pressure on natural resources, often resulting in the release of hazardous pollutants into the environment. Among these, heavy metals stand out as persistent contaminants commonly associated with municipal solid waste and dumpsites [2]. Unlike

organic pollutants, heavy metals are non-biodegradable, tend to persist in soils, water bodies, and crops, and can bioaccumulate in food chains, thereby posing long-term ecological and human health risks [3].

Soils, serving as the primary sink for heavy metals, are particularly vulnerable to contamination from unmanaged waste disposal. These metals may leach into groundwater or be absorbed by crops cultivated on contaminated soils, increasing dietary exposure to local populations [4]. Evidence from prior studies shows that heavy metal concentrations in dumpsite soils often exceed regulatory thresholds, highlighting the risks of cultivating food crops in such environments [5]. The problem is further compounded by leachate migration during rainfall events and atmospheric dispersion of contaminated dust, both of which extend the impact beyond soil to air and water systems. This scenario is evident in Nigerian urban centers, where dumpsites are frequently located near residential and agricultural areas, thereby increasing direct human exposure [6].

Given the persistence, toxicity, and bioaccumulative nature of heavy metals, systematic monitoring of dumpsite-impacted soils is essential for risk assessment and sustainable land management. Such assessments not only provide critical data for ecological and human health protection but also inform regulatory frameworks and community-level

interventions [7]. The present study therefore investigates the concentrations and potential risks of heavy metals in agricultural soils surrounding waste dumpsites in Egume, Nigeria, with the aim of better understanding towards ecological risk mitigation and sustainable waste management strategies.

Material and Methods

Study Area

This study was carried out in Egume, an agricultural area of Kogi State in the North-Central region of Nigeria. The area lies within the Guinea savanna ecological zone, characterized by a tropical climate with distinct wet and dry seasons, fertile alluvial soils, and intensive agricultural activity [8]. Egume functions as both a socio-cultural and commercial hub of the Igala people and has witnessed rapid urbanization, informal industrial growth, and the proliferation of unmanaged waste dumpsites located near both residential and agricultural lands [9].

Geographically, the study area is situated between 07° 28' 23" N latitude and 07° 14' 56" E longitude, encompassing varied land-use patterns influenced by both natural soil-forming processes and anthropogenic inputs. These features render the site particularly suitable for examining waste-related soil pollution in active agricultural zones.

Soil Sampling

Five active farmlands situated within 10–15 m of waste dumpsites were purposively selected for sampling, based on their direct exposure to solid waste disposal activities. The sites included farmlands at Acharu, Alade, Efikpo and Adumu, all actively used for crop cultivation. A control site was established at Egume Abejukolo, located >50 m away from visible anthropogenic disturbance, to serve as a baseline for comparison of soil quality.

At each test site, surface soils (0–10 cm) were collected using a pre-cleaned stainless steel scoop to avoid cross-contamination. To capture spatial variability, each location was divided into four quadrants, from which sub-samples were collected and homogenized to generate a composite sample. This strategy reduces micro-scale variability and increases representativeness [10]. Sampling was conducted in triplicate per site, thereby supporting statistical robustness in subsequent analyses.

Sample Handling and Pretreatment

Collected soils were sealed in labeled polyethylene bags, transported to the laboratory, and air-dried at room temperature. Dried samples were ground, passed through a 2 mm stainless steel sieve, and further homogenized using an agate mortar and pestle [11]. The pre-treated samples were stored in airtight containers under controlled conditions prior to physicochemical and geochemical analyses.

Determination of Physicochemical Soil Properties

The physicochemical properties of the soils were determined using standard procedures to ensure accuracy and reproducibility. Soil pH, a key indicator of acidity or alkalinity influencing nutrient availability and metal solubility, was measured using the 1:2.5 soil-to-water suspension method with a calibrated digital pH meter [12].

Soil moisture content, which reflects the water-holding capacity and affects microbial activity and contaminant mobility, was determined gravimetrically by oven-drying approximately 20 g of fresh soil at 105 °C for 24 h, with weight loss expressed as a percentage of the initial weight [13]. Soil texture, an important property governing water retention, aeration, and pollutant transport, was analyzed using the Bouyoucos hydrometer method and classified according to the USDA textural triangle [14].

Electrical conductivity (EC), providing insight into soluble salts and ionic strength, was measured in a 1:5 soil-to-water extract using a digital conductivity meter [15]. Soil organic carbon (SOC), a parameter that influences nutrient cycling, aggregate stability, and metal binding, was estimated by the Walkley–Black dichromate wet oxidation method, while organic matter content was derived using the standard factor of 1.724 [16]. Finally, cation exchange capacity (CEC), which reflects the soil's ability to retain and exchange essential nutrients and heavy

metals, was determined by the ammonium acetate method (pH 7.0), in which exchangeable NH_4^+ ions were displaced by NaCl and quantified [17].

Heavy Metal Analysis

Soil samples were digested using aqua regia ($\text{HCl}:\text{HNO}_3$, 3:1 v/v) following standard wet acid digestion protocols [18]. Exactly 1 g of each soil sample was digested, evaporated to near dryness on a hotplate under a fume hood, and reconstituted with deionized water. The digests were filtered and diluted to 25 mL in acid-washed polyethylene vials. Concentrations of cadmium, copper, nickel, manganese, and lead were determined using Flame Atomic Absorption Spectrophotometry (FAAS), with instrument calibration performed against certified multi-element standards. Analytical quality control was ensured through procedural blanks, replicate analyses, and recovery checks with certified reference materials.

All measurements were conducted in triplicate and expressed in mg/kg dry weight to align with WHO guideline limits. Method validation confirmed the reliability of the results: limits of detection (LOD) ranged from 0.01 to 0.05 mg/kg, while limits of quantification (LOQ) were between 0.05 and 0.15 mg/kg depending on the element. Precision, expressed as relative standard deviation (RSD), was generally below 5%, and recovery values fell between 92% and 106%, ensuring both accuracy and reproducibility of the reported concentrations.

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:

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

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.

- $I_{\text{geo}} \leq 0$: Uncontaminated
- $0 < I_{\text{geo}} \leq 1$: Uncontaminated to moderately contaminated
- $1 < I_{\text{geo}} \leq 2$: Moderately contaminated
- $2 < I_{\text{geo}} \leq 3$: Moderately to heavily contaminated
- $3 < I_{\text{geo}} \leq 4$: Heavily contaminated
- $4 < I_{\text{geo}} \leq 5$: Heavily to extremely contaminated
- $I_{\text{geo}} > 5$: Extremely contaminated

Nemerow Pollution Index (NPI)

The Nemerow index is calculated using the equation:

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

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:

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

$EF < 2$: Deficiency to minimal enrichment

$2 \leq EF < 5$: Moderate enrichment

$5 \leq EF < 20$: Significant enrichment

$EF \geq 20$: Very high enrichment

Manganese (Mn) 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:

$$E_r = T_r \times CF$$

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

$$R_I = \sum E_r$$

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

Soil pH values ranged 5.8 and 7.5 in the affected sites, indicating slightly acidic to near-neutral conditions, while the control soils maintained a more stable, slightly alkaline pH of 7.2. The more acidic soils exhibited greater mobility of Cd and Pb, reflecting higher solubility and leaching potential compared with the control, where near-neutral pH likely favored adsorption or precipitation. This observation reinforces earlier

reports that acidic environments enhance metal release into soil solution [5].

Moisture content varied markedly across the soils, ranging from 6.4% to 43.5%, compared with 9.6% at the control site. Elevated moisture, particularly in soils closer to dumpsites, was associated with higher soluble Mn levels, consistent with redox-driven mobilization under waterlogged conditions. Similar trends have been described by [18] and [19] who noted that excessive soil moisture promotes temporal spikes in metal solubility and groundwater leaching.

Textural analysis revealed predominantly sandy loam compositions (48–66% sand, 18–30% silt, 12–22% clay) compared to the finer loam texture of the control site (38% sand, 36% silt, 26% clay). The higher sand fractions in dumpsite soils imply fewer adsorption sites and weaker metal retention, whereas the higher silt and clay contents of the control site suggest greater capacity for immobilizing Cu and Ni through adsorption and ion exchange, corroborating the findings of [20].

Electrical conductivity values further distinguished the soils, ranging between 136 and 426 $\mu\text{S}/\text{cm}$ in dumpsite-impacted sites, but only 88 $\mu\text{S}/\text{cm}$ in the control soils. The elevated EC reflects the presence of soluble ions and salts derived from decomposing waste, which increase ionic strength and consequently enhance metal solubility. This observation aligns with [21] who highlighted EC as a reliable proxy for

anthropogenic contamination in urban and peri-urban soils.

Soil organic carbon content varied between 1.2% and 6.8%, with the control site recording 1.5%. Higher SOC values in the dumpsite soils suggest enhanced metal complexation potential, particularly with Pb and Cd. While organic matter can stabilize heavy metals and reduce their immediate bioavailability, its eventual microbial or chemical degradation may release metals back into the soil solution, creating long-term risks. These dynamics agree with the work of [22] and [23] who emphasized the dual role of organic matter in metal stabilization and remobilization. Cation exchange capacity ranged from 10.3 to 28.7 cmol(+)/kg in the impacted soils, compared

with 21.8 cmol(+)/kg in the control. Higher CEC values in certain dump-affected soils were associated with reduced metal mobility, suggesting stronger retention, whereas soils with lower CEC and sandy texture exhibited greater concentrations of exchangeable Ni and Cd, reflecting weaker sorption potential. This finding supports [24] who underscored the protective role of CEC in mitigating heavy metal leaching in waste-affected environments.

Collectively, the interplay of soil physicochemical properties in Egume farmlands illustrates how waste dumpsites alter soil functionality, enhancing heavy metal mobility and ecological risk through shifts in pH, texture, ionic strength, and retention capacity.

Table 4.1: Soil Physicochemical Parameters

Physicochemical Parameters	Acharu	Alade	Adumu	Efikpo	Control
Soil pH	6.9	6.12	6.3	7.5	7.2
Soil Moisture Content (%)	6.4	21.6	18.3	43.5	9.6
Soil Texture	Sandy loam (48 % sand)	Sandy loam (53 % sand)	Sandy loam (61 % sand)	Sandy loam (66 % sand)	Loam (38 % sand)
Electrical Conductivity ($\mu\text{S}/\text{cm}$)	136	254	377	426	88
Soil Organic Carbon (%)	1.2	3.7	4.4	6.8	1.5
Cation Exchange Capacity (cmol(+)/kg)	28.7	23.4	14.9	10.3	21.8

Heavy Metals

Cadmium (Cd)

Cadmium concentrations in soils from all dumpsite-affected farmlands demonstrated substantial enrichment relative to the control site and international safety benchmarks. Measured Cd levels ranged from 0.59 mg/kg at Acharu to 1.43 mg/kg at Efikpo, compared with 0.16 mg/kg in the control soil. Importantly, all observed values exceeded the World Health Organization (WHO) threshold of 0.3 mg/kg, with the highest concentration at Efikpo nearly ninefold higher than both the guideline and the control. Such elevated concentrations reflect strong anthropogenic inputs, primarily from indiscriminate disposal of batteries, plastics, pigments, stabilizers, and electroplated scraps waste streams commonly associated with cadmium release [25].

The geochemical behavior of cadmium exacerbates its ecological risk, as it is highly mobile, readily leaches through soil profiles, and accumulates in plant tissues. Unlike essential micronutrients, cadmium has no biological role and is toxic even at trace levels. Chronic exposure is linked to renal dysfunction, skeletal demineralization, and carcinogenesis, making its presence in agricultural soils a significant public health concern [26]. The consistent exceedance of Cd thresholds across all studied sites underscores the urgent need for targeted remediation strategies and stricter regulation of Cd-bearing wastes to prevent further soil degradation and associated food-chain transfer.

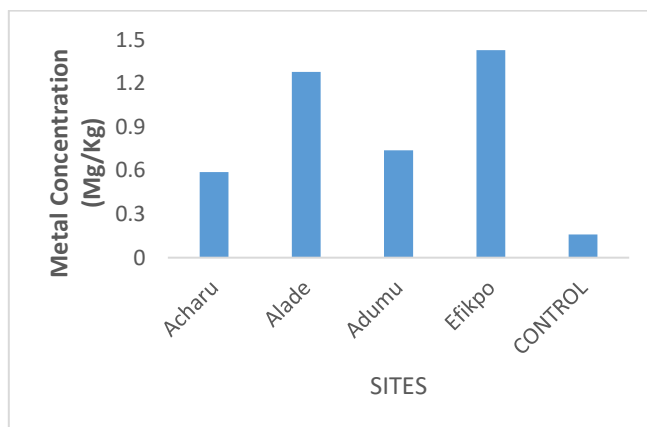


Figure 1: Concentration of Cadmium in the Sampling and Control Sites

Copper (Cu)

Copper concentrations in soils from the studied dumpsites ranged between 1.65 mg/kg (Adumu) and 3.56 mg/kg (Efikpo), compared to 0.58 mg/kg at the control site. Although all measured values remained well below the WHO (2021) permissible limit of 36 mg/kg for agricultural soils, they were markedly enriched relative to the control, with Alade and Efikpo recording concentrations three- to sixfold higher. The elevated levels point to anthropogenic inputs, most likely from the indiscriminate disposal of copper-bearing wastes such as electrical wiring, printed circuit boards, roofing materials, plumbing pipes, and obsolete electronic devices, which are prevalent in municipal dumpsites [27].

From a soil plant interaction perspective, copper is an essential micronutrient involved in photosynthesis, respiration, and enzymatic redox reactions. However, excessive accumulation can

induce phytotoxic effects, including oxidative stress, chlorosis, root necrosis, and inhibition of key enzymatic pathways in plants [28]. While the concentrations observed in the present study do not exceed toxicological thresholds, the consistent enrichment at dumpsite soils signals the early onset of contamination that could intensify with

progressive waste deposition and geochemical accumulation. Long-term buildup is particularly concerning, as copper exhibits strong affinity for soil organic matter and clay minerals, which may lead to persistent contamination and reduced soil fertility.

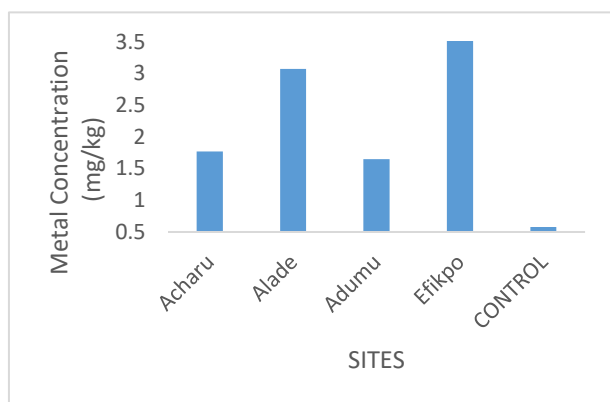


Figure 2: Concentration of Copper in the Sampling and Control Sites

Nickel

Nickel concentrations in dumpsite soils ranged from 1.86 mg/kg (Efikpo) to 3.54 mg/kg (Alade), compared to 1.14 mg/kg at the control site. Although all values were well below the WHO (2021) permissible limit of 50 mg/kg, enrichment was evident, particularly at Alade, where concentrations exceeded the control by more than threefold. The elevated Ni levels are attributable to anthropogenic inputs from discarded stainless steel

utensils, metallic alloys, pigments, ceramics, and rechargeable batteries, common wastes in open dumps that gradually leach into soils [28].

Nickel has limited biological significance, functioning as a cofactor for certain plant and microbial enzymes, but excess accumulation is detrimental. Elevated soil Ni is associated with oxidative stress, inhibition of germination and root elongation, and reduced crop productivity. In humans, chronic exposure is linked to dermatological disorders, respiratory complications, and carcinogenic outcomes [29].

While current levels pose no immediate ecological or public health threat, the consistent enrichment across sites signals potential long-term risk if waste mismanagement persists. Proactive monitoring and control of Ni-bearing wastes are therefore essential to prevent progressive accumulation and to safeguard soil health and food security in dumpsite-

impacted

farmlands.

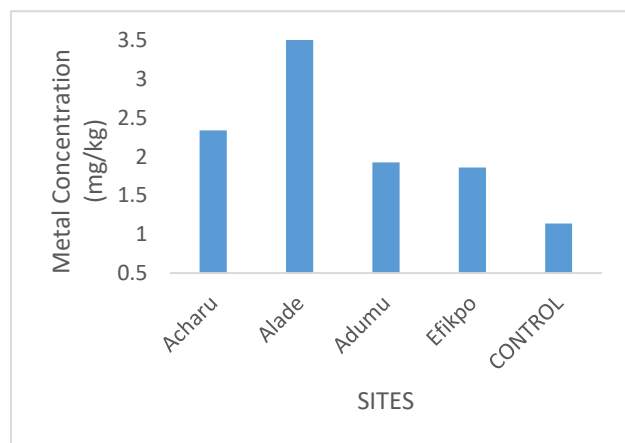


Figure 3: Concentration of Nickel in the Sampling and Control Sites

Manganese

Manganese concentrations were the highest among the analyzed metals, with values ranging from 2.96 mg/kg (Efikpo) to 4.64 mg/kg (Acharu), compared to 2.08 mg/kg at the control site. Despite being markedly elevated relative to the control, all measured concentrations remained well below the WHO (2021) threshold of 2000 mg/kg. The enrichment at dumpsites, particularly at Acharu, is likely linked to the disposal of dry-cell batteries, paints, fertilizers, and steel components, which are recognized Mn-bearing wastes [30]. As an essential micronutrient, Mn supports photosynthesis, chlorophyll synthesis, and enzymatic regulation in plants. However, excessive levels can disrupt iron uptake, impair metabolic balance, and induce phytotoxicity. In humans, chronic exposure to elevated manganese, particularly via contaminated water or inhalation, is associated with neurotoxic

effects, including manganism and symptoms resembling Parkinson's disease [31].

Although the recorded Mn values indicate no immediate ecological or health hazard, the consistent enrichment across dumpsites highlights early signs of anthropogenic influence. Regular monitoring is therefore crucial to prevent cumulative build-up that could compromise soil quality, crop safety, and human health.

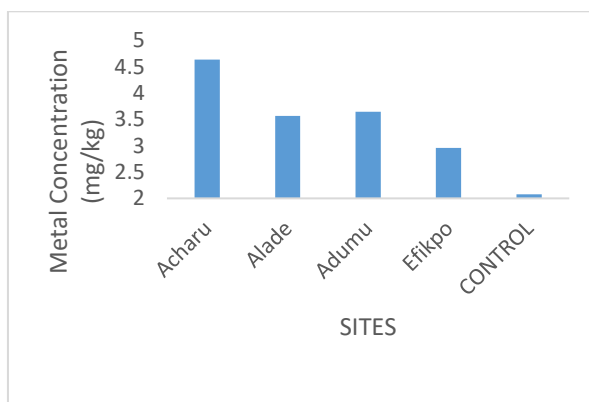


Figure 4: Concentration of Manganese in the Sampling and Control Sites

Lead

Lead concentrations across the dumpsites ranged from 0.13 mg/kg (Adumu) to 0.65 mg/kg (Alade), compared with 0.02 mg/kg at the control site. Although these values are substantially below the WHO (2021) permissible limit of 85 mg/kg, they represent 7–32-fold increases relative to background levels. The highest concentration at Alade likely reflects inputs from discarded lead-acid batteries, automotive parts, paints, ceramics, and metallic residues, all of which are common Pb

sources in municipal and mechanic-related waste streams [32].

Despite the relatively low absolute concentrations, lead is a persistent and highly toxic metal with no known biological function. Even trace levels can bioaccumulate and exert adverse effects, including neurodevelopmental impairments in children, renal dysfunction, hematological toxicity, and cardiovascular complications in adults. Its non-biodegradable nature and strong affinity for soil particles make it a long-term environmental contaminant, with risks of gradual mobilization into the food chain under changing physicochemical conditions [33].

The observed enrichment, though within regulatory thresholds, indicates an early stage of contamination that could escalate with continued dumping practices. Proactive interventions in waste management and routine monitoring are recommended to mitigate progressive Pb accumulation and associated ecological and public health risks.

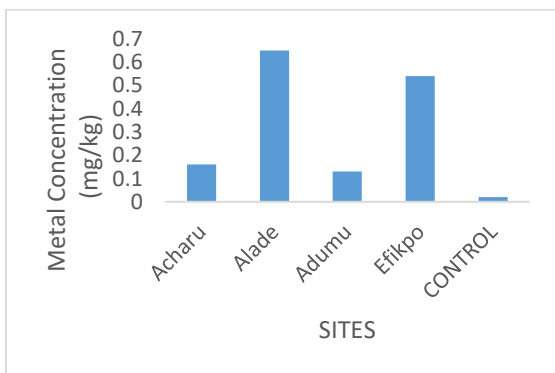


Figure 5: Concentration of Lead in the Sampling and Control Sites

3.3 Assessment of Metal Contamination

Contamination Factor (CF)

The contamination factor (CF) analysis for cadmium (Cd), copper (Cu), nickel (Ni), manganese (Mn), and lead (Pb) across the studied dumpsite soils provides clear evidence of substantial anthropogenic enrichment, predominantly arising from indiscriminate waste disposal and inadequate environmental management practices. Cadmium displayed consistently elevated CF values across all sites, indicating considerable to very high contamination. Acharu recorded a CF of 3.69, Adumu 4.63, while Alade (8.00) and Efikpo (8.94) exhibited extremely high contamination.

The likely sources include batteries, plastics, electroplating residues, and e-waste components. Given cadmium's high toxicity, mobility in soils, and potential for bioaccumulation in plants, such levels raise critical concerns for both environmental safety and food chain contamination.

Copper also showed moderate to high contamination. Acharu (3.05) and Adumu (2.84) reflected moderate CFs, whereas Alade (5.29) and Efikpo (6.14) indicated considerable to high contamination. Probable inputs include corroded wiring, vehicle parts, spent ammunition, and chemical containers. Although copper is an essential micronutrient, excess levels may disrupt soil microbial activity and biochemical cycles, particularly in soils with low buffering capacity [34]. Nickel contamination factors fell within the

moderate range, with CF values of 2.05 (Acharu), 3.10 (Alade), 1.69 (Adumu), and 1.63 (Efikpo). Sources are traceable to stainless steel residues, metal-coated packaging, rechargeable batteries, and industrial waste. While less toxic than Cd or Pb, nickel bioaccumulates and may impair enzymatic functions in soil microbiota, thereby altering ecosystem functioning [35].

Manganese, a typically geogenic element, showed moderate contamination levels across all dumpsites: Acharu (2.23), Alade (1.72), Adumu (1.75), and Efikpo (1.42). Though Mn is essential for plant nutrition, excessive accumulation can disrupt nutrient uptake and cause toxicity under poorly aerated conditions [36].

Major contributors are likely dry-cell batteries, corroded ferrous metals, and discarded electronic devices. Lead presented the highest contamination burden, with CF values far exceeding the high

contamination threshold ($CF > 6$). Acharu recorded 8.00, Adumu 6.50, while Alade (32.50) and Efikpo (27.00) indicated extremely hazardous enrichment. Discarded lead-acid batteries, paints, cables, and automotive wastes are the probable sources. Lead's persistence, strong adsorption to soil particles, and non-biodegradability amplify its ecological and health risks. Chronic lead exposure is associated with neurodevelopmental impairments in children, renal dysfunction, hematological disorders, and long-term groundwater contamination [37]. The CF results highlights the significant environmental burden imposed by dumpsite activities, with cadmium and lead emerging as the most critical contaminants. While Cu, Ni, and Mn indicate moderate risks, the extreme enrichment of Cd and Pb reflects both acute and chronic ecological hazards.

Table 2: Contamination Factors of Heavy Metals in the Soil Samples

SITES	Cd	Cu	Ni	Mn	Pb
Acharu	3.69	3.05	2.05	2.23	8.00
Alade	8.00	5.29	3.10	1.72	32.50
Adumu	4.63	2.84	1.69	1.75	6.50
Efikpo	8.94	6.14	1.63	1.42	27.00

Pollution Load Index (PLI)

The Pollution Load Index (PLI) offers a composite measure of heavy metal contamination by integrating the cumulative effects of multiple contaminants into a single metric. By definition, a PLI value greater than 1 indicates soil pollution, with progressively higher values reflecting increasing degrees of ecological risk. In this study, all sampled dumpsite soils exhibited PLI values well above unity, confirming that the sites are polluted and environmentally compromised [38].

Among the sites, **Alade recorded the highest PLI (5.93)**, signifying an extreme and cumulative burden of heavy metals. This elevated value is consistent with the exceptionally high contamination factors previously observed at the site, particularly for cadmium (CF = 5.29) and lead (CF = 32.50). The magnitude of this pollution strongly implicates long-term and uncontrolled disposal of hazardous wastes such as automotive batteries, e-waste, and metal-rich refuse, establishing Alade as a critical hotspot for heavy metal accumulation [39].

Efikpo followed closely with a PLI of 5.09, similarly indicative of severe pollution. This observation aligns with its high cadmium (CF = 8.94) and lead (CF = 27.00) contamination factors, suggesting a persistent influx of metal-bearing wastes. Likely sources include lead-based paints, solder residues, rusted engine parts, and dry-cell batteries typical of unmanaged municipal

and mechanical workshop wastes that dominate dumpsite inputs.

In comparison, **Acharu recorded a moderate PLI of 3.33**, still well above the safe threshold, yet lower than those of Alade and Efikpo. This relatively reduced pollution burden may reflect either a lower intensity of hazardous waste deposition or a shorter history of waste accumulation at this site. Nevertheless, the contamination factors for cadmium (CF = 3.69) and lead (CF = 8.00) indicate that significant ecological risks remain, requiring proactive monitoring and intervention.

Adumu displayed the lowest PLI (3.02) among the dumpsites, but its value was still three times above the pollution-free baseline, signifying substantial contamination. The relatively lower cumulative load may be attributed to differences in waste composition, soil buffering capacity, or depositional dynamics [40]. However, the persistence of high cadmium (CF = 4.63) and lead (CF = 6.50) levels highlights the site's compromised ecological status and potential threat to agricultural productivity.

Geoaccumulation Index (I_{geo})

The geo-accumulation index (I_{geo}) analysis revealed a heterogeneous pattern of heavy metal contamination across the studied dumpsites, with cadmium (Cd) and lead (Pb) emerging as the most critical pollutants. Cadmium exhibited I_{geo} values between 1.298 (Acharu) and 2.575 (Efikpo), placing the soils within Classes 2–3,

indicative of moderate to heavy pollution. This enrichment reflects clear anthropogenic influence, most plausibly from indiscriminate disposal of batteries, plastics, pigments, and electronic waste, with Efikpo representing the site under greatest contamination stress.

Lead contamination was even more pronounced, with I_{geo} values ranging from 2.115 (Adumu) to 4.437 (Alade), corresponding to Classes 3–5 (heavy to extreme pollution). The magnitude of Pb enrichment points to persistent inputs from automotive batteries, metallic residues, and lead-based paints common in open dumpsites. Given lead's persistence and neurotoxic potential, these elevated levels constitute a severe ecological and public health risk [41].

Copper (Cu) contamination was comparatively moderate, with I_{geo} values of 0.923–2.033, falling within Classes 1–2. This suggests unpolluted to moderately polluted conditions, likely arising from discarded wires, printed circuit boards, and electrical waste [42]. Nickel (Ni), with I_{geo} values spanning 0.121–1.050 (Classes 0–1), showed minimal enrichment, implying limited anthropogenic contributions and a probable partial geogenic origin. In contrast, manganese (Mn) displayed values below zero to marginally positive (–0.076 to 0.573), classifying all sites as unpolluted (Class 0). Its distribution suggests natural background presence rather than substantial waste-derived input.

Table 3: Geoaccumulation Index of Heavy Metals in the Soil Samples

SITES	Cd	Cu	Ni	Cr	Pb
Acharu	1.298	1.025	0.453	0.573	2.415
Alade	2.415	1.819	1.050	0.194	4.437
Adumu	1.624	0.923	0.175	0.226	2.115
Efikpo	2.575	2.033	0.121	-0.076	4.170

Nemerow pollution Index (NPI)

The Nemerow Pollution Index (NPI) provides a comprehensive understanding of the overall pollution status of a site, integrating the mean contamination factor (CF_{mean}) and the maximum contamination factor (CF_{max}) of the

measured heavy metals. This approach reflects both the general level of contamination and the influence of the most heavily polluted parameter, offering a balanced view of environmental quality.

The NPI analysis revealed distinct variations in pollution intensity across the studied sites, reflecting differences in waste composition and management practices. At Acharu, the NPI value of 4.43 indicates moderate pollution, with lead (CF = 8.00) as the dominant contributor, supplemented by cadmium (3.69) and copper (3.05). The elevated Pb levels suggest recurrent inputs from discarded lead-acid batteries, paints, and e-waste, posing long-term risks of bioaccumulation in soils and food crops despite the overall moderate classification [43].

In contrast, Alade exhibited the highest NPI (17.03), categorizing it as severely polluted. This extreme contamination is primarily driven by lead (32.50), followed by cadmium (8.00) and copper (5.29). Such values highlight intense anthropogenic influence, likely from indiscriminate dumping of metallic scraps, municipal waste, and possibly nearby industrial activities. The severe pollution status underscores potential ecological degradation, loss of soil fertility, and significant public health risks

through groundwater contamination and food chain transfer [44].

Adumu recorded a comparatively lower NPI of 3.69, falling within the light to moderate category. Here, moderate contributions from Mn (1.75), Ni (1.69), and Cu (2.84) were observed, with Pb (6.50) and Cd (4.63) remaining the key pollutants. The lower overall impact may reflect reduced exposure to direct leachate pathways or greater distance from active waste dumping zones. Nevertheless, the persistent presence of Pb and Cd warrants periodic monitoring to prevent progressive accumulation.

Efikpo, with an NPI of 14.23, also falls under severe pollution, dominated by Pb (27.00), Cd (8.94), and Cu (6.14). The elevated indices suggest substantial contamination pressure arising from proximity to dumpsites and lack of waste segregation. Long-term exposure under such conditions may disrupt soil biogeochemical cycles, suppress microbial diversity, and elevate the risk of heavy metal transfer into edible crops [45].

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

Sites	CF mean	CFmax	NPI	Pollution Status
Acharu	3.804	8.00	4.43	Moderate Pollution
Alade	10.122	32.50	17.03	Severe Pollution
Adumu	3.482	6.50	3.69	Light to Moderate Pollution
Efikpo	9.026	27.00	14.23	Severe Pollution

Enrichment Factor (EF)

The Enrichment Factor (EF) is a widely applied index for differentiating anthropogenic inputs of heavy metals from natural background concentrations in environmental samples. Manganese (Mn) 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.

The enrichment factor (EF) analysis revealed varying degrees of anthropogenic influence on heavy metal accumulation in the farmland soils. Cadmium showed the highest enrichment, with values ranging from 1.65 at Acharu to 6.29 at Efikpo, indicating a variation from minimal to significant enrichment, reflecting substantial inputs from dumpsite-related wastes such as batteries, plastics, pigments, and electronic components. Given cadmium's high toxicity and strong bioaccumulative potential, its enrichment poses serious ecological and food safety risks [46].

Copper enrichment was comparatively lower, with EF values between 1.37 at Acharu and 4.31 at Efikpo. The results also suggest minimal to moderate enrichment at the remaining sites, likely due to a mixture of lithogenic contributions and anthropogenic sources such as discarded wires, plumbing materials, and engine parts. Although an essential micronutrient, excessive copper levels can disrupt soil microbial activity and induce phytotoxicity [47].

Nickel exhibited low EF values, ranging from 0.92 at Acharu to 1.81 at Alade, corresponding to little or no enrichment at Efikpo and Adumu. This suggests that Ni is largely derived from natural soil-forming processes, though slight anthropogenic influence from alloys, fossil fuel residues, and steel fragments is possible. Lead showed strong site variability, with moderate enrichment in Acharu (3.59) and Adumu (3.71), but significant enrichment in Alade (18.97) and Efikpo (19.00). The higher values in Alade and Efikpo likely reflect inputs from disposed batteries, paints, and automotive parts, highlighting the persistence of Pb even at low enrichment levels.

Table 5: Enrichment Factors of Heavy Metals in the Soil Samples

Sites	Cd	Cu	Ni	Pb
Acharu	1.65	1.37	0.92	3.59
Alade	4.66	3.08	1.81	18.97
Adumu	2.64	1.62	0.96	3.71
Efikpo	6.29	4.31	1.15	19.00

Ecological Risk Index and Potential Ecological Risk Index

The ecological risk assessment revealed that cadmium (Cd) consistently posed the highest risk across all farmland sites, reflecting its high toxicity factor ($Tf = 30$) and environmental significance even at low concentrations. Efikpo and Alade recorded the highest individual risk values for Cd ($Er = 135.00$ and 162.50 , respectively), indicating very high ecological risk. These elevated values are attributable to the high Cd concentrations relative to the control, combined with its substantial toxicity weighting, and likely reflect leaching or transport from adjacent dumpsites [48]. The pervasive Cd risk highlights the urgent need for targeted remediation and monitoring strategies. Lead (Pb) also contributed substantially to ecological risk, particularly at

Efikpo and Alade, with Er values of 135.00 and 162.50 , respectively. Despite a lower toxicity factor ($Tf = 5$), the markedly elevated Pb concentrations relative to background levels significantly influenced the overall risk index (RI). The enrichment of Pb in these soils likely originates from the disposal of automotive batteries, paints, and plastics, posing persistent and bioaccumulative threats to soil quality, crop safety, and human health [49].

Other metals, including copper (Cu), nickel (Ni), and manganese (Mn), exhibited lower individual risk values (e.g., $Er = 30.70$ for Cu at Efikpo, 15.50 for Ni at Alade, and 2.23 for Mn at Acharu), indicating minor ecological impact. While their immediate contributions to RI were limited, cumulative effects over prolonged exposure cannot be disregarded, particularly under continuous dumping

conditions. Total RI values further highlighted the gradient of ecological concern, with Alade (RI = 446.17) and Efikpo (RI = 443.47) under very high ecological risk, while Acharu (RI = 178.43) and Adumu (RI = 195.80) fell within moderate risk

categories. This pattern corresponds closely with the intensity and proximity of dumping activities, confirming the significant influence of anthropogenic inputs on soil contamination.

Table 6: Ecological Risk Index and Potential Ecological Risk Index of Heavy Metals in the Soil Samples

Sites	Cd (Tf = 30)	Cu (Tf = 5)	Ni (Tf = 5)	Mn (Tf = 1)	Pb (Tf = 5)	RI
Acharu	110.70	15.25	10.25	2.23	40.00	178.43
Alade	240.00	26.45	15.50	1.72	162.50	446.17
Adumu	138.90	14.20	8.45	1.75	32.50	195.80
Efikpo	268.20	30.70	8.15	1.42	135.00	443.47

Conclusion and Recommendations

This study assessed the physicochemical properties and heavy metal contamination of soils from farmlands adjacent to municipal dumpsites. Soils near dumpsites exhibited slightly acidic to near-neutral pH, elevated moisture content, high electrical conductivity, sandy loam texture, and variable soil organic carbon, all of which

favor heavy metal mobility and accumulation. Cadmium (Cd) and lead (Pb) were identified as the most critical contaminants, with concentrations far exceeding WHO and FAO limits, high contamination factors (CF up to 32.50), ecological risk indices (Er_i) indicating high to considerable risk, and enrichment factors ($EF > 20$) signifying very high anthropogenic inputs. Copper (Cu) and nickel (Ni) showed

moderate enrichment ($2 \leq EF < 5$), while manganese (Mn) remained largely within natural background levels ($EF < 2$). Composite indices, including the Pollution Load Index ($PLI > 5$) classified Acharu and Adumu under moderate risk, while Alade and Efikpo fell within the considerable risk category, confirming the strong influence of anthropogenic inputs and the potential for metal transfer into the food chain. These findings indicate that continued agricultural use of these soils without intervention poses serious threats to food safety, human health, and ecological integrity. Immediate mitigation is recommended, including proper waste management, routine soil monitoring, and site-specific remediation strategies such as phytoremediation, soil amendments, and soil washing. Public awareness campaigns and stricter enforcement of environmental regulations are essential to prevent further contamination and safeguard the health of local communities.

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