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Research Article

Assessment of Heavy Metals Contamination and Ecological Risks at Tundun Wada Dumpsite, Karu L.G.A of Nasarawa State, Nigeria

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Abstract

Municipal solid waste dumpsites constitute major point sources of heavy metal contamination in rapidly urbanizing environments, particularly in developing countries where waste management infrastructure remains inadequate. This study evaluated the physicochemical properties, heavy metal concentrations, and associated ecological risks of soils from the Tudun Wada active solid waste dumpsite during the dry season. Composite soil samples collected from the dumpsite and a designated control site were analyzed for pH, electrical conductivity, organic matter, nutrients, and particle size distribution, alongside metal concentrations of Zn, Fe, Pb, Cr, Ni, Mn, Cu, Cd, Co, Mg, Ca, K, and Na using standard analytical procedures. To comprehensively assess contamination status and ecological implications, multiple pollution indices were calculated, including the Contamination Factor (CF), Degree of Contamination (Cd), Enrichment Factor (EF), Geo-accumulation Index (Igeo), Metal Pollution Index (MPI), and Potential Ecological Risk Index (PERI). Results revealed significantly elevated concentrations of Zn and Cu in dumpsite soils relative to control soils, reflecting strong anthropogenic inputs associated with the indiscriminate disposal of metal-containing wastes, such as batteries, electronic components, and scrap materials. Other metals, including Pb, Fe, Mn, Ni, and Cd, also showed enrichment above background levels, although with varying degrees of statistical significance. The calculated CF and EF values indicated moderate to very high contamination and enrichment for several metals, while the Cd and MPI values confirmed severe overall pollution at the dumpsite. Geo-accumulation index classifications further identified Zn and Cu as major pollutants, with values indicating heavy to significant contamination. The PERI results indicated a considerable ecological risk level, with Cu and Cd contributing disproportionately due to their high toxicity response factors. Overall, the findings demonstrate that soils at the Tudun Wada dumpsite are substantially *impacted by anthropogenic metal inputs, posing potential risks to soil quality, ecosystem stability, and human health. The study highlighted the urgent need for improved waste management practices, continuous environmental monitoring, and the implementation of appropriate remediation strategies to mitigate long-term ecological and public health consequences.*

Keywords: Soil pollution, heavy metals, dumpsite, ecological risk, contamination indices, Nigeria

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Introduction

Rapid urbanization and socioeconomic development in many developing countries have led to a substantial increase in municipal solid waste generation. In Nigeria, ineffective waste segregation, inadequate collection systems, and poorly engineered disposal facilities have led to the widespread establishment of open dumpsites, which now serve as persistent sources of environmental pollution (Yang et al., 2022; Akanbi & Nurudeen, 2024). These dumpsites receive heterogeneous waste streams, including household refuse, electronic waste, batteries, plastics, and metal scraps, many of which contain potentially toxic elements that can contaminate surrounding soils and water resources (Chen et al., 2022; Gupta et al., 2022).

Heavy metals are of serious environmental concern due to their persistence, non-biodegradability, and tendency to bio-accumulate in ecological systems. Once introduced into soil environments, metals such as zinc (Zn), copper (Cu), lead (Pb), cadmium (Cd), and nickel (Ni) may remain for extended periods, adversely affecting soil physicochemical properties, microbial activity, and plant productivity (Khan et al., 2022; Wang et al., 2022). Human exposure to these metals may occur through multiple pathways, including direct ingestion of contaminated soil, inhalation of metal-laden dust, consumption of crops grown on polluted soils, and ingestion of contaminated groundwater resulting from leaching processes (Olawoyin & Oyewole, 2022; Uwem, 2025).

Soils surrounding waste dumpsites often act as sinks for heavy metals released during waste decomposition, weathering, and leachate migration. Numerous studies across Nigeria have reported elevated concentrations of Zn, Cu, Pb, Cd, and Ni in dumpsite soils, frequently exceeding background levels and raising serious ecological and public health concerns (Okakpu et al., 2023; Ilechukwu & Okoye, 2024; Awoyemi et al., 2025). Seasonal variability further influences metal distribution, with dry-season conditions often associated with higher concentrations due to reduced leaching, increased evaporation, and enhanced dust re-suspension (Eze et al., 2023).

To quantitatively evaluate the intensity of contamination and its ecological implications, several pollution indices have been developed and widely applied. The Contamination Factor (CF) and Degree of Contamination (Cd) assess individual and cumulative metal enrichment relative to background concentrations. At the same time, the Enrichment Factor (EF) distinguishes anthropogenic contributions from natural geochemical sources. The Geo-accumulation Index (*Igeo*) provides a standardized classification of pollution, and the Metal Pollution Index (MPI) integrates the overall metal burden. Additionally, the Potential Ecological Risk Index (PERI), based on the Hakanson framework, incorporates metal toxicity and contamination levels to estimate ecological risk (Gupta et al., 2022; Jiang et al., 2023; Singh et al., 2024).

Despite extensive studies on dumpsite-related contamination in Nigeria, particularly in Awka (Okakpu *et al.,* 2024) Ado-Ekiti (Ogunmodede *et al.,* 2013), and the Abuja Metropolis (Uwem, 2025), integrated assessments that combine physicochemical properties with multiple contamination and ecological risk indices remain limited for the Tudun Wada area. Moreover, dry-season assessments are scarce, despite their relevance for capturing peak contamination conditions. This study, therefore, aims to evaluate heavy metal contamination levels and associated ecological risks in soils from the Tudun Wada active solid waste dumpsite during the dry season using multiple pollution indices, thereby generating data critical for environmental management and policy formulation

Methodology

Study Area

Tudun Wada (located at approximately: Latitude: 8.9926°N and Longitude: 7.6134°E is an urban settlement characterized by dense residential areas, commercial activities, and informal waste disposal practices. The area experiences distinct wet and dry seasons, with the dry season favoring contaminant accumulation due to reduced dilution and leaching.

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Sample Collection

Soil samples were collected from multiple locations within the active dumpsite at a depth of 0–20 cm using a stainless-steel auger. Control samples were obtained from an uncontaminated area several meters away. Samples were air-dried for about two weeks, homogenized, and sieved through a 2mm mesh prior to analysis.

Physicochemical and Heavy Metal Analysis

Soil pH and electrical conductivity were determined using standard electrode methods. Nutrients and organic parameters were analyzed following established protocols. Heavy metals were quantified after acid digestion using atomic absorption spectrophotometry (AAS), with quality assurance ensured through reagent blanks and replicate analyses (Mohammed et al., 2023).

Pollution Indices:

Contamination Factor: This was calculated using equation (1) below:

$$C_f^i = \frac{C_{sample}^i}{C_{background}^i} \qquad (1)$$

Where C_{sample} is the concentration of soil sample and $C_{background}$ is the background concentration of the soil.

Enrichment Factor: This was calculated using equation (2) below:

$$EF = \frac{\left(\frac{C_i}{C_{ref}}\right)_{sample}}{\left(\frac{B_i}{B_{ref}}\right)_{background}} \qquad (2)$$

Where C_{ref} is the concentration of the reference element and B_{ref} is the background value of the soil's reference element.

Geoaccumulation index: This was calculated using equation (3) below:

$$I_{geo} = log_2\left(\frac{C_n}{1.5B_n}\right) \qquad (3)$$

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Where C_n is measured concentration of heavy metal of interest and B_n is the geochemical background concentration of the heavy metal.

Metal Pollution Index: This was calculated using equation (4) below:

$$\text{MPI} = \frac{Concentration\ of\ metals\ in\ soil}{Reference\ soil\ (control)} \qquad (4)$$

Potential Ecological Risk Index (PERI): This was calculated using equations (5) and (6) below:

$$E_r^i = T_r^i \times \frac{C_i}{B_i} \qquad (5)$$

Where E_r is the potential ecological risk index for a single metal pollution

$$\text{PERI} = \sum_{i=1}^{n} E_r^i \qquad (6)$$

Statistical Analysis

The results for the heavy metals were presented using descriptive statistics (minimum, maximum, average, mean ± SD) and the variations between the dumpsites and the control were measured using one-way ANOVA (analysis of variance).

Results

Physicochemical Characteristics

The dumpsite soil in table 1 exhibited slightly acidic pH (6.55 ± 0.02), significantly lower than the control soil (7.41 ± 0.03), suggesting acidification due to organic waste decomposition. Elevated electrical conductivity reflected increased ionic content, while higher organic matter and nutrient levels indicated substantial organic waste input. These conditions enhance metal retention and mobility in soil matrices.

Heavy Metal Concentrations

Zn, Cu, Pb, Fe, Mn, and Ni concentrations were markedly higher in dumpsite soils compared to controls. Zn and Cu exhibited particularly high mean values, consistent with inputs from metal scraps, batteries, and electronic waste. Although Pb and Cd did not show statistical significance, their concentrations exceeded background levels, raising environmental concern due to their toxicity.

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Table 1: Physicochemical Properties of Sampled Soil at Tudun Wada Active Solid Waste Dumpsite in Dry Season.

Parameter	Maximum	Minimum	Mean ± SD	Control (Mean ± SD)	p-value	Significance (α = 0.05)
pH	6.59	6.52	6.55 ± 0.02	7.41 ± 0.03	0.0001	*Significant*
Electrical Conductivity (µS/cm)	245.00	238.50	242.91 ± 1.77	108.39 ± 2.99	0.0001	*Significant*
% Nitrogen	1.69	0.96	1.29 ± 0.19	0.45 ± 0.14	0.0003	*Significant*
Chloride (mg/kg)	11.42	8.78	10.29 ± 0.77	6.76 ± 0.40	0.0002	*Significant*
Nitrate (mg/kg)	9.23	7.30	8.14 ± 0.63	2.83 ± 0.21	0.0001	*Significant*
Phosphate (mg/kg)	15.08	12.35	13.90 ± 0.74	0.51 ± 0.07	0.0000	*Significant*
Sulphate (mg/kg)	121.01	109.89	116.07 ± 2.77	26.03 ± 0.98	0.0000	*Significant*
Oxidizable Organic Carbon (%)	1.14	0.80	0.97 ± 0.09	0.56 ± 0.05	0.0001	*Significant*
Total Organic Carbon (%)	1.52	1.07	1.29 ± 0.12	0.75 ± 0.06	0.0001	*Significant*
Organic Matter (%)	2.63	1.85	2.23 ± 0.21	1.29 ± 0.11	0.0001	*Significant*
Clay (%)	9.40	1.84	4.43 ± 2.46	3.65 ± 1.30	0.308	*Not Significant*
Silt (%)	9.62	2.10	6.45 ± 2.77	7.71 ± 1.83	0.418	*Not Significant*
Sand (%)	91.98	86.64	89.11 ± 1.59	88.64 ± 1.70	0.613	*Not Significant*

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Table 2: Elemental Concentrations of Soil Samples at Tudun Wada Active Solid Waste Dumpsite in Dry Season

Metals	Maximum	Minimum	Mean ± SD (mg/kg)	Control (Mean ± SD)	*p*-value	Significance
Zn	407.96	41.82	194.10 ± 85.02	5.70 ± 5.94	0.002	Highly significant
Fe	6,556.32	83.62	4,997.59 ± 1,773.02	2,342.82 ± 638.94	0.007	*Significant*
Pb	1,536.21	BDL	199.93 ± 380.55	46.31 ± 21.29	0.072	ns
Cr	27.01	BDL	2.45 ± 6.77	BDL	0.324	ns
Ni	34.13	15.50	25.43 ± 4.63	14.41 ± 15.95	0.032	*Significant*
Mn	632.72	219.47	332.82 ± 102.86	168.81 ± 43.58	0.017	*Significant*
Cu	395.71	BDL	108.59 ± 105.31	3.66 ± 7.43	0.003	Highly significant
Cd	5.01	BDL	1.07 ± 1.46	0.54 ± 0.66	0.288	ns
Co	36.96	BDL	4.98 ± 9.35	BDL	0.328	ns
Mg	465.78	390.15	412.89 ± 18.23	250.53 ± 61.41	0.014	*Significant*
Ca	9,722.97	2,511.28	7,434.07 ± 1,989.11	BDL	0.000	Highly significant
K	3,517.79	543.08	1,460.86 ± 814.61	543.64 ± 233.05	0.041	*Significant*
Na	566.97	93.15	280.93 ± 154.42	35.14 ± 37.52	0.011	*Significant*

Key: BDL = Below Detection Limit, ns = not significant

Table 3. Contamination Factor (CF), Contamination degree and Metal pollution index

Metal	Mean (mg/kg)	Control (mg/kg)	CF	Contamination Level
Zn	194.10	5.70	34.05	Very high
Fe	4997.59	2342.82	2.13	Moderate
Pb	199.93	46.31	4.32	Considerable
Ni	25.43	14.41	1.76	Moderate
Mn	332.82	168.81	1.97	Moderate
Cu	108.59	3.66	29.67	Very high
Cd	1.07	0.54	1.98	Moderate
Contamination degree			75.88	
Metal Pollution index			187.6	

Table 4. Enrichment Factor (EF)

Metal	EF	Enrichment Category
Zn	15.98	Significant enrichment
Pb	2.03	Moderate enrichment
Ni	1.65	Minimal–moderate
Mn	1.08	Minimal
Cu	13.94	Significant enrichment
Cd	0.93	Deficiency to minimal

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Table 5. Geo-accumulation index (*Igeo*)

Metal	*Igeo*	Pollution Class
Zn	4.51	Heavily–extremely polluted
Pb	1.53	Moderately polluted
Ni	0.23	Unpolluted–moderately
Mn	0.39	Unpolluted–moderately
Cu	4.30	Heavily–extremely polluted
Cd	0.39	Unpolluted–moderately

Table 6. Potential Ecological Risk Index (PERI)

Metal	CF	Tr	Er
Zn	34.05	1	34.05
Pb	4.32	5	21.60
Ni	1.76	5	8.80
Mn	1.97	1	1.97
Cu	29.67	5	148.35
Cd	1.98	30	59.40
Total PERI			274.17

Contamination Indices Interpretation

The CF results in table 3 demonstrated very high contamination with Zn and Cu, moderate contamination with Fe, Ni, Mn, and Cd, and considerable contamination with Pb. The high Cd value (75.88) confirmed severe cumulative contamination. EF and *Igeo* analyses demonstrated in tables 4 and 5 respectively, further indicated significant anthropogenic enrichment, particularly for Zn and Cu, implicating waste-related sources rather than natural soil composition.

PERI in Table 6 revealed a considerable ecological risk level (274.17), with Cu and Cd contributing most significantly due to their high toxicity response factors. Although Cd concentrations were relatively low, its high toxicity coefficient amplified its ecological risk contribution. These findings suggest that contamination may have adverse effects on soil biota and surrounding ecosystems if it persists.

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Discussion

The present study provides a comprehensive evaluation of heavy metal contamination and associated ecological risks in soils from the Tudun Wada active solid waste dumpsite during the dry season. The findings demonstrate substantial anthropogenic alteration of soil quality, as evidenced by elevated metal concentrations, altered physicochemical properties, and high pollution and ecological risk indices. These results (tables 1 to 6) reinforce concerns that unmanaged municipal dumpsites constitute persistent sources of environmental degradation in rapidly urbanizing Nigerian cities (Akanbi & Nurudeen, 2024; Ilechukwu & Okoye, 2024).

The markedly higher concentrations of Zn and Cu in dumpsite soils relative to control samples indicate strong inputs from waste-related activities. Zn and Cu are commonly associated with discarded batteries, electrical components, metal scraps, alloys, and pigments, which are abundant in municipal solid waste streams (Yang et al., 2022; Nnaji & Onyekachi, 2024). Similar dominance of Zn and Cu has been reported in dumpsite soils across Nigeria, including Awka (Okakpu et al., 2023), Ado-Ekiti (Awoyemi et al., 2025), and Abuja Metropolis (Uwem, 2025), suggesting a recurring pattern of contamination linked to unregulated waste disposal practices. The consistency of these findings across diverse locations underscores the systemic nature of dumpsite-induced soil pollution.

The Contamination Factor (CF) analysis in table 3 revealed very high contamination for Zn and Cu, moderate contamination for Fe, Mn, Ni, and Cd, and considerable contamination for Pb. According to established classification schemes, CF values exceeding six reflect severe contamination, indicative of significant anthropogenic enrichment (Gupta et al., 2022; Olatunji et al., 2025).

The exceptionally high Degree of Contamination (Cd) recorded in this study confirms cumulative pollution pressure from multiple metals and aligns with reports from other heavily impacted dumpsites in Nigeria and comparable developing-country settings (Alabi et al., 2023; Sulaiman & Yusuf, 2025).

The Enrichment Factor (EF) results shown in table 4 further clarify contamination sources by distinguishing anthropogenic inputs from natural geogenic contributions. Elevated EF values for Zn and Cu strongly suggest non-crustal origins, implicating waste-derived materials as the primary contributors (Mohammed et al., 2023; Chakraborty & Mukherjee, 2024). Similar anthropogenic enrichment signatures have been documented in urban soils subjected to prolonged dumping activities, where EF values often exceed

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five for Zn, Cu, and Pb (Chen et al., 2022; Zhang & Wang, 2024). These findings confirm that the metal burden at Tudun Wada is not merely a function of background soil composition but rather the result of sustained human activities.

Geo-accumulation Index (*Igeo*) values in table 5 classified Zn and Cu contamination levels as heavily to extremely polluted. *Igeo* has been widely applied in soil pollution studies due to its robustness in assessing long-term contamination trends (Wang et al., 2022; Feng et al., 2025). The high *Igeo* classes observed in this study are consistent with those reported for tropical dumpsite soils subjected to continuous waste deposition and minimal remediation (Bashir et al., 2022; Rahman et al., 2023). These results emphasize the chronic nature of pollution at Tudun Wada and highlight the limited self-recovery capacity of soils under persistent anthropogenic stress.

The Metal Pollution Index (MPI) in table 3 provided an integrated assessment of overall metal loading and corroborated the severe contamination status of the dumpsite soils. MPI is particularly valuable for comparing pollution intensity across sites and has been applied extensively in urban and peri-urban soil assessments (Xiao et al., 2023). The high MPI recorded in this study aligns with values reported for severely contaminated soils in densely populated regions, reinforcing the conclusion that Tudun Wada represents a pollution hotspot requiring urgent management intervention.

Of particular concern is the Potential Ecological Risk Index (PERI) in table 6 which indicated a considerable ecological risk level. PERI integrates contamination levels with metal-specific toxicity response factors, thereby providing a more ecologically meaningful assessment than concentration-based metrics alone (Jiang et al., 2023; Singh et al., 2024). In this study, Cu and Cd were the dominant contributors to ecological risk. Although Cd concentrations were relatively moderate, its high toxicity coefficient significantly amplified its contribution to overall risk, a trend consistently reported in ecological risk assessments worldwide (Obasi & Akudinobi, 2022; Zhou et al., 2025). This finding highlights the importance of considering metal toxicity alongside abundance when evaluating ecological threats.

Physicochemical soil properties observed at the dumpsite likely influenced metal behavior and risk potential. The slightly acidic pH recorded can enhance metal solubility and bioavailability, increase the likelihood of plant uptake and leach into groundwater (Khan et al., 2022; Olawoyin & Oyewole, 2022). Elevated electrical conductivity and organic matter content further suggest increased ionic strength and complexation capacity, both of which can facilitate metal retention and mobility within the soil matrix

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(Eze et al., 2023; Rahman et al., 2023). These conditions collectively elevate the potential for ecological disruption and human exposure, particularly through food-chain transfer.

Comparative analysis with other Nigerian studies reveals both similarities and spatial variability in contamination patterns. While Abuja dumpsite soils also exhibit elevated metal concentrations, some locations reported lower ecological risk levels, possibly due to differences in waste composition, soil texture, and site age (Uwem, 2025). In contrast, studies from southeastern and southwestern Nigeria often report higher geo-accumulation and pollution indices, reflecting prolonged dumping and limited waste management infrastructure (Okakpu et al., 2023; Awoyemi et al., 2025). Such variability underscores the need for site-specific assessments rather than generalized assumptions about the impacts of dumpsites.

Overall, the convergence of high CF, Cd, EF, Igeo, MPI, and PERI values indicates that the Tudun Wada active dumpsite poses a significant ecological threat. Without intervention, continued waste deposition will likely exacerbate soil degradation, threaten terrestrial biota, and increase human health risks through direct contact and food-chain contamination. Sustainable waste management practices, routine environmental monitoring, and targeted remediation strategies, such as soil amendments or phytoremediation, are therefore essential to mitigate ongoing contamination and safeguard environmental quality (Yang et al., 2022; Zhang & Wang, 2024).

Conclusion

This study demonstrates that soils from the Tudun Wada active solid waste dumpsite are significantly contaminated with heavy metals, with zinc and copper identified as the dominant pollutants. The application of multiple contamination indices indicated a very high degree of contamination and a strong anthropogenic influence resulting from prolonged, unregulated waste disposal. Although some metals occurred at moderate concentrations, ecological risk assessment showed a considerable overall ecological risk, particularly due to the high toxicity of copper and cadmium. The slightly acidic soil pH, elevated electrical conductivity, and increased organic matter content further enhance metal mobility and potential bioavailability, thereby increasing risks to soil organisms, plants, and nearby human populations. These findings highlight the urgent need for improved waste management practices, including waste segregation, controlled disposal, and regular environmental monitoring. In addition, remediation strategies such as phytoremediation and soil amendments should be considered to mitigate contamination and reduce long-term ecological and public health impacts in the Tudun Wada area.

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