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Seasonal Assessment of Heavy Metal Contamination, Pollution Indices, And Human Health Risks in Dumpsite Soils of Abakpa Bridge, Enugu State, Nigeria.

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Abstract
This study assessed heavy metal contamination and associated ecological and human health risks at a municipal dumpsite using established pollution indices and risk models. Soil samples collected from three stations (A–C) during rainy and dry seasons were analyzed for Cd, As, Fe, Zn, Cr, Pb, and Hg. Results showed clear seasonal and spatial variations, with higher concentrations generally recorded in the dry season. Cadmium exhibited the highest contamination, with CF values ranging from 12.74–23.40 and EF values of 191.6–211.6, indicating very high anthropogenic enrichment. The Igeo values for Cd (3.09–3.96) classified the site as strongly polluted, while Pb showed moderate pollution (Igeo: 0.60–1.65). Other metals remained largely within unpolluted categories (Igeo ≤ 0). The degree of contamination (Cd) ranged from 16.74–31.78, indicating considerable contamination, while PLI values (0.51–1.01) suggested moderate overall pollution with localized deterioration. Ecological risk assessment identified Cd as the major contributor to risk, reflecting its high toxicity and elevated concentration. Human health risk assessment revealed ingestion as the dominant exposure pathway. The total hazard index (THI) for children (3.97×10^{2}) was significantly higher than for adults (4.25×10^{1}), exceeding the safety threshold (THI > 1). Arsenic and cadmium contributed most to risk, with ingestion HQ values of 205.3 and 70.0, respectively, for children. Dermal exposure contributed moderately, while inhalation was negligible (10^{-3}).
Overall, the dumpsite poses significant ecological and human health risks, necessitating improved waste management, environmental monitoring, and remediation strategies.

Keywords: Heavy metals, Dumpsite, Contamination, Pollution indices, Human health risk assessment;

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INTRODUCTION

Unregulated dumpsites remain a serious environmental problem in Nigeria, acting as major sources of heavy metal contamination in soils, groundwater, farmlands, and nearby communities. The movement and concentration of these metals are influenced by seasonal changes, particularly the differences between the dry and rainy seasons. Understanding these seasonal effects is therefore important for accurately assessing contamination levels and associated risks, especially in vulnerable locations such as the Abakpa Bridge dumpsite in Enugu State.

Studies across Nigeria have reported elevated levels of heavy metals such as Fe, Pb, Cd, Zn, and Cr in soils affected by waste disposal. These levels often exceed natural background values, with the highest concentrations typically found at the centre of the dumpsite and decreasing with distance and soil depth (Ihedioha *et al.,* 2017; Afolabi *et al.,* 2021; Ale *et al.,* 2024). Based on pollution indices such as contamination factor (CF), geo-accumulation index (I_geo), and pollution load index (PLI), many dumpsites are classified as moderately to highly polluted (Afolagboye *et al.,* 2020; Agho *et al.,* 2022). Among these metals, cadmium, lead, and chromium are often identified as key contributors to environmental risk (Omada *et al.,* 2024; Aralu *et al.,* 2024).

Seasonal variation also plays a key role in metal distribution. Concentrations are generally higher during the dry season due to accumulation, while rainfall during the wet season promotes dilution and leaching into deeper soil layers and groundwater (Alao *et al.,* 2024; Saravanan & Ramesh, 2023). In addition, contamination levels tend to decrease with increasing distance from the dumpsite, reflecting the influence of waste input and leachate movement (Omada *et al.,* 2024).

Exposure to heavy metals from dumpsites poses potential health risks to nearby populations. People may be exposed through ingestion, inhalation, or skin contact, with children being more vulnerable due to higher exposure rates relative to body weight. Previous studies have reported elevated hazard indices and cancer risks associated with metals such as Pb, Cd, Cr, and As (Agho *et al.,* 2022; Kamunda *et al.,* 2016; Zerizghi *et al.,* 2021). Even when risk levels appear moderate, long-term exposure can still have serious environmental and public health implications (Aralu *et al.,* 2024).

In view of these concerns, this study evaluates the concentrations of selected heavy metals in soils from the Abakpa Bridge dumpsite and assesses their potential ecological and human health risks. The findings will provide useful information for environmental monitoring and improved waste management practices in the area.

MATERIALS AND METHODS

Study Area

The study was carried out at the Abakpa Bridge dumpsite in Enugu State, southeastern Nigeria, located around latitude 6.47° N and longitude 7.53° E. The dumpsite has existed for over two decades and serves as a disposal site for mixed municipal wastes generated from nearby households, markets, and small businesses. Waste materials are dumped beneath the bridge as well as along the sides and lower parts surrounding the bridge structure. A river flows close to the dumpsite, creating concerns about the possible movement of pollutants into the nearby environment.

The surrounding area is heavily populated, with many residential buildings located close to the dumpsite, while the well-known Abakpa Market is situated a few kilometers away. Because of the closeness of the dumpsite to human activities and the nearby river, there is growing concern about the spread of contaminants, especially heavy metals, into surrounding soils and water bodies.

The area experiences a tropical climate with clearly defined rainy and dry seasons, which can influence the movement and distribution of contaminants through runoff and leaching. Figure 1: below presents a map of the study area, showing the location of the dumpsite in relation to nearby roads, residential areas, the river, and the various sampling points used during the study.

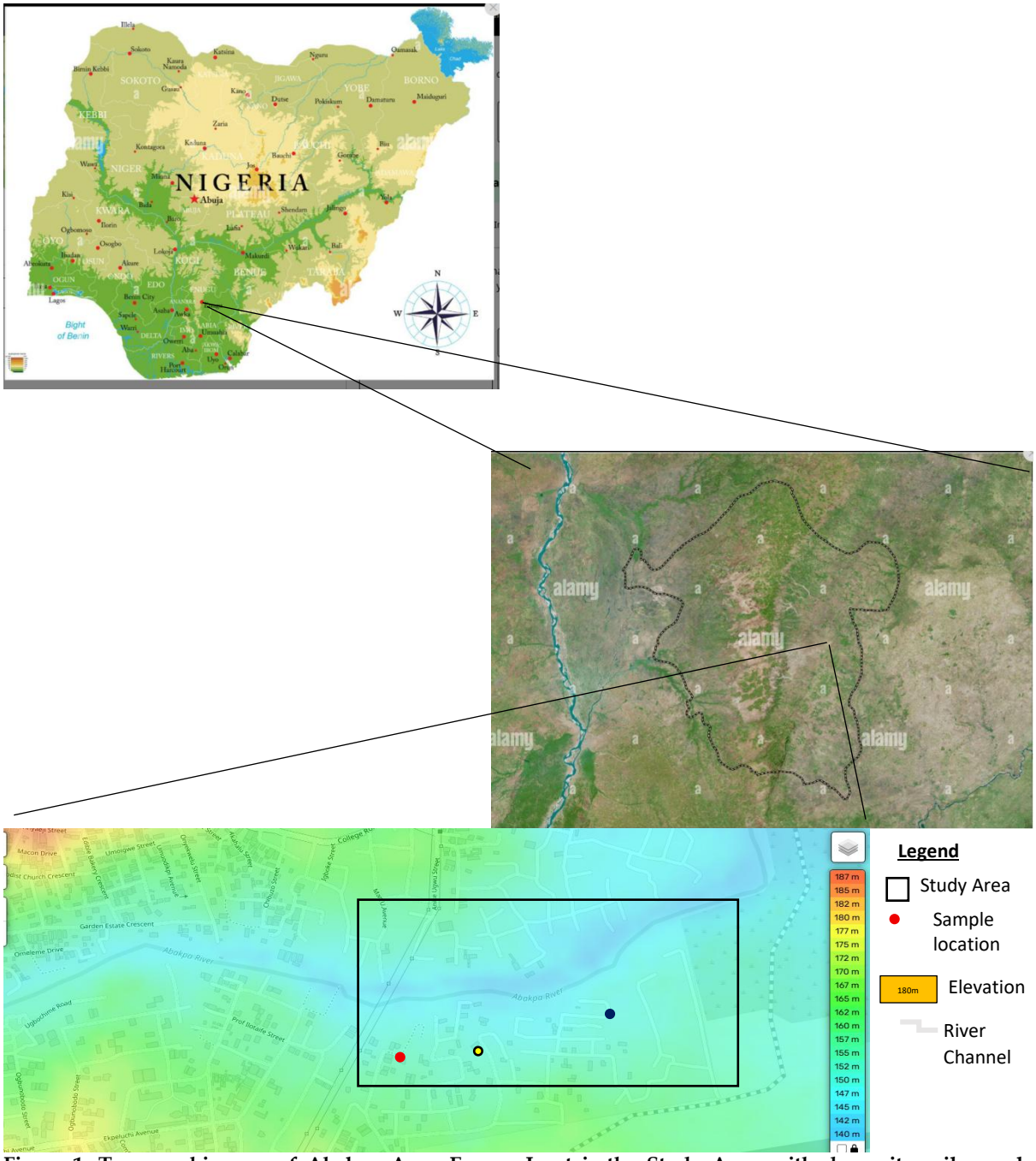

Figure 1: Topographic map of Abakpa Area, Enugu. Inset is the Study Area, with dumpsite soil sample locations.

Sample Collection and Preparation

Soil samples were collected from the Abakpa Bridge dumpsite in Enugu State during both the rainy season (May–July) and the dry season (December–February), giving a total of eighteen (18) samples, with three collected each month.

To ensure good coverage of the site, the dumpsite was divided into three zones: upper, middle, and lower sections, based on how waste was distributed across the area. From each zone, composite soil samples were taken at a depth of 0–15 cm using a clean stainless-steel hand trowel to reduce contamination and capture surface-deposited materials.

The samples were then placed in clean, labeled, airtight polyethylene bags and transported to the laboratory. There, they were air-dried at room temperature for seven days, gently crushed, sieved to obtain a uniform texture, and stored in a desiccator until further analysis.

Acid Digestion and Heavy Metal Analysis of Soil Samples

Heavy metals in the soil samples were extracted using a standard acid digestion procedure. Approximately 2.0 g of dried and homogenized soil was accurately weighed into a clean digestion flask. A mixed acid solution (20 mL) containing concentrated nitric acid (HNO_3), perchloric acid ($HClO_4$), and sulfuric acid (H_2SO_4) in the proportions 650 mL, 80 mL, and 20 mL, respectively, was carefully added to the soil sample. The acid mixture was used to break down the soil matrix and release metals bound within it. The mixture was then gently heated on a hot plate in a fume hood until a clear solution was obtained, indicating complete digestion.

After cooling, the digest was filtered through Whatman No. 42 filter paper into a volumetric flask and made up to a final volume of 50 mL using deionized water. The solution was then stored in clean, labeled polyethylene bottles prior to heavy metal analysis.

To ensure data reliability, all glassware was thoroughly washed before use, and reagent blanks were prepared alongside the samples using the same procedure but without soil samples to account for possible contamination.

The concentrations of heavy metals in the digested samples were determined using a Varian AA240 Atomic Absorption Spectrophotometer, following standard procedures recommended by the American Public Health Association (APHA, 2015).

ASSESSMENT OF POLLUTION INDICES

Geo-Accumulation Index (Igeo)

The geo-accumulation index (Igeo) was calculated using the Müller (1969) model (Singh et al., 2017; Jena et al., 2019), according to Equation (1):

$$I_{geo} = \mathrm{Log}_2\left(\frac{Cn}{1.5 \times Bn}\right) \quad (1)$$

where Cn is the measured metal concentration and Bn is the geochemical background value. In the absence of local background data, global crustal averages from Turekian and Wedepohl (1961) were used (Cd 0.30, Zn 95, Pb 20, Cr 90, Fe 47,200, As 13, Hg 0.4 mg/kg). The Igeo scale ranges from ≤0 (uncontaminated) to >5 (extremely polluted), with intermediate classes indicating increasing contamination.

Enrichment factor (EF)

The enrichment factor (EF) was used to evaluate whether soil metal concentrations originate from natural or anthropogenic sources, with Fe as the normalizing element (El Zokm et al., 2020). EF was calculated as:

$$EF = \frac{\left(\frac{\mathrm{Metal}}{\mathrm{Fe}}\right)\mathrm{Sediment}}{\left(\frac{\mathrm{Metal}}{\mathrm{Fe}}\right)\mathrm{Shale}} \quad (2)$$

using an average shale Fe value of 47,200 mg/kg (Turekian and Wedepohl, 1961). EF values were classified as: <2 (no enrichment), 2–<5 (moderate), 5–<20 (significant), 20–<40 (very high), and >40 (extremely high enrichment) (Sutherland, 2000).

Contamination Factor (CF)

The contamination factor (CF) is a simple index for assessing heavy metal contamination (Hakanson, 1980), calculated as

$$CF = \frac{\text{C metal}}{\text{C background}} \quad (3)$$

where C_{metal} is the measured concentration and $C_{background}$ is the background value. Global average concentrations from Turekian and Wedepohl (1961) were used as background values. CF is classified as: <1 (low), 1–<3 (moderate), 3–<6 (considerable), and ≥6 (very high contamination) (Hakanson, 1980).

Degree of Contamination (Cd)

To ascertain the level of contamination in the soil, the degree of contamination (Cd) is often computed as the total of all contamination factors, which is expressed as follows:

$$Cd = \sum CF \quad (4)$$

Cd is classified as: Cd<8 indicates low contamination, 8≤Cd<16 indicates moderate contamination, 16≤Cd<32 indicates considerable contamination, and 32≥Cd indicates very high contamination, in that order (Biose and Oyagha 2024).

Pollution Load Index (PLI)

The pollution load index (PLI) evaluates overall soil toxicity and contamination (Hakanson, 1980), calculated as

$$PL1 = [\mathrm{CF}_1 \times \mathrm{CF}_2 \times \mathrm{CF}_3 \times ---\times CF_n]^{1/n} \quad (5)$$

where n is the number of metals. Pollution levels are classified as low (CF<1), moderate (1–3), considerable (3–6), and high (CF>6). A PLI of 1 indicates baseline conditions, PLI > 1 reflects declining site quality and PLI<1 denotes an unpolluted state (Mohiuddin et al., 2010).

Potential Ecological Risk Index (PERI)

Heavy metal pollution in soil was assessed using Hakanson's (1980) potential ecological risk index method.

$$\mathrm{Er}^{\mathrm{i}} = \mathrm{Tr}.\,\mathrm{Cf} \quad (6)$$

Tr represents the toxic-response factor of each metal (Cr = 2, Cd = 30, Hg = 40, Pb = 5, Zn = 1, As = 10), while Cf is the contamination factor. The ecological risk factor (Er_i) is classified as: <40 (low), 40–<80 (moderate), 80–<160 (considerable), 160–<320 (high), and ≥320 (very high risk) (Hakanson, 1980).

The potential ecological risk index (RI) is the sum of all individual risk factors, similar to the degree of contamination

$$RI = \sum Er^i \quad (7)$$

Assuming i = 1, Er_i represents the ecological risk factor. The potential ecological risk index (RI) is classified as: <150 (low), 150–<300 (moderate), 300–<600 (considerable), and >600 (very high ecological risk) (Hakanson, 1980).

Human Health Risk Assessment

Human health risks from heavy metals were assessed following USEPA (1989, 1996) methods (Ihedioha et al., 2017), considering exposure through inhalation (ADD_{inh}), ingestion (ADD_{ing}), and dermal absorption (ADD_{erm}).

$$ADD_{inh} = \frac{C \times R_{inh} \times EF \times ED}{PEF \times BW \times AT} \quad (8)$$

$$ADD_{ing} = \frac{C \times R_{ing} \times EF \times ED \times 10^{-6}}{BE \times AT} \quad (9)$$

$$ADD_{derm} = \frac{C \times SL \times SA \times ABS \times EF \times ED \times 10^{-6}}{BW \times AT} \quad (10)$$

$ADD_{(inh)}$, $ADD_{(ing)}$, and $ADD_{(derm)}$ represent average daily doses (mg/kg/day) for non-carcinogenic exposure via inhalation, ingestion, and dermal contact, calculated using mean metal concentrations and standard exposure parameters (body weight, intake rates, exposure duration/frequency, skin area, adherence, absorption, and particle emission). Health risks were assessed using the Hazard Quotient (HQ), defined as the ratio of ADD to the reference dose (RfD), which represents a safe daily exposure level unlikely to cause adverse effects over a lifetime.

$$HQ = \frac{ADD}{RfD} \quad (11)$$

ADD is the average daily dose (mg/kg/day) and RfD the reference dose, with $RfD_{(inh)}$ calculated from RfC adjusted for age-specific inhalation rates and body weight. Overall risk from multiple metals is expressed as the Total Hazard Index (THI), the sum of individual HQs

$$\text{Total hazard index } (THI) = HQ_1 + HQ_2 + \cdots + HQ_n \quad (11)$$

If THI < 1.0, significant additive or toxic effects are unlikely; no further evaluation is needed. If THI > 1.0, there may be concern for non-cancer health effects.

Data Analysis

All determinations were conducted in triplicates and data generated were analyzed statistically using SPSS version 27 and Microsoft Excel 2016.

RESULTS AND DISCUSSION

Tables 1 and 2 present the concentrations of heavy metals in the evaluated dumpsite soil, providing a detailed overview of their distribution across the sampled locations.

Table 1: Heavy Metal Concentrations in the Evaluated Dumpsite Soil During the Rainy Season

Parameters	Unit	Station A (Mean ± SD)	Station B (Mean ± SD)	Station C (Mean ± SD)	TEC	PEC	FMEnv/ NESREA
Cadmium	Ppm	3.822 ± 0.082	4.761 ± 0.079	5.313 ± 0.099	0.99	4.98	3–6
Arsenic	Ppm	3.661 ± 0.071	4.015 ± 0.072	4.188 ± 0.083	9.79	330	20
Iron	Ppm	3042 ± 53	3656 ± 73	4007 ± 82	NA	NA	NA
Zinc	Ppm	72.38 ± 0.79	80.16 ± 1.23	85.81 ± 0.92	121	459	50–300
Chromium	Ppm	3.964 ± 0.079	4.905 ± 0.092	5.472 ± 0.106	43.4	111	100–1000
Lead	Ppm	45.592 ± 0.75	62.080 ± 1.12	59.538 ± 0.77	35.8	128	85–164
Mercury	Ppm	0.230 ± 0.009	0.250 ± 0.007	0.402 ± 0.014	0.18	1.06	0.1–0.5

Table 2: Heavy Metal Concentrations in the Evaluated Dumpsite Soil During the Dry Season

Parameters	Unit	Station A (Mean ± SD)	Station B (Mean ± SD)	Station C (Mean ± SD)	TEC	PEC	FMEnv/ NESREA
Cadmium	Ppm	5.67 ± 0.13	6.25 ± 0.14	7.02 ± 0.17	0.99	4.98	3–6
Arsenic	Ppm	4.92 ± 0.11	5.38 ± 0.09	6.68 ± 0.16	9.79	330	20
Iron	Ppm	4655 ± 89.6	4779 ± 117.6	5126 ± 115.0	NA	NA	NA
Zinc	Ppm	92.50 ± 2.37	123.5 ± 2.86	167.6 ± 5.16	121	459	50–300
Chromium	Ppm	5.82 ± 0.13	6.75 ± 0.15	7.44 ± 0.17	43.4	111	100–1000
Lead	Ppm	56.34 ± 1.07	63.85 ± 1.37	94.74 ± 3.16	35.8	128	85–164
Mercury	Ppm	0.35 ± 0.01	0.55 ± 0.02	0.47 ± 0.02	0.18	1.06	0.1–0.5

Key: Station A = Water sample from upstream at coordinates latitude N 6°28′34.734′′ and longitude E 7°31′3.216′′
Station B = Water sample from midstream at coordinates latitude N 6°28′34.752′′ and longitude E7°31′2.50212′′
Station C = Water sample from downstream at coordinates latitude N 6°28′34.41′′ and longitude E7°32′ 8.90988′′
TEC = Threshold Effect Concentration
PEC = Probable Effect Concentration

A comparison of Tables 1 and 2 reveals clear seasonal and spatial variations in heavy metal concentrations across the study area. In general, metal concentrations are higher in the dry season than in the rainy season at all stations (A, B, and C). This trend is consistent with findings from similar studies in Nigeria, where reduced leaching and increased accumulation during the dry season leads to elevated metal levels in soils (Alao *et al.,* 2024; Saravanan & Ramesh, 2023).

Cadmium exhibits a marked increase from 3.822 ± 0.082 ppm (Station A, rainy) to 5.67 ± 0.13 ppm (dry), and up to 7.02 ± 0.17 ppm at Station C in the dry season. These values exceed the TEC (0.99 ppm) in all cases and surpass the PEC (4.98 ppm) during the dry season, indicating high ecological risk. Moreover, dry season concentrations exceed the FMEnv/NESREA limit (3 – 6 ppm) at all stations. This dominance of cadmium in contributing to ecological risk agrees with previous Nigerian studies, where Cd is often identified as a major pollutant due to its high mobility and toxicity (Okpanachi *et al.,* 2025; Afolabi *et al.,* 2021).

Arsenic concentrations increased moderately from 3.66 – 4.19 ppm (rainy) to 4.92 – 6.68 ppm (dry). Despite this increase, values remain well below the TEC (9.79 ppm) and regulatory limits, suggesting low ecological risk. The observed seasonal rise is consistent with reduced dilution during the dry season (Agho *et al.,* 2022).

Iron recorded the highest concentrations among all metals, increasing from 3042 – 4007 ppm (rainy) to 4655 – 5126 ppm (dry). Although no regulatory limits are specified, the high concentrations may reflect both natural (geogenic) contributions and anthropogenic inputs from waste materials. The consistent increase from Station A to C further supports proximity to the dumpsite core as a key factor influencing metal distribution (Ihedioha *et al.,* 2017).

Zinc concentrations increased significantly from 72.38 – 85.81 ppm (rainy) to 92.50 – 167.6 ppm (dry). While rainy season values fall below the TEC (121 ppm), dry season concentrations at Stations B and C exceed this threshold, indicating However, all values remain within the FMEnv/NESREA guideline (50 – 300 ppm). This suggests increasing accumulation but not yet severe pollution, consistent with findings in other Nigerian dumpsites (Afolagboye *et al.,* 2020).

Chromium concentrations rose from 3.96 – 5.47 ppm (rainy) to 5.82 – 7.44 ppm (dry). These values remain far below the TEC (43.4 ppm) and guideline limits, indicating minimal ecological risk. The relatively low levels suggest limited anthropogenic input or reduced mobility compared to other metals (Omada *et al.,* 2024).

Lead concentrations increased from 45.59–62.08 ppm (rainy) to 56.34 – 94.74 ppm (dry). All values exceed the TEC (35.8 ppm), indicating potential ecological effects. The dry season value at Station C (94.74 ppm) approaches the upper FMEnv/NESREA range (85 – 164 ppm),

suggesting moderate to high contamination**.** Elevated Pb levels are commonly associated with waste components such as batteries, paints, and electronic materials (Agho *et al.,* 2022; Aralu *et al.,* 2024).

Mercury concentrations increased from 0.23 – 0.40 ppm (rainy) to 0.35 – 0.55 ppm (dry)**.** All values exceed the TEC (0.18 ppm)**,** and the dry season value at Station B **(**0.55 ppm**)** slightly exceeds the FMEnv/NESREA limit (0.1– 0.5 ppm)**.** This indicates moderate ecological risk and highlights the potential for mercury accumulation in the absence of rainfall-driven leaching (Alao *et al.,* 2024).

The results demonstrate a clear seasonal influence on heavy metal distribution**,** with higher concentrations during the dry season due to reduced leaching and increased retention in the topsoil. Spatially, concentrations follow the order: Station C > Station B > Station A This trend indicates that contamination is highest closest to the dumpsite core and decreases with distance, a pattern widely reported in dumpsite studies (Ihedioha *et al.,* 2017; Afolagboye *et al.,* 2020). This classification aligns with previous findings that identify cadmium and lead as major contributors to ecological and human health risks in contaminated soils (Omada et al., 2024; Aralu *et al.,* 2024).

Geo-Accumulation Index (Igeo) of the Dumpsite

Tables 3 and 4 display the geo-accumulation index (Igeo) of the evaluated dumpsite soil during the rainy and dry seasons, indicating the level of metal accumulation and the degree of human influence on soil contamination across the sampled sites.

Table 3: Geo-accumulation Index (Igeo) of Dumpsite Soil During the Rainy Season

Parameters	Station A	Igeo class	Station B	Igeo class	Station C	Igeo class
Cadmium	3.09	3 < Igeo ≤ 4	3.40	3 < Igeo ≤ 4	3.56	3 < Igeo ≤ 4
Arsenic	-2.41	Igeo ≤ 0	-2.28	Igeo ≤ 0	-2.22	Igeo ≤ 0
Iron	-4.54	Igeo ≤ 0	-4.27	Igeo ≤ 0	-4.14	Igeo ≤ 0
Zinc	-0.98	Igeo ≤ 0	-0.83	Igeo ≤ 0	-0.73	Igeo ≤ 0
Chromium	-5.09	Igeo ≤ 0	-4.79	Igeo ≤ 0	-4.63	Igeo ≤ 0
Lead	0.60	0 < Igeo ≤ 1	1.05	1 < Igeo ≤ 2	0.99	0 < Igeo ≤ 1
Mercury	-1.38	Igeo ≤ 0	-1.21	Igeo ≤ 0	-0.52	Igeo ≤ 0

Table 4: Geo-accumulation Index (Igeo) of Dumpsite Soil During the Dry Season

Parameters	Station A	Igeo class	Station B	Igeo class	Station C	Igeo class
Cadmium	3.66	3 < Igeo ≤ 4	3.80	3 < Igeo ≤ 4	3.96	3 < Igeo ≤ 4
Arsenic	-1.98	Igeo ≤ 0	-1.85	Igeo ≤ 0	-1.53	Igeo ≤ 0
Iron	-3.93	Igeo ≤ 0	-3.89	Igeo ≤ 0	-3.79	Igeo ≤ 0
Zinc	-0.62	Igeo ≤ 0	-0.20	Igeo ≤ 0	0.24	0 < Igeo ≤ 1
Chromium	-4.53	Igeo ≤ 0	-4.31	Igeo ≤ 0	-4.17	Igeo ≤ 0
Lead	0.90	0 < Igeo ≤ 1	1.08	1 < Igeo ≤ 2	1.65	1 < Igeo ≤ 2
Mercury	-0.78	Igeo ≤ 0	-0.13	Igeo ≤ 0	-0.36	Igeo ≤ 0

The Igeo results show that metal contamination at the dumpsite varies with both season and location, with generally higher values in the dry season. This suggests that metals tend to accumulate more when there is less rainfall and reduced leaching (Alao *et al.,* 2024; Saravanan & Ramesh, 2023).

Cadmium (Cd) is clearly the most serious pollutant. Its values increase from 3.09–3.56 (rainy season) to 3.66–3.96 (dry season), placing it in the strongly polluted category ($3 < Igeo \leq 4$) across all stations. The steady rise from Station A to Station C also shows that contamination is highest near the dumpsite core. This agrees with earlier studies highlighting cadmium as a major environmental risk in Nigerian dumpsites (Okpanachi *et al.,* 2025; Afolabi *et al.,* 2021). Lead (Pb) shows moderate pollution, with values rising from 0.60–1.05 in the rainy season to 0.90–1.65 in the dry season. While some locations fall within the unpolluted to moderately polluted range ($0 < Igeo \leq 1$), others—especially Station C in the dry season—reach the moderately polluted class ($1 < Igeo \leq 2$). This indicates increased accumulation during dry conditions and points to human-related sources (Agho *et al.,* 2022; Aralu *et al.,* 2024).

For zinc (Zn), the site is mostly unpolluted in the rainy season (−0.98 to −0.73), but shows a slight increase in the dry season, reaching 0.24 at Station C, which suggests early-stage contamination near the dumpsite (Afolagboye *et al.,* 2020). On the other hand, arsenic (As), chromium (Cr), iron (Fe), and mercury (Hg) all have negative Igeo values ($Igeo \leq 0$) in both seasons. This means they are generally unpolluted and mainly influenced by natural background levels rather than strong human input (Ihedioha *et al.,* 2017; Omada *et al.,* 2024). However, their potential health effects should still be considered.

Overall, contamination tends to increase from Station A to Station C, confirming that areas closer to the dumpsite are more affected. In summary, the site is strongly polluted with cadmium, moderately affected by lead, shows slight zinc buildup, while other metals remain low. These results highlight the environmental concern of the dumpsite and the need for proper monitoring and management.

Enrichment Factor (EF) of the Dumpsite

Tables 5 and 6 present the enrichment factor of the evaluated dumpsite soil during the rainy and dry seasons, providing insight into the degree of heavy metal enrichment and the possible influence of anthropogenic activities on soil quality across the sampled locations.

Table 5: Enrichment factor (EF) of the Dumpsite During the Rainy Season

Parameters	Station A	EF Class	Station B	EF Class	Station C	EF Class
Cadmium	197.60	EF>40	204.60	EF>40	211.60	EF>40
Arsenic	4.37	2≤EF<5	3.98	2≤EF<5	3.80	2≤EF<5
Zinc	1.18	EF < 2	1.09	EF < 2	1.06	EF < 2
Chromium	0.68	EF < 2	0.70	EF < 2	0.72	EF < 2
Lead	35.3	20≤EF<40	40.0	20≤EF<40	35.0	20≤EF<40
Mercury	8.92	5≤EF<20	8.07	5≤EF<20	11.84	5≤EF<20

Table 6: Enrichment factor (EF) of the Dumpsite During the Dry Season

Parameters	Station A	EF Class	Station B	EF Class	Station C	EF Class
Cadmium	191.6	EF>40	197.5	EF>40	207.6	EF>40
Arsenic	3.84	2≤EF<5	4.09	2≤EF<5	4.73	2≤EF<5
Zinc	0.99	EF < 2	1.28	EF < 2	1.63	EF < 2
Chromium	0.65	EF < 2	0.74	EF < 2	0.76	EF < 2
Lead	28.5	20≤EF<40	31.5	20≤EF<40	43.6	20≤EF<40
Mercury	8.87	5≤EF<20	13.6	5≤EF<20	10.8	5≤EF<20

The enrichment factor results clearly show that heavy metal contamination at the dumpsite is largely influenced by human activities, with noticeable differences across metals, seasons, and sampling locations.

Cadmium (Cd) stands out as the most critical pollutant, with extremely high EF values in both seasons. In the rainy season, values range from 197.60 to 211.60, while in the dry season they remain similarly high (191.6–207.6), all falling within EF > 40. This indicates severe anthropogenic contamination across all stations, especially toward Station C. This pattern is consistent with reports that identify cadmium as a major risk contributor in Nigerian dumpsites (Afolabi *et al.,* 2021; Okpanachi *et al.,* 2025).

Lead (Pb) also shows strong contamination, with EF values of 35.3–40.0 (rainy season) and 28.5–43.6 (dry season). These fall within the very high enrichment category (20 ≤ EF < 40), although the value of 43.6 at Station C suggests conditions approaching extreme enrichment. This reflects significant human inputs, likely from common waste materials such as batteries and electronic components (Agho *et al.,* 2022; Aralu *et al.,* 2024).

For mercury (Hg), EF values range from 8.07 to 11.84 in the rainy season and 8.87 to 13.6 in the dry season, indicating significant enrichment (5 ≤ EF < 20). This suggests a clear anthropogenic influence, even though other indices may classify mercury as low contamination. This difference highlights the importance of EF in identifying pollution sources (Alao *et al.,* 2024).

Arsenic (As) shows moderate enrichment, with values between 3.80–4.37 (rainy) and 3.84–4.73 (dry). This suggests a combination of natural background levels and human contributions, with a slight increase observed in the dry season (Agho *et al.,* 2022).
In contrast, zinc (Zn) and chromium (Cr) show low EF values (EF < 2) across all stations and seasons. Zinc ranges from 1.06 to 1.63, indicating only minor enrichment, while chromium remains consistently low (0.65–0.76), suggesting that both metals are largely controlled by natural sources rather than dumpsite activities (Ihedioha *et al.,* 2017; Omada *et al.,* 2024).
Seasonally, EF values show only slight variation. Some metals (e.g., As, Zn, Hg) are slightly higher in the dry season, while others (Cd and Pb) are marginally higher in the rainy season. This is mainly due to the influence of iron (Fe), which is used as the reference element in EF calculations and can vary with seasonal conditions (Alao *et al.,* 2024).

Spatially, there is a consistent increase in EF values from Station A to Station C, indicating that contamination is highest closer to the dumpsite core. This trend aligns with previous findings that pollutant levels decrease with distance from the source (Afolagboye *et al.,* 2020; Ihedioha *et al.,* 2017).

Overall, the dumpsite is severely contaminated with cadmium, highly contaminated with lead, and significantly affected by mercury, while arsenic shows moderate influence and zinc and chromium remain relatively low. These results confirm strong human impact and highlight the environmental concern associated with the site.

Contamination Factor (CF) of the Dumpsite
Tables 7 and 8 present the contamination factor of the evaluated dumpsite soil during the rainy and dry seasons, highlighting the extent of heavy metal contamination across the sampled locations.

Table 7: Contamination Factor (CF) of the Dumpsite During the Rainy Season

Parameters	Station A	CF Class	Station B	CF Class	Station C	CF Class
Cadmium	12.74	CF ≥ 6	15.87	CF ≥ 6	17.71	CF ≥ 6
Arsenic	0.28	CF < 1	0.31	CF < 1	0.32	CF < 1
Iron	0.06	CF < 1	0.08	CF < 1	0.08	CF < 1
Zinc	0.76	CF < 1	0.84	CF < 1	0.90	CF < 1
Chromium	0.04	CF < 1	0.05	CF < 1	0.06	CF < 1
Lead	2.28	1 ≤ CF < 3	3.10	3 ≤ CF < 6	2.98	1 ≤ CF < 3
Mercury	0.58	CF < 1	0.63	CF < 1	1.01	1 ≤ CF < 3

Table 8: Contamination Factor (CF) of the Dumpsite During the Dry Season

Parameters	Station A	CF Class	Station B	CF Class	Station C	CF Class
Cadmium	18.90	CF ≥ 6	20.83	CF ≥ 6	23.40	CF ≥ 6
Arsenic	0.38	CF < 1	0.41	CF < 1	0.51	CF < 1
Iron	0.10	CF < 1	0.10	CF < 1	0.11	CF < 1
Zinc	0.97	CF < 1	1.30	1 ≤ CF < 3	1.76	1 ≤ CF < 3
Chromium	0.06	CF < 1	0.08	CF < 1	0.08	CF < 1
Lead	2.82		3.19	3 ≤ CF < 6	4.74	3 ≤ CF < 6
Mercury	0.88	CF < 1	1.38	1 ≤ CF < 3	1.18	1 ≤ CF < 3

The CF results show clear seasonal and location-based differences in contamination across the dumpsite. In general, values are higher in the dry season, which suggests that metals accumulate more when there is less rainfall and reduced leaching (Alao *et al.,* 2024; Saravanan & Ramesh, 2023).

Cadmium (Cd) is the most concerning metal, with very high CF values in both seasons. It ranges from 12.74–17.71 in the rainy season and increases to 18.90–23.40 in the dry season, all within CF ≥ 6. This confirms severe contamination across all stations, especially toward Station C, and points to strong human-related inputs (Afolabi *et al.,* 2021; Okpanachi *et al.,* 2025). Lead (Pb) shows moderate to considerable contamination, with values of 2.28–3.10 (rainy) and 2.82–4.74 (dry). The higher values in the dry season, particularly at Stations B and C, suggest increased accumulation and influence from waste materials such as batteries and electronics (Agho *et al.,* 2022; Aralu *et al.,* 2024). For zinc (Zn), contamination is low in the rainy season (0.76–0.90) but increases in the dry season to 1.30–1.76, indicating moderate contamination at some locations. This suggests gradual buildup near the dumpsite core (Afolagboye *et al.,* 2020).

Mercury (Hg) shows mostly low contamination, with values of 0.58–0.63 in the rainy season and 0.88–1.38 in the dry season, although some stations reach moderate levels. This indicates a smaller but noticeable human contribution. In contrast, arsenic (As), chromium (Cr), and iron (Fe) all have CF values below 1 across both seasons (As: 0.28–0.51, Cr: 0.04–0.08, Fe: 0.06–0.11), showing low contamination and suggesting that their levels are mainly from natural sources (Ihedioha *et al.,* 2017; Omada *et al.,* 2024).

A consistent pattern is also observed across locations, with contamination generally increasing from Station A to Station C, indicating stronger impact closer to the dumpsite. Overall, the dumpsite is heavily contaminated with cadmium, moderately affected by lead, and shows increasing levels of zinc and mercury, especially in the dry season, while other metals remain low. These results highlight the environmental impact of the site and the need for proper monitoring and management.

Degree of Contamination (Cd) and Pollution Load Index (PLI) of the Dumpsite

Table 9 shows the Degree of Contamination (Cd) and Pollution Load Index (PLI) of the evaluated dumpsite soil for both the rainy and dry seasons, indicating the extent of overall heavy metal pollution and the combined effects of contamination at the sampled sites

Table 9: Degree of Contamination (Cd) and Pollution Load Index (PLI) of the Dumpsite

Season	Locations	CD	CD Class	PLI	PLI Class
Rainy	Station A	16.74	16≤Cd<32	0.51	**PLI < 1**
	Station B	20.88	16≤Cd<32	0.61	**PLI < 1**
	Station C	23.06	16≤Cd<32	0.69	**PLI < 1**
Dry	Station A	24.11	16≤Cd<32	0.72	**PLI < 1**
	Station B	27.29	16≤Cd<32	0.87	**PLI < 1**
	Station C	31.78	16≤Cd<32	1.01	PLI > 1

The results presented in Table 9 provide a combined view of the overall contamination status of the dumpsite using both the Degree of Contamination (Cd) and the Pollution Load Index (PLI). These indices reveal clear seasonal and spatial variations, with contamination levels generally increasing during the dry season and toward the core of the dumpsite.

The Cd values indicate that all stations fall within the range of considerable contamination ($16 \leq Cd < 32$) in both seasons. During the rainy season, Cd values increase from 16.74 at Station A to 23.06 at Station C, while in the dry season they rise further from 24.11 to 31.78. This consistent increase from Station A to Station C suggests that contamination is more intense closer to the dumpsite source. The higher Cd values observed in the dry season reflect reduced leaching and increased accumulation of heavy metals in the soil, a trend widely reported in similar studies (Alao *et al.,* 2024; Saravanan & Ramesh, 2023). The dominance of Cd values across all stations is largely driven by the very high contamination factors recorded for metals such as cadmium and lead in earlier tables, which significantly elevate the overall contamination burden (Afolabi *et al.,* 2021; Okpanachi *et al.,* 2025).

In contrast, the PLI values present a slightly different perspective. In the rainy season, PLI values range from 0.51 to 0.69, indicating that the sites are generally unpolluted ($PLI < 1$) despite the considerable contamination suggested by Cd. A similar pattern is observed in the dry season for Stations A (0.72) and B (0.87), which still fall below the pollution threshold. However, at Station C, the PLI value reaches 1.01, indicating the onset of pollution at this location. This suggests that while contamination exists, it is not uniformly distributed across all metals, and only becomes critical at locations closest to the dumpsite core.

The apparent difference between Cd and PLI results can be explained by the nature of the indices. While Cd is a summative index that reflects the cumulative effect of all metals, PLI is a geometric mean, which reduces the influence of extreme values. As a result, metals with low contamination factors (such as Fe, Cr, and As) tend to offset the high contributions from metals like Cd and Pb, leading to lower overall PLI values (Ihedioha *et al.,* 2017; Omada *et al.,* 2024).

Overall, the results indicate that the dumpsite is experiencing considerable contamination, particularly driven by a few highly enriched metals, with conditions worsening during the dry season. Although the overall pollution level (PLI) remains mostly below the critical threshold, the situation at Station C suggests a transition toward polluted conditions, highlighting the need for continuous monitoring and improved waste management practices to prevent further environmental degradation.

Potential Ecological Risk Index (PERI) of the Dumpsite

Table 10 shows the Potential Ecological Risk Index (PERI) of the evaluated dumpsite soil during the rainy and dry seasons, indicating the overall ecological risk associated with heavy metal contamination across the sampled locations.

Table 10: Potential Ecological Risk Index (PERI) of the Dumpsite

Season	Location	Potential Ecological risk factor (Er^i)						RI	Risk grade
		Cd	As	Zn	Cr	Pb	Hg		
Raining	Station A	382.2	2.8	0.76	0.08	11.4	23.2	420.44	considerable ecological risk
	Station B	476.1	3.1	0.84	0.10	15.5	25.2	520.84	considerable ecological risk
	Station C	531.3	3.2	0.90	0.12	14.9	40.4	590.82	considerable ecological risk
Dry	Station A	567.0	3.8	0.97	0.12	14.1	35.2	621.19	very high ecological risk.
	Station B	624.9	4.1	1.30	0.16	15.95	55.2	701.61	very high ecological risk.
	Station C	702.0	5.1	1.76	0.16	23.7	47.2	779.92	very high ecological risk.
Potential risk	ecological	very high	low	low	low	low	low → moderate		

The Potential Ecological Risk Index (PERI) results (Table 10) reveal clear seasonal and spatial variations in ecological risk across the dumpsite, with values increasing from Station A to Station C and from the rainy to the dry season. This pattern reflects both proximity to the contamination source and the influence of seasonal conditions on metal accumulation.

During the rainy season, the total ecological risk index (RI) ranges from 420.44 at Station A to 590.82 at Station C**,** placing all stations within the category of considerable ecological risk ($300 \leq RI < 600$) according to Hakanson (1980). The steady increase across stations indicates that ecological risk intensifies closer to the dumpsite core. Among the metals, cadmium (Cd**)** is the dominant contributor, with individual risk values ranging from 382.2 to 531.3**,** which fall within the very high ecological risk category ($Er^i \geq 320$)**.** In contrast, metals such as arsenic (2.8–3.2), chromium (0.08–0.12), and zinc (0.76–0.90) contribute minimally to the overall risk**.** Lead (11.4–15.5) and mercury (23.2–40.4) show low to moderate contributions, although mercury approaches the moderate risk threshold at Station C. The dominance of Cd in driving ecological risk has been widely reported in similar studies of dumpsite soils in Nigeria (Afolabi *et al.,* 2021; Okpanachi *et al.,* 2025).

In the dry season, the ecological risk becomes more severe, with RI values increasing to 621.19, 701.61, and 779.92 for Stations A, B, and C, respectively. These values fall within the very high ecological risk category ($RI > 600$)**,** indicating a significant deterioration in environmental quality. The increase in risk during the dry season can be attributed to reduced leaching and enhanced accumulation of heavy metals in the soil, a trend consistent with previous findings (Alao *et al.,* 2024; Saravanan & Ramesh, 2023). Again, cadmium remains the primary contributor**,** with extremely high risk values ranging from 567.0 to 702.0**,** confirming its critical role in environmental degradation. Mercury also shows increased contributions in the dry season **(**35.2–55.2), reaching the moderate ecological risk range ($40 \leq Er^i < 80$) at some locations, while lead values (14.1–23.7) remain within the low-risk category but still contribute to the cumulative index.

A consistent spatial trend is observed in both seasons, with ecological risk increasing from Station A to Station C, suggesting that Station C is closest to the pollution source. This aligns with established findings that heavy metal concentrations and associated risks decrease with increasing distance from dumpsite cores (Ihedioha *et al.,* 2017; Afolagboye *et al.,* 2020).

Overall, the PERI assessment indicates that the dumpsite poses a considerable ecological risk during the rainy season and a very high ecological risk during the dry season, with cadmium identified as the most critical pollutant. These findings highlight the significant environmental threat posed by the dumpsite and emphasize the need for effective waste management and continuous environmental monitoring to mitigate long-term ecological and public health impacts.

Table 11: Human Health Risk Assessment of Heavy Metals in the Dumpsite

Metals	Metal Conc. (mg/kg)	Age Group	Inhalation			Ingestion			Dermal		
			ADD	RfD	HQ	ADD	RfD	HQ	ADD	RfD	HQ
Cd	5.47 ± 1.12	Children	5.96×10^{-9}	6.67×10^{-6}	8.94×10^{-4}	7.00×10^{-2}	1.0×10^{-3}	70.0	1.53×10^{-4}	2.5×10^{-5}	3.1×10^{-1}
		Adult	3.72×10^{-9}	2.86×10^{-6}	1.30×10^{-3}	7.49×10^{-3}	1.0×10^{-3}	7.49	6.56×10^{-5}		1.3×10^{-1}
As	4.81 ± 1.11	Children	5.24×10^{-9}	2.00×10^{-5}	2.62×10^{-4}	6.16×10^{-2}	3.0×10^{-4}	205.3	1.35×10^{-4}	2.85×10^{-4}	1.13
		Adult	3.27×10^{-9}	8.57×10^{-6}	3.82×10^{-4}	6.59×10^{-3}	3.0×10^{-4}	21.97	5.77×10^{-5}		4.8×10^{-1}
Fe	4210.8 ± 784.0	Children	4.59×10^{-6}	—	—	5.39×10^{1}	7.0×10^{-1}	77.0	1.18×10^{-1}	7.0×10^{-2}	1.7×10^{-1}
		Adult	2.86×10^{-6}	—	—	5.77×10^{0}	7.0×10^{-1}	8.24	5.05×10^{-2}		7.0×10^{-2}
Zn	103.66 ± 35.93	Children	1.13×10^{-7}	2.00×10^{-4}	5.65×10^{-4}	1.33×10^{0}	3.0×10^{-1}	4.43	2.90×10^{-3}	9.0×10^{-2}	1.0×10^{-2}
		Adult	7.05×10^{-8}	8.57×10^{-5}	8.23×10^{-4}	1.42×10^{-1}	3.0×10^{-1}	4.7×10^{-1}	1.24×10^{-3}		4.0×10^{-3}
Cr	5.73 ± 1.25	Children	6.25×10^{-9}	6.67×10^{-5}	9.37×10^{-5}	7.33×10^{-2}	3.0×10^{-3}	24.4	1.60×10^{-4}	7.5×10^{-5}	3.0×10^{-2}
		Adult	3.90×10^{-9}	2.86×10^{-5}	1.36×10^{-4}	7.85×10^{-3}	3.0×10^{-3}	2.62	6.88×10^{-5}		1.0×10^{-2}
Pb	63.69 ± 16.52	Children	6.94×10^{-8}	—	—	8.15×10^{-1}	—	—	1.22×10^{-2}		—
		Adult	4.33×10^{-8}	—	—	8.72×10^{-2}	—	—	1.31×10^{-3}		—
Hg	0.38 ± 0.13	Children	4.14×10^{-10}	2.00×10^{-4}	2.07×10^{-6}	4.86×10^{-3}	3.0×10^{-4}	16.2	1.06×10^{-5}	2.1×10^{-5}	1.1×10^{-1}
		Adult	2.58×10^{-10}	8.57×10^{-5}	3.01×10^{-6}	5.20×10^{-4}	3.0×10^{-4}	1.73	4.56×10^{-6}		5.0×10^{-2}
THI		Children			1.82×10^{-3}			3.97×10^{2}			1.76
		Adult			2.64×10^{-3}			4.25×10^{1}			7.44×10^{-1}

Human Health Risk Assessment of Heavy Metals in the Dumpsite

The human health risk assessment results (Table 11) indicate clear differences in exposure between children and adults, as well as across exposure pathways. The Total Hazard Index (THI) shows that children are at significantly higher risk than adults, which is consistent with previous studies. This is largely due to children's lower body weight, higher ingestion rates, and frequent hand-to-mouth activities (Agho *et al.,* 2022; Kamunda *et al.,* 2016).

Ingestion is identified as the dominant exposure pathway, contributing the largest proportion of the total risk. The ingestion THI for children ($\approx 3.97 \times 10^{2}$) is substantially higher than contributions from dermal contact (≈ 1.76) and inhalation ($\approx 1.82 \times 10^{-3}$). A similar trend is observed in adults, where ingestion ($\approx 4.25 \times 10^{1}$) far exceeds dermal ($\approx 7.44 \times 10^{-1}$) and inhalation exposure ($\approx 2.64 \times 10^{-3}$). This pattern agrees with earlier findings that soil ingestion is the primary pathway for heavy metal exposure in contaminated environments (Yahaya *et al.,* 2022).

The very high ingestion-related hazard quotients are strongly linked to the level of contamination at the dumpsite. For instance, cadmium (Cd) recorded very high contamination factor (CF) values ranging from 12.74 to 23.40, indicating severe contamination. Similarly, enrichment factor (EF) values for Cd ranged from 191.6 to 211.6, which falls within the category of extremely high enrichment (EF > 40), confirming significant anthropogenic input. The geo-accumulation index (Igeo) values for Cd (3.09–3.96) further classify the site as strongly polluted. These results explain the elevated exposure doses and the resulting high ingestion hazard indices (Afolabi *et al.,* 2021; Okpanachi *et al.,* 2025).

Among the metals analyzed, arsenic (As) and cadmium (Cd) are the major contributors to health risk. Arsenic shows very high ingestion HQ values of 205.3 for children and 21.97 for adults, while cadmium contributes 70.0 and 7.49 for children and adults, respectively. These values are consistent with reports from similar studies, where these metals are identified as dominant contributors to non-carcinogenic risk due to their toxicity and low reference dose values (Kamunda *et al.,* 2016; Yahaya *et al.,* 2022).

Dermal exposure contributes moderately to the overall risk, with higher values observed in 76children compared to adults. Arsenic (HQ = 1.13) is the primary contributor via this pathway, followed by cadmium and chromium. Although dermal exposure is less significant than ingestion, continuous contact with contaminated soil still poses a potential health concern (Agho *et al.,* 2022).

In contrast, inhalation exposure contributes negligibly to the overall risk, with hazard indices in the order of 10^{-3}. This indicates that airborne exposure pathways are of minimal concern in this study, which aligns with findings from similar environmental assessments (Zerizghi *et al.,* 2021).

Lead (Pb) was excluded from the hazard quotient calculation due to the absence of a well-defined reference dose, as it is considered a non-threshold toxicant. However, this does not imply safety, as lead remains a significant public health concern, particularly for children (Zerizghi *et al.,* 2021).

It is also important to note that iron (Fe), despite showing relatively high hazard values (e.g., 77.0 for children via ingestion), is an essential element and is not typically classified among priority toxic metals in risk assessment studies. Its inclusion may therefore contribute to an overestimation of the overall risk (Ihedioha *et al.,* 2017; Omada *et al.,* 2024).

Overall, the THI values for both children and adults exceed the acceptable limit of 1, indicating potential non-carcinogenic health risks. The higher risk observed in children, combined with strong evidence from CF, EF, and Igeo indices, confirms that the dumpsite is a significant source of heavy metal exposure. These findings highlight the need for improved waste

management practices and continuous environmental monitoring to reduce long-term health risks (Afolabi *et al.,* 2021; Agho *et al.,* 2022).

Conclusion

The study demonstrates that the dumpsite is significantly contaminated, with cadmium identified as the dominant pollutant based on high CF (12.74–23.40), EF (>190), and Igeo (3.09–3.96) values. Seasonal variation showed higher contamination during the dry season, while spatial trends indicated increasing pollution toward Station C. Ecological risk assessment confirmed cadmium as the major contributor to environmental risk.

Human health risk results revealed that ingestion is the primary exposure pathway, with THI values exceeding unity for both children (~3.97×10^2) and adults (~4.25×10^1), indicating potential non-carcinogenic risk. Children were more vulnerable due to higher exposure rates. Arsenic and cadmium were the key risk-driving metals.

These findings highlight the need for improved waste management practices, continuous monitoring, and remediation to reduce environmental contamination and protect public health.

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