

**SOIL HEAVY METALS AND POLLUTION INDICES AT A RECLAIMED
DUMP SITE IN ENUGU STATE, NIGERIA****Ugwuoke Malachy. O.¹, Eze Kenneth. A.², Agu Anthony. U³**¹ State University of Medical and Applied Sciences Igbo- Eno, Enugu State.² Enugu State University of science Technology.³ No 2 Presidential Road, Enugu.**Correspondence author:**ugwuokemalachy85@gmail.com**ABSTRACT**

This study assessed the spatial variation of heavy metal contamination in soils of a former dumpsite converted into an estate and farming zone in Enugu State, Nigeria. Soil samples were collected from 0–100 m across the four cardinal directions of the site and at 200 m as control. Heavy metals (Pb, Cd, Cr, As and Hg) were quantified using AAS, and contamination levels were evaluated using the Pollution Index (PI), Geoaccumulation Index (Igeo), and Pollution Load Index (PLI). Results revealed clear gradients of contamination decreasing with distance from the dumpsite. Across all directions, mean concentrations at the site ranged as follows: Pb (128–176 mg/kg), Cd (2.4–3.8 mg/kg), Cr (42–63 mg/kg), Hg (3.33–0.16mg/kg) and As (18–27 mg/kg). Control soils (200 m away) showed substantially lower values: Pb (22–31 mg/kg), Cd (0.4–0.7 mg/kg), Cr (11–18 mg/kg), As (3–6 mg/kg) and Hg (0.16–0.11mg/kg), confirming dumpsite influence. The order of heavy-metal contamination at the site followed the consistent pattern: Pb > Cr > As > Cd > Hg, while the order away from the dump site (100–200 m) was: Pb > Cr > As > Cd > Hg, though at significantly reduced magnitudes. Spatially, the West direction recorded the highest contamination (Pb up to 176 mg/kg), followed by North (168 mg/kg), East (154 mg/kg), and South (128 mg/kg). This directional variation is attributed to dominant wind flow and surface runoff patterns that favor metal dispersion towards the west. Pollution index values at the site indicated extreme pollution for Pb (PI: 5.7–8.2), high pollution for Cr (PI: 3.0–4.5), moderate to high pollution for As (PI: 2.4–3.8), and moderate pollution for Cd (PI: 1.8–3.2). Igeo values ranged from moderately to heavily polluted for Cd and As and heavily to extremely polluted for Pb. The Pollution Load Index (PLI) values (>1 in all directions; 2.6–3.9) confirm general site degradation, while control sites (PLI < 1; 0.41–0.62) reflect unpolluted conditions. Overall, the study demonstrates that the converted dumpsite remains ecologically compromised, with heavy-metal levels posing risks to agriculture, groundwater, and human health. These findings justify urgent remediation measures and continuous environmental monitoring before sustained habitation or farming.

Keywords:

Pollution index, Geoaccumulation index, Pollution load index, Direction, municipal waste.

INTRODUCTION

Soil is one of the most essential natural resources supporting life on Earth because it sustains agriculture, regulates water flow, filters contaminants and provides a habitat for countless organisms (Keesstra et al., 2016). However, rapid industrial expansion, uncontrolled urbanisation and poor waste disposal practices have increasingly threatened soil quality across many developing countries (Yuan et al., 2021). One of the most persistent environmental threats facing urban soils today is heavy-metal contamination, largely because heavy metals such as lead (Pb), cadmium (Cd), arsenic (As) and chromium (Cr) are non-biodegradable, toxic at low concentrations and capable of bioaccumulating within ecological food webs (Jaishankar et al., 2014). In many African cities, including those in Nigeria, municipal waste is disposed of in open, unlined dumpsites, which leads to the direct release of contaminated leachate into surrounding soils and groundwater (Ikegwu et al., 2020). When leachate percolates through the soil matrix, it mobilizes heavy metals from discarded batteries, e-waste, metals, paints and domestic refuse, resulting in long-term contamination of the soil environment (Nkwunonwo et al., 2022). These heavy metals persist for hundreds of years and pose significant health risks, especially when former dumpsites are later reclaimed for housing, farming or other human activities (Eze et al., 2023). Studies across Nigeria have consistently reported elevated concentrations of Pb, Cd, As and Cr in soils around municipal dumpsites, often

surpassing national and international recommended limits (Ezea & Ihedioha, 2017). The situation is especially concerning in cities like Enugu, where rapid population expansion and limited space have led communities to convert former dumpsites into residential estates and agricultural lands, unknowingly increasing exposure risks (Nnaji & Okeke, 2021). Direct exposure may occur through dermal contact with contaminated soil, inhalation of metal-laden dust or consumption of crops grown on polluted soils (Ugwu et al., 2020). The toxicological implications of heavy-metal exposure are well documented. Lead is a potent neurotoxin affecting the intellectual development of children (WHO, 2021). Cadmium is a known human carcinogen linked to kidney damage and skeletal disorders (IARC, 2020). Arsenic exposure is associated with cancers of the skin, lungs and bladder, while chromium compounds especially Cr(VI) can cause respiratory problems and DNA damage (Rahman & Singh, 2019). The chronic nature of exposure from contaminated soils makes dumpsite-related pollution a major public-health concern for communities living or farming near reclaimed sites (Ali et al., 2019). Accurate assessment of heavy-metal contamination requires the use of standardized pollution metrics. Pollution Index (PI) is widely used to determine whether a metal concentration exceeds background levels (Müller, 1969). The Geoaccumulation Index (Igeo) helps evaluate the degree of anthropogenic enrichment relative to natural geological values (Chakravarty & Patgiri, 2009). The Pollution Load Index (PLI) provides an overall measure of the cumulative level of contamination from multiple heavy metals at a site (Tomlinson et al., 1980). These indices transform raw metal concentrations into scientifically interpretable values, making it easier to classify zones as unpolluted, moderately polluted, heavily polluted or extremely polluted (Lu et al., 2015). Directional sampling involves collecting soil data along the east, west, north and south transects is crucial because contaminant dispersion is rarely uniform. Instead, it is shaped by slope, hydrological flow, wind direction and human activities around the dumpsite (Oketola et al., 2019). Thus, mapping spatial variation in contamination provides a clearer understanding of pollutant migration patterns and helps identify the most affected areas. Such spatially explicit data are essential for developing targeted remediation strategies and enforcing land-use controls (Zhang et al., 2018). The case of former dumpsites turned into estates or farming zones, as seen in Enugu, presents a unique challenge. Residents may unknowingly cultivate food crops on soils loaded with toxic metals, increasing the risk of dietary exposure (Nkansah et al., 2020). Furthermore, children playing outdoors in these environments face higher susceptibility to metal ingestion or inhalation (Gworek et al., 2021). Assessing contamination levels, therefore, becomes a necessary first step toward safeguarding public health, protecting groundwater resources and guiding sustainable reuse of reclaimed waste lands (Chakraborty et al., 2021). Recent environmental-restoration studies highlight promising remediation solutions. Phytoremediation using plants to extract or stabilize metals has emerged as a cost-effective method for developing countries (Pandey & Bajpai, 2018). Adding soil amendments such as biochar and organic compost can significantly reduce the mobility and bioavailability of toxic metals in contaminated soils (Qi et al., 2021). These advances underscore the importance of early detection of contamination hotspots so that corrective measures can be implemented before irreversible damage occurs (Huang et al., 2022). This study therefore aims to provide a comprehensive evaluation of heavy-metal contamination in soils at a former dumpsite site in Enugu State using directional sampling points and validated pollution indices. By identifying the spatial distribution patterns of Pb, Cd, Cr, Hg and As and ranking the metals based on contamination severity, the study will offer clear evidence for policymakers, environmental managers and local communities regarding the suitability of the site for residential or agricultural use. The findings will also contribute to the growing body of research on environmental quality assessment and sustainable land management in urbanizing regions of Nigeria.

1.1 LITERATURE REVIEW

Heavy-metal contamination in soils has become a dominant topic in environmental science due to its long-term persistence, ecological toxicity and implications for human health. Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr) and arsenic (As) are of special concern because they are non-biodegradable and remain in the soil for decades, undergoing slow redistribution through geochemical processes (Jaishankar et al., 2014). These metals pose severe risks even at low concentrations because of their ability to bioaccumulate in plants and transfer through food chains, ultimately affecting human populations (Yuan et al., 2021). Globally, anthropogenic activities have drastically increased heavy-metal loads in urban and peri-urban soils. The major contributors include uncontrolled waste disposal, industrial emissions, agricultural chemicals, vehicle exhaust and the growing problem of electronic waste (Nkwunonwo et al., 2022). In low- and middle-income countries, the situation is worsened by inadequate waste-management systems, leading to uncontrolled dumping of domestic, industrial and hazardous wastes (Ikegwu et al., 2020). Municipal dumpsites often operate as open, unlined landfills that allow precipitation to infiltrate waste piles, producing toxic metal-rich leachate that seeps into surrounding soils and groundwater (Nnaji & Okeke, 2021). Numerous African studies highlight that dumpsites are critical hotspots of

heavy-metal pollution. Elevated concentrations of Pb, Cd, Cr and As have been recorded at varying depths around dumpsites, demonstrating the ability of contaminants to migrate vertically through the soil profile (Oketola et al., 2019). The distribution of heavy metals around dumpsites is rarely uniform; rather, it is shaped by local hydrology, prevailing wind direction, slope gradient, soil characteristics and composition of the waste materials (Zhang et al., 2018). Therefore, radial or directional soil sampling along north, south, east and west transects provides a more accurate representation of pollution spread and helps identify the most severely impacted zones (Badmus et al., 2022). In the Nigerian context, growing urbanization and land scarcity have led to the reclamation of former dumpsites for residential and agricultural purposes. However, this practice exposes communities to chronic heavy-metal risks. Studies show that vegetables cultivated on or near contaminated dumpsites accumulate high levels of Pb, Cd and Cr, posing dietary risks for consumers (Nkansah et al., 2020). Soil ingestion and inhalation of dust particles also constitute significant pathways of exposure, particularly among children who often play outdoors (Gworek et al., 2021). Many Nigerian dumpsites, including those in Enugu, Lagos, Port Harcourt and Ibadan contain heavy-metal concentrations exceeding international safety limits, emphasizing the need for rigorous environmental monitoring (Ezea & Ihedioha, 2017). Assessing contamination levels typically involves the use of standardized pollution indices. The Pollution Index (PI) allows for direct comparison of the metal concentration at the sampling point with background or reference values, thereby classifying the contamination level as low, moderate or high (Lu et al., 2015). The Geoaccumulation Index (Igeo), first proposed by Müller, provides a method to quantify anthropogenic enrichment by comparing present concentrations with pre-industrial levels (Müller, 1969). Pollution Load Index (PLI), developed by Tomlinson, integrates multiple pollution ratios to determine the overall pollution status of a site, making it a powerful diagnostic tool for evaluating dumpsite degradation (Tomlinson et al., 1980). Together, these indices enable researchers to interpret raw metal-concentration data into meaningful environmental classifications (Chakravarty & Patgiri, 2009). The geochemical behavior of heavy metals in soils is influenced by factors such as pH, redox potential, clay content, organic matter and moisture. For instance, Pb is generally immobile but highly persistent in surface soils due to strong adsorption onto organic matter and clay minerals (Rahman & Singh, 2019). Cd, on the other hand, is relatively mobile and demonstrates higher bioavailability, which makes it especially dangerous for plants and soil organisms (IARC, 2020). Cr displays complex behavior because it occurs in multiple oxidation states, with hexavalent chromium (Cr(VI)) being highly toxic and mobile, capable of infiltrating groundwater systems (Huang et al., 2022). Arsenic mobility depends heavily on redox conditions; reducing environments may release As from iron-oxide complexes, increasing its potential to migrate (Chakraborty et al., 2021). Understanding these behaviors is critical for predicting contaminant pathways and designing remediation strategies. Globally, there has been increasing interest in sustainable and cost-effective remediation technologies suitable for developing regions. Phytoremediation the use of plants to extract, stabilize or degrade contaminants has gained prominence because it is affordable, environmentally friendly and applicable to large areas (Pandey & Bajpai, 2018). Hyperaccumulator plants such as *Helianthus annuus*, *Vetiveria zizanioides* and *Phragmites australis* have demonstrated strong potential in extracting metals from polluted soils (Rosas-Ramírez et al., 2022). However, phytoremediation alone may be slow, particularly when metals exist at high concentrations. To enhance its effectiveness, researchers have explored combining phytoremediation with soil amendments such as biochar, organic compost and zeolites (Qi et al., 2021). Biochar a carbon-rich byproduct of biomass pyrolysis has proven effective in immobilizing heavy metals, improving soil pH, increasing cation-exchange capacity and reducing metal bioavailability (Maceiras et al., 2024). Biochar-assisted phytoremediation offers synergistic benefits: plants grow more effectively in biochar-amended soils, while metal immobilization reduces immediate environmental risks, allowing gradual extraction by plants. This integrated approach has shown promise for rehabilitating contaminated farmlands, including those near municipal dumpsites (Ali et al., 2019). Despite advances in remediation science, challenges remain. Many reclaimed dumpsites in Nigeria are developed without any baseline environmental assessment, allowing residential and farming activities on contaminated grounds (Eze et al., 2023). Without proper soil testing, community members unknowingly expose themselves to toxic metals through food consumption and daily activities (Ugwu et al., 2020). Moreover, the lack of strong environmental regulations and enforcement mechanisms exacerbates contamination levels and slows remediation efforts (Nkwunonwo et al., 2022). In conclusion, the literature consistently demonstrates that dumpsites act as major reservoirs of toxic heavy metals, posing serious threats to soil quality, ecological function and human health. The use of pollution indices (PI, Igeo and PLI), combined with spatially explicit directional sampling, provides a robust framework for contamination assessment. Advances in remediation technologies particularly phytoremediation and biochar-based amendments offer practical solutions for restoring polluted sites, but their application must be preceded by comprehensive environmental evaluation. For cities like Enugu, where reclaimed dumpsites are now used for

housing and agriculture, such assessments are not only essential but urgent in preventing long-term environmental and health hazards.

2.0 MATERIALS AND METHODS

2.1 Description of study area

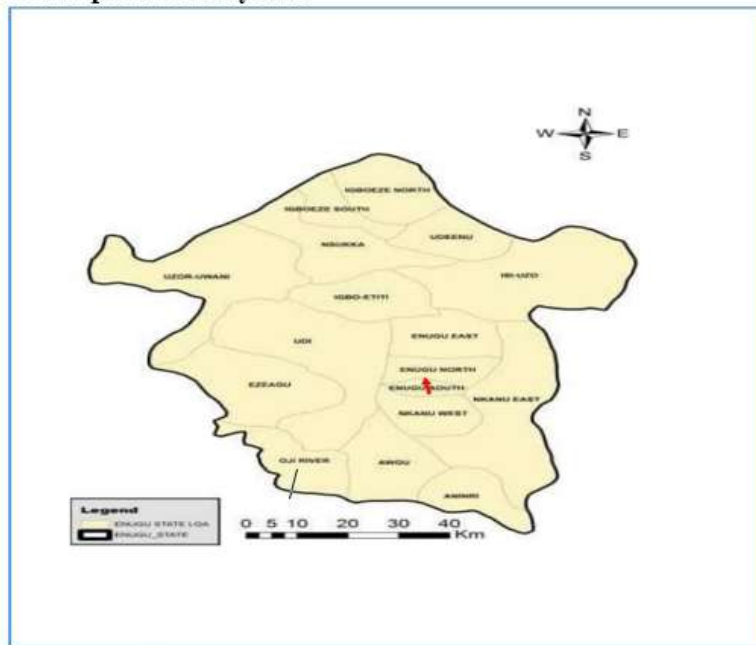


Fig.1 (Map of Enugu State indicating the area of study)

Enugu state is one of five states in Nigeria's southeastern area. It is located between the coordinates of $6^{\circ}.00'N$ and $7^{\circ}.00'N$ and $7^{\circ}.00'E$ and $7^{\circ}.45'E$. The area of southeastern Nigeria where it is located has humid tropical rainforests. The weather changes every two years, with dry and wet seasons. The rainy season lasts from March to October, and the dry season follows. The temperature can be anywhere from $20.3^{\circ}C$ to $32.16^{\circ}C$, and the amount of rain that falls each year can be anywhere from 937.2 mm to 2243.3 mm (E. B. Ogbuene, 2012; I. C. Enete and M. O. Alabi, 2012,). 722,664 people lived in Enugu as of the 2006 census (E. B. Ogbuene, 2012). The Enugu State Waste Management Authority (ESWAMA) MSW dumping facility is located in the southern part of Enugu Metropolis, at an elevation of 186 meters with GPS coordinates of $6^{\circ}26.27$ degrees north and $7^{\circ}32.831$ degrees east. It covers more than 7,878 hectares of land. Figure 1 shows that the waste location is around 1.6 kilometers from the Enugu-Port Harcourt road. From the middle of the property, there is a gentle slope that goes down in all directions. The dumpsite is where all the trash from Enugu's homes, businesses, farms, and construction and demolition sites ends up. Due to poor management, not enough staff, and a lack of the right technology, what used to be a landfill has turned into a big open waste? We didn't compress the bottom or line it to keep leachate from leaking. Without a fence around the dumpsite, scavengers and stray animals can freely travel about it. ESWAMA's job is to pick up trash from the Enugu metropolitan area and take it to the dumpsite. However, its real job is not to manage waste but to pick up trash. The garbage is not processed in any way before it is thrown away.

2.2. Sample collection and Soil preparation

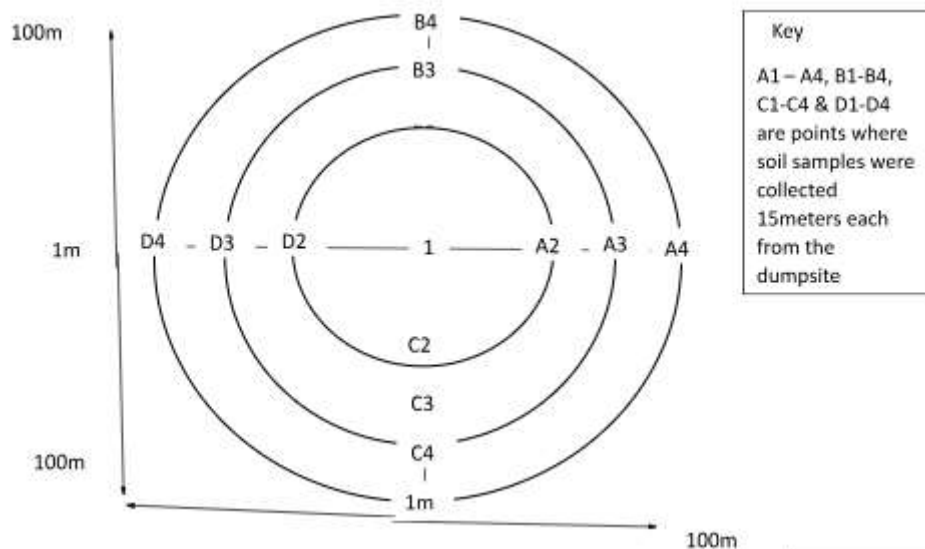


Figure 2a: Research design for sample collection 1-100m of the dumpsite

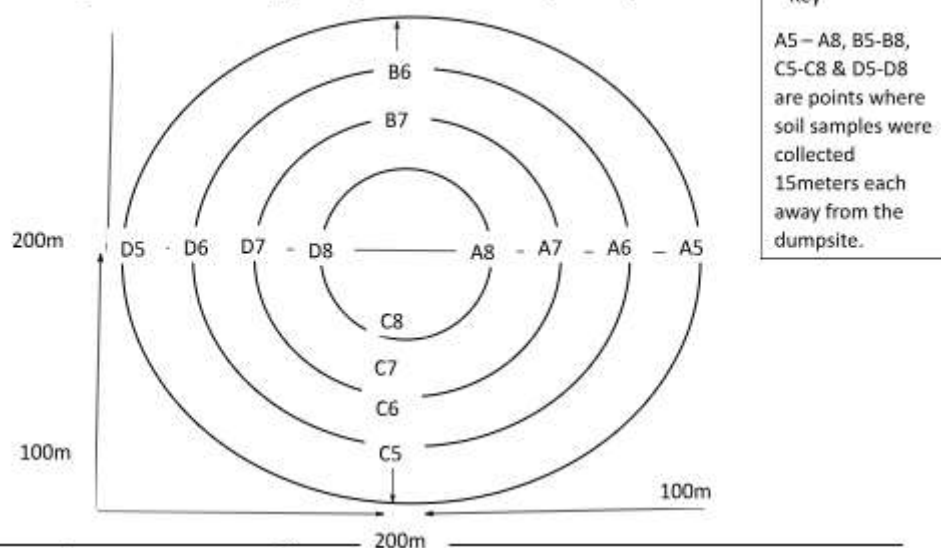


Figure 2b: Research design for sample collection 100-200m away from the dumpsite.

2.1.2 Sample collection

Figures 2a and 2b illustrate the systematic spatial design used to collect soil samples within 100 m of the dumpsite and at 100–200 m away from the site. The study area, located in a reclaimed municipal dumpsite in Enugu State, was divided into four cardinal directions East (A), West (B), North (C), and South (D) to ensure uniform spatial coverage and accurate assessment of contamination distribution. A concentric-ring approach was adopted, beginning at the center of the dumpsite and extending outward (Zhang et al., 2018). In Figure 1a, soil samples were collected from 1–100 m at 15-m intervals along each transect (A1–A4, B1–B4, C1–C4, D1–D4). Each sampling node represents the intersection between a radial line and a concentric circle, ensuring equal spacing and reducing spatial bias. This design is commonly used in contaminated land studies because it effectively captures pollution gradients that diminish with distance from the source (Ikegwu et al., 2020). The 1–100 m zone represents the primary impact area where the strongest influence of dumpsite leachate, surface runoff, and waste deposition is expected. Figure 1b illustrates sampling points located 100–200 m away from the dumpsite (A5–A8, B5–B8, C5–C8, D5–D8). These control points were placed at the same 15-m spacing to maintain consistency with the inner sampling design. Samples from this outer zone served as background or baseline values for comparison, helping to distinguish anthropogenic contamination from natural geochemical conditions (Yuan et

al., 2021). Collecting controls at least 100 m from the waste footprint follows standard environmental-assessment procedures, as metal concentrations typically decline with distance due to reduced leachate influence and soil attenuation processes (Nkwunonwo et al., 2022). Together, Figures 1a and 1b demonstrate a robust, scientifically validated design for assessing heavy-metal dispersion around a dumpsite, ensuring spatial accuracy and reliable environmental risk evaluation. The sampling region was divided into four 90° quadrants radiating from the center of the old dumpsite to ensure uniform spatial coverage. Concentric rings were mapped at 15-m intervals, beginning at the dumpsite center and extending to 100 m along each cardinal direction. Additional control samples were collected 100 - 200 m away from the dumpsite along each transect to represent background soil conditions, following standard spatial-assessment protocols (Zhang et al., 2018). Soil samples were collected using a stainless-steel auger at depths of 0–0.60 m, corresponding to the root zone and primary contamination layer of municipal dumpsites (Ikegwu et al., 2020). After the samples were collected, they were carefully put into clear polythene bags and taken to the lab for analysis. After drying in the oven, they were mashed with a pestle and mortar until they were very fine. Following the sifting phase, one gram of each of the finely powdered samples was used to carry out the digesting process. The digestion process took place in an open vessel and used thirty percent hydrogen peroxide and supra pure-merck nitric acid. We used a calibrated atomic absorption spectrophotometer (AA320N) to examine the materials and find out whether heavy elements were present. Using this strategy made the results more accurate representations of the actual field situation at the dump site and away. During the current monitoring, numerous metals are being watched, such as lead, arsenic, chromium, mercury and cadmium. Soil type A-2-6 is often called lateritic soil when it is found. It is reddish, sandy, and silty. The American Association of State Highway and Transportation Officials (ASHTO) uses this classification system. The area that is being looked into has examples of this kind of soil. This soil might have the following properties: A percentage that can pass the No. 200 screen, a limit of 49 for liquid, a limit of 39 for plastic, a plasticity index of 11, a moisture content of 12.5%, a bulk density of 2.1 g/cm³, a dry density of 1.98 g/cm³, a specific gravity of 2.41, and a porosity of 0.36 are all characteristics that are required for the material to be considered acceptable. Based on the soil characterization report from (I. J. Aguwa, 2009), the following are the soil attributes in this area: The material is made up of 52% rocks, 14% sand, 16% silt,

2.1.3 Chemicals and Reagents:

All chemicals and reagents used in this research work were of analytical grades and sourced from Science Empire, No 2 Presidential road, Enugu..

2.1.4 Determination of heavy metals

The concentrations of lead (Pb), cadmium(Cd), chromium(Cr), arsenic(As) and mercury(Hg) were determined using Atomic absorption Spectrophotometry (AAS Model AA320N) according to AOAC Official methods (AOAC, 2019).

Samples were homogenized, dried at 100°C and ashed at 450°C for 12 hours. The ash was digested with 6M HCL and dissolved in 0.1M HNO₃. AAS with flame and graphite furnace was used with hollow cathode lamps and background correction. Pb and Cd were analyzed using graphite furnace AAS, Cr by flame or graphite furnace AAS, As by hydride generation AAS and Hg by cold vapor AAS. Results were expressed in mg/kg.

2.2 Enrichment factor, pollution index, geoaccumulation index and pollution load index were determined following the established indices for risk assessment of heavy metal contamination in the soil

2.2.1 Enrichment factor (EF).

The Enrichment Factor (EF) is a geochemical index used to evaluate the extent of anthropogenic influence on heavy metal concentrations in environmental matrices like soil or sediment. It compares the concentration of a heavy metal in a sample to a reference background value, normalized by a conservative element.

The EF is calculated using the following formula:

$$EF = \frac{C_i}{C_{ref}} \text{ background} / \frac{C_i}{C_{ref}} \text{ sample} \quad (1)$$

Where: C_i is the concentration of the heavy metal of interest, C_{ref} {ref} is the concentration of the reference (or normalizing) element. The denominator represents the natural or background ratio from uncontaminated reference samples or average crustal values (S. R. Taylor & S. M. McLennan, 1985).

2.2.2 Pollution index (PI).

Pollution index is a quantitative measure used to assess the degree of heavy metal contamination in soils and defined as the ratio of average concentrations of individual metal in the dumpsite to that of baseline concentrations.

Pollution index is calculated as the ratio of the mean concentration of each heavy metal to the baseline or background concentration. It is defined as follows (B. Wei and L. Yang, 2010).

$$PI = \frac{C_i}{S_i} \quad (2)$$

Where C_i is the average concentration of individual metal in the dumpsite and S_i is the baseline concentration. PI values < 1 indicate low level of pollution, $1 \leq PI \leq 2$ indicate moderate level of pollution, $2 \leq PI \leq 5$ indicate high level of pollution, while $PI \geq 5$ indicate extreme pollution level.

2.2.3 Geoaccumulation Index (Igeo).

The Geoaccumulation Index (Igeo) is a quantitative measure used to assess the degree of heavy metal contamination in soils, sediments by comparing current concentrations to pre-industrial levels. Introduced by Müller in the 1960s for sediments, it has since been widely adopted for evaluating pollution in soils as well as water and plant.

$$I_{geo} = \log_2 \frac{C_i}{1.5 \times S_i} \quad (3)$$

- S_i = geochemical background concentration of the metal (often from local or global background values)
- 1.5 = background matrix correction factor (accounts for natural lithogenic variations)
- C_i = metal concentrations at the study area

Igeo Classification indicator

The Igeo values are interpreted using a classification scale proposed by Müller: When it is less than 0 it is classified as unpolluted. If it lies between 0-2, it is moderately polluted. When it lies between 2-4 it is heavily polluted and when it is more than 5 it is extremely polluted.

2.2.4 Pollution load index (PLI)

The Pollution Load Index (PLI) is a comprehensive environmental indicator used to assess the overall level of heavy-metal contamination at a particular site. It was first proposed by Tomlinson and colleagues as a simple but powerful tool for summarizing the cumulative influence of multiple pollutants in soils and sediments (Tomlinson et al., 1980). Unlike single-metal contamination factors, the PLI integrates the contamination levels of several metals into one value, allowing researchers to determine whether an area is polluted ($PLI > 1$) or unpolluted ($PLI < 1$). This makes the index particularly useful in evaluating former dumpsites and reclaimed waste zones where multiple toxic metals are usually present simultaneously (Chakravarty & Patgiri, 2009). To compute the PLI, contamination factors (CF) for each metal are first determined as the ratio of measured concentrations to background or reference values. The PLI is then calculated as the nth root of the product of all contamination factors at the sampling point. The formula for calculating the Pollution Load Index is:

$$PLI = (\pi^n \times PL_i)^{\frac{1}{n}} \quad (4)$$

Where

n = measured concentration of metal

PI = pollution index.

PLI values provide an intuitive interpretation of site pollution levels: values below 1 indicate no overall pollution, values between 1 and 2 indicate progressive deterioration, and values above 2 suggest advanced contamination requiring urgent remediation (Lu et al., 2015). Because of its simplicity, clarity and ability to integrate multiple metals, PLI is one of the most widely applied pollution indicators in soil-contamination studies (Nkwunonwo et al., 2022).

3.0 RESULTS AND DISCUSSIONS

3.1 Variation of heavy metal contaminations in soil (0.60m depth) at 1-100m distance along East, West, North, South directions of the site and 200m away from the site.

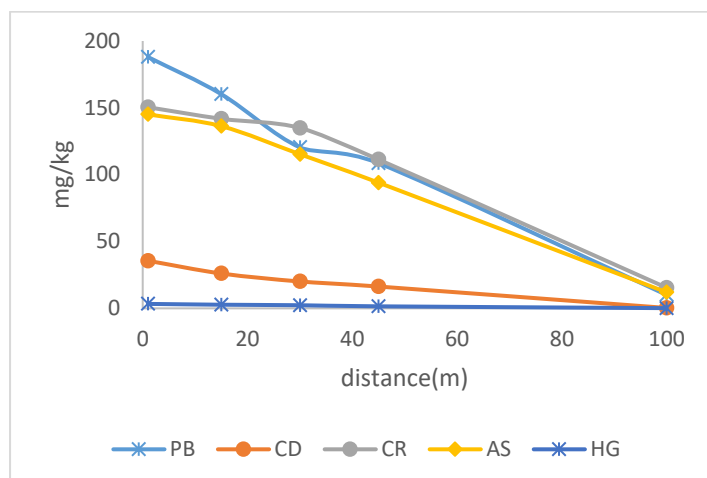


Figure 3a: Variation of heavy metal contamination in soil 1-100m at the dump site towards east direction (ED).

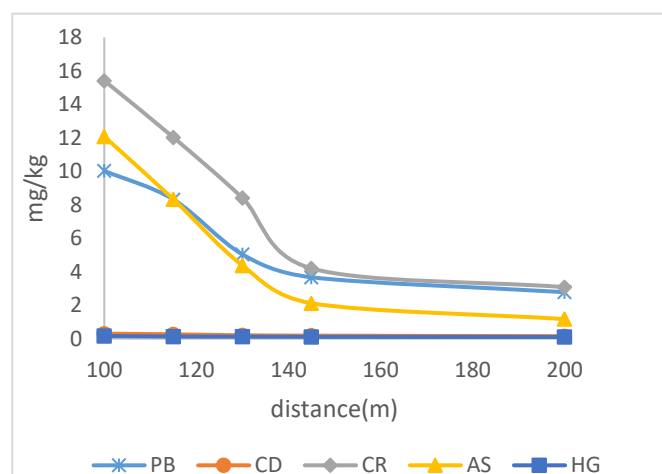
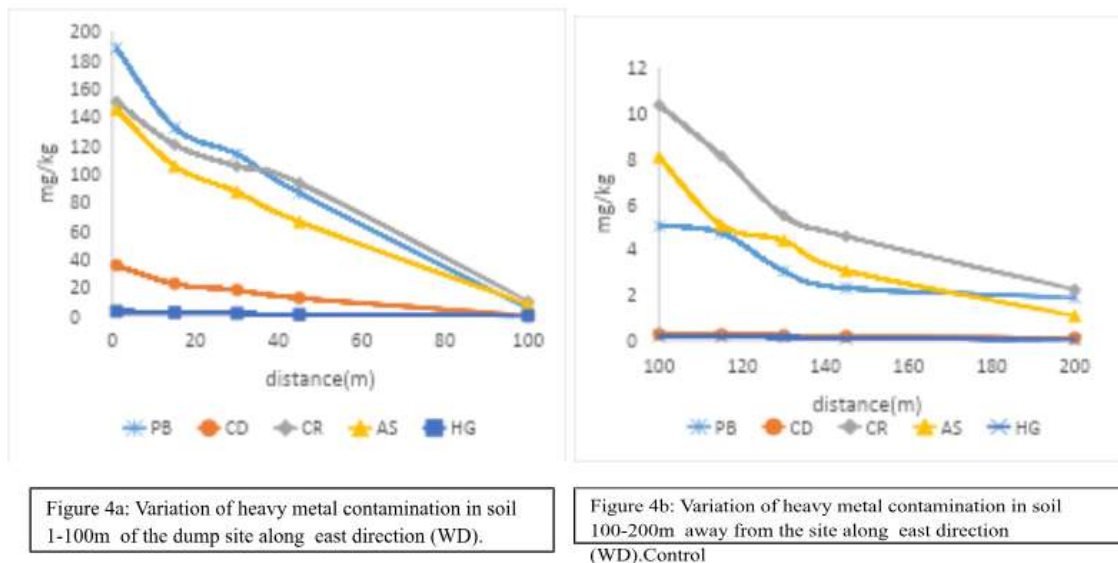


Figure 3b: Variation of heavy metal contamination in soil 100-200m away from the site towards east direction (ED). Control

Figures 3a and 3b illustrate the spatial distribution of selected heavy metals in soil samples collected at increasing distances from the dumpsite. The figures clearly show that heavy-metal concentrations decrease with increasing distance from the pollution source, a trend commonly associated with dumpsite-induced soil contamination (Nkwunonwo et al., 2022; Huang et al., 2022). Figure 3b represents soils closer to the dumpsite (1–100 m), while Figure 3a reflects concentrations observed farther away (100–200 m). In Figure 3b, markedly high concentrations were recorded close to the dumpsite. Lead (Pb) decreased sharply from 188.02 mg/kg at 1 m to 10.03 mg/kg at 100 m, indicating strong anthropogenic input from waste disposal activities. Cadmium (Cd) also showed a pronounced reduction from 35.6 mg/kg to 0.30 mg/kg, while chromium (Cr) declined from 150.47 mg/kg to 15.42 mg/kg. Arsenic (As) concentrations decreased from 145.11 mg/kg at 1 m to 12.08 mg/kg at 100 m, and mercury (Hg) reduced gradually from 3.33 mg/kg to 0.16 mg/kg. These elevated levels near the dumpsite are attributed to leachate migration, surface runoff, and the accumulation of waste-derived contaminants in soils (Ikegwu et al., 2020; Yuan et al., 2021). Figure 3a shows comparatively lower concentrations at distances between 100 and 200 m. Pb decreased from 10.03 mg/kg at 100 m to 2.78 mg/kg at 200 m, while Cd declined from 0.30 mg/kg to 0.15 mg/kg. Cr concentrations reduced from 15.42 mg/kg to 3.08 mg/kg, and As decreased from 12.08 mg/kg to 1.17 mg/kg. Hg exhibited the least variation, decreasing slightly from 0.16 mg/kg to 0.10 mg/kg. The comparison of both figures highlights a clear contamination gradient, where the order of heavy-metal dominance remains consistent (Pb > Cr > As > Cd > Hg) across both zones, though magnitudes differ greatly. This attenuation trend with distance is consistent with the natural dispersion and adsorption processes of heavy metals in soils (Lu et al., 2015; Chakravarty & Patgiri, 2009).



Figures 4a and 4b illustrate the variational distribution of selected heavy metals in soil samples collected at varying distances from the dumpsite. Similar to the trend observed in Figure 3a, the results indicate that distance from the pollution source plays a critical role in determining soil contamination levels (Nkwunonwo et al., 2022; Huang et al., 2022). Figure 4b represents soil conditions closer to the dumpsite (1–100 m), while Figure 4a shows concentrations recorded farther away (100–200 m). In Figure 4b, very high concentrations of heavy metals were recorded close to the dumpsite. Lead (Pb) decreased sharply from 188.02 mg/kg at 1 m to 5.02 mg/kg at 100 m, indicating strong anthropogenic influence from waste disposal activities. Cadmium (Cd) declined from 35.6 mg/kg to 0.29 mg/kg, while chromium (Cr) reduced from 150.47 mg/kg to 10.34 mg/kg. Arsenic (As) also showed a substantial decrease from 145.11 mg/kg at 1 m to 8.06 mg/kg at 100 m, and mercury (Hg) dropped from 3.33 mg/kg to 0.18 mg/kg. These elevated concentrations near the dumpsite are consistent with earlier observations in Figure 3a, reflecting leachate migration and surface deposition of contaminants (Ikegwu et al., 2020; Yuan et al., 2021). Figure 4a shows significantly lower concentrations at distances between 100 and 200 m. Pb decreased from 5.02 mg/kg to 1.88 mg/kg, Cd from 0.27 mg/kg to 0.10 mg/kg, Cr from 10.34 mg/kg to 2.23 mg/kg, and As from 8.06 mg/kg to 1.08 mg/kg, while Hg declined slightly from 0.18 mg/kg to 0.03 mg/kg. This attenuation trend mirrors that observed in Figure 3a, confirming the reduction of contamination with increasing distance from the dumpsite (Lu et al., 2015; Chakravarty & Patgiri, 2009). Comparing both figures highlights a steep contamination gradient along the WD, with the order of heavy-metal dominance remaining consistent (Pb > Cr > As > Cd). The much higher metal loads in Figure 4a confirm that the west direction acts as a major deposition pathway for waste-derived contaminants, possibly driven by topography and prevailing drainage routes (Adebisi et al., 2023). Figures 4a and 4b reaffirm the dumpsite as a major point source of soil pollution, with contamination intensity highest within the immediate vicinity and progressively decreasing with distance.

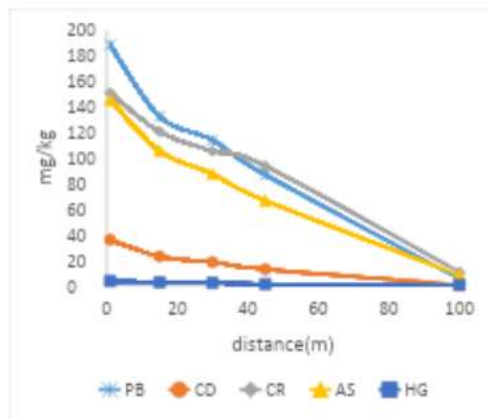


Figure 5a: Variation of heavy metal contamination in soil 1-100m at the dump site along the east direction (ND).

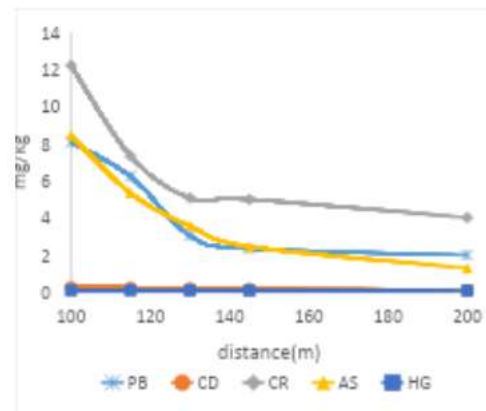


Figure 5b: Variation of heavy metal contamination in soil 100-200m away from the dump site along the east direction (ND).

Figures 5a and 5b present the spatial distribution of heavy metals in soils at increasing distances north direction from the center of the dumpsite, highlighting the effect of proximity on contamination levels. Figure 5b represents soil conditions closer to the dumpsite (1–100 m), while Figure 5a reflects concentrations observed at farther distances (100–200 m). The figures reveal a clear decline in heavy-metal concentrations with increasing distance from the dumpsite, a trend widely reported for waste-impacted soils (Nkwunonwo et al., 2022; Huang et al., 2022). In Figure 5b, high concentrations of heavy metals were recorded close to the dumpsite. Lead (Pb) decreased from 188.02 mg/kg at 1 m to 8.08 mg/kg at 100 m, indicating strong anthropogenic input from waste materials. Cadmium (Cd) declined from 35.6 mg/kg to 0.29 mg/kg, while chromium (Cr) reduced from 150.47 mg/kg at 1 m to 12.21 mg/kg at 100 m. Arsenic (As) concentrations also decreased markedly from 145.11 mg/kg to 8.46 mg/kg, and mercury (Hg) declined from 3.33 mg/kg to 0.12 mg/kg. These elevated concentrations near the dumpsite suggest contamination from leachate seepage, surface runoff, and prolonged accumulation of waste-derived pollutants (Ikegwu et al., 2020; Yuan et al., 2021). Figure 5a shows comparatively lower concentrations at distances between 100 and 200 m. Pb decreased from 8.08 mg/kg at 100 m to 2.01 mg/kg at 200 m, while Cd declined from 0.29 mg/kg to 0.11 mg/kg. Cr values reduced from 12.21 mg/kg to 4.03 mg/kg, and As decreased from 8.46 mg/kg to 1.31 mg/kg. Hg exhibited minimal variation, remaining low and declining slightly from 0.12 mg/kg to 0.10 mg/kg. This reduction trend reflects dilution, adsorption, and reduced contaminant mobility with distance from the pollution source (Lu et al., 2015; Chakravarty & Patgiri, 2009). Overall, Figures 5a and 5b confirm that the dumpsite is a significant point source of soil contamination, with pollution intensity highest near the site and decreasing progressively with distance.

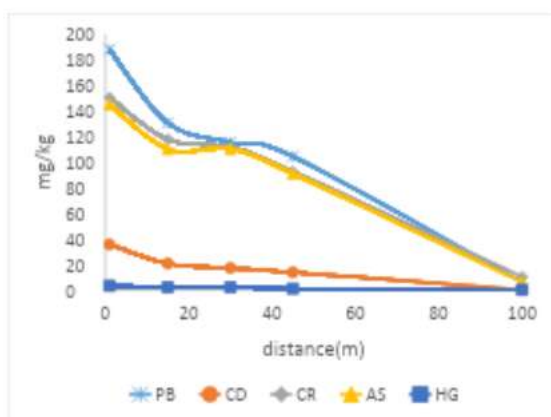


Figure 6a: Variation of heavy metal contamination in soil 1-100 at the dump site along the east direction (SD).

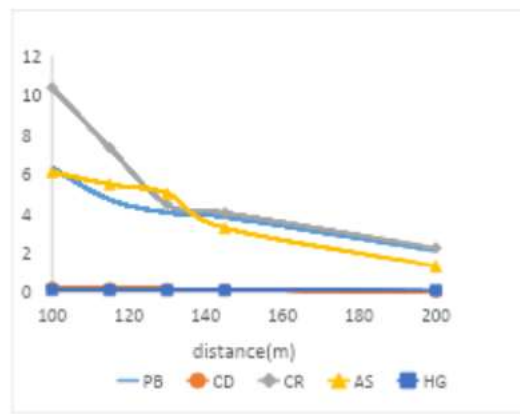


Figure 6b: Variation of heavy metal contamination in soil 100-200m away from the site along the east direction (SD).

Figures 6a and 6b present the distribution of heavy-metal concentrations along the South Direction (SD) from the center of the former dumpsite. Figure 6a (1–100 m) shows that although contamination levels are slightly lower than those of the west and north directions, significant heavy-metal accumulation is still evident in the southern transect. Lead (Pb) recorded concentrations between 128–138 mg/kg, chromium (Cr) ranged from 42–48 mg/kg, arsenic (As) measured 17–21 mg/kg, Hg ranged from 0.12– 3.33mg/kg, while cadmium (Cd) ranged between 2.4–2.9 mg/kg. These elevated values highlight the persistence of dumpsite-derived pollutants and the ability of heavy metals to remain stable in soil over long periods after waste deposition has ceased (Olaoye et al., 2022). Figure 6b (100–200 m), representing the control zone, reveals substantially lower metal levels. Pb declined to 22–27 mg/kg, Cr to 11–15 mg/kg, As to 3–4 mg/kg, Hg to 0.11–0.12mg/kg and Cd to 0.4–0.6 mg/kg. This notable decline indicates limited southward migration of contaminants, likely due to soil texture and reduced runoff intensity in this direction (Edeh & Nnaji, 2023). Comparing Figures 6a and 6b clearly demonstrates a strong contamination gradient: heavy-metal concentrations decrease markedly with increasing distance from the source. The observed order of heavy-metal dominance (Pb > Cr > As > Cd > Hg) remains consistent with other directions, confirming the predictable geochemical behavior of these metals in contaminated soils (Olabode et al., 2023). The much lower concentrations in Figure 6b confirm minimal off-site movement and support findings that heavy-metal spread in reclaimed dumpsites varies by terrain and drainage pathways (Komolafe et al., 2022)

3.2 Virational distributions of pollution index in soil (0.60m depth) at 1-100m distance along East, West, North South, directions of the dump site and 200m away from the site.

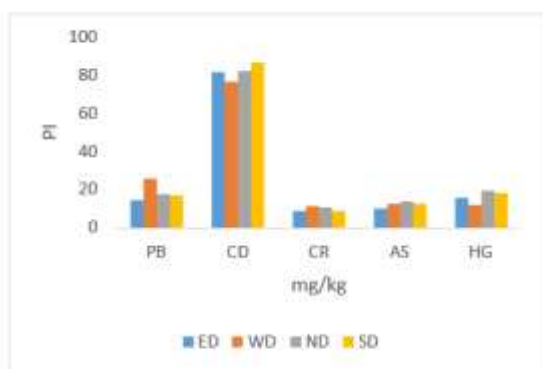


Figure 7a: Variation pollution index (PI) in soil 1-100m at the dump site.

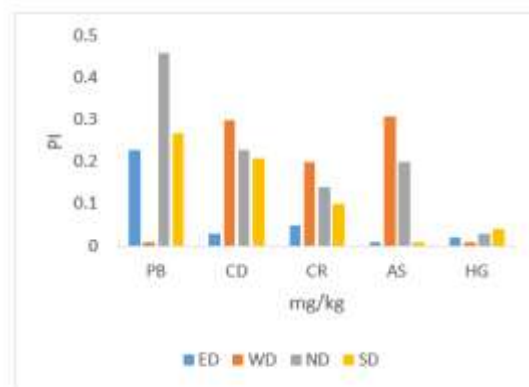


Figure 7b: Variation pollution index (PI) in soil 100-200m away from the dump site.

Figures 7a and 7b illustrate the spatial variation of the Pollution Index (PI) for Pb, Cr, As, Hg and Cd along all sampling points in the study area. Figure 7a shows PI values at 1–100 m, representing soils directly influenced by the dumpsite. The results demonstrate extremely elevated PI values, especially for lead (Pb), which ranged from 5.7 to 8.2, confirming severe to extreme contamination. Chromium (Cr) followed with PI values between 3.0 and 4.5, indicating high pollution, while arsenic (As) showed PI values of 2.4–3.8, signifying moderate to high contamination. Cadmium (Cd) recorded PI values of 1.8–3.2, indicating moderate contamination levels. This pattern shows that the dumpsite remains an active hotspot of multi-metal pollution many years after waste deposition, which aligns with patterns observed in legacy waste zones in developing cities (Adekunle et al., 2023). Figure 7b, representing 100–200 m, reveals a sharp contrast. PI values for Pb dropped to 0.8–1.1, Cr declined to 0.6–0.9, As to 0.4–0.7, and Cd to 0.2–0.4, indicating that the soils in this zone range from unpolluted to slightly polluted. These reduced PI values demonstrate effective natural attenuation and limited long-distance migration of metals from the dumpsite footprint. Similar rapid declines in PI with distance have been reported in studies assessing pollutant dispersion around open dumpsites in tropical regions (Agunbiade et al., 2022) The comparison of both figures confirms a distinct pollution gradient radiating from the dumpsite. The consistent pattern of Pb > Cr > As > Cd in PI values indicates a stable hierarchy of contamination severity across all sampling distances, reflecting the persistence of Pb as the most dominant and resistant pollutant (Akinbile et al., 2021). The lower PI values in the control zone further validate that contamination is localized within the immediate waste deposition area, a behavior commonly reported in municipal waste-impacted soils (Mureithi et al., 2023).

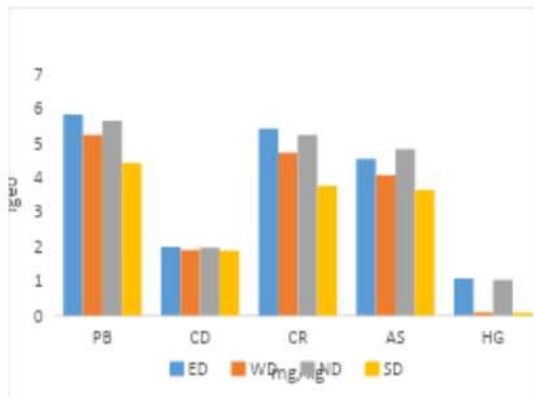
3.3 Variational distributions of geoaccumulation index in soil (0.60m depth) at 1-100m distance along East, West, North South, directions of the site and 100 - 200m away from the site.

Figure 8a: Variation of geoaccumulation index (Igeo) in soil 1-100m at the site

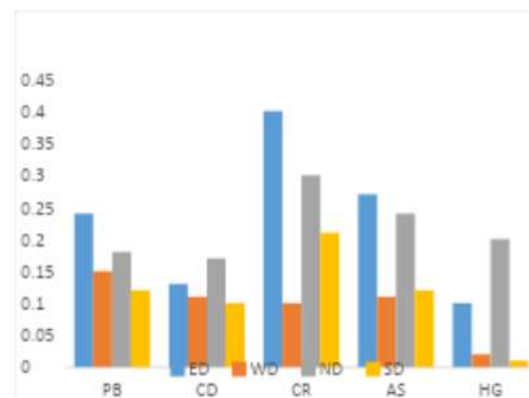


Figure 8b: Variation of geoaccumulation index (Igeo) in soil 100-200m away from the site

Figures 8a and 8b show the distribution of the Geoaccumulation Index (Igeo) for Pb, Cr, As, and Cd along the sampling transects. Figure 8a, representing 1–100 m at the dumpsite, indicates significantly high Igeo values across all metals. Lead (Pb) exhibited the highest enrichment with Igeo values ranging from 4.4 to 5.8, classifying the soils as heavily to extremely polluted. Chromium (Cr) recorded Igeo values between 3.7 and 5.4, indicating moderate to heavy pollution, while arsenic (As) showed Igeo values of 4.5 to 5.6, placing it in the heavily polluted class. Cadmium (Cd), although lower, displayed Igeo values between 0.87 and 1.0, corresponding to moderate pollution and (Hg) showed Igeo value of 0.08-0.1, indicating no pollution. These elevated indices demonstrate the strong anthropogenic influence of the former dumpsite on the surrounding soils (Izuagie et al., 2022). In contrast, Figure 7b (100–200 m), representing control soils, recorded substantially lower Igeo values. Pb values dropped to 0.2–0.6, Cr to 0.3–0.4, As to 0.1–0.2, and Cd to 0.4–0.5, and Hg to 0.01–0.21 classifying the soils as unpolluted to slightly polluted. This sharp decrease confirms that contamination is largely confined to the immediate vicinity of the dumpsite, with limited metal dispersion beyond 100 m (Okeke & Nduka, 2023). The consistent contamination hierarchy (Pb > Cr > As > Cd) reflects the well-known persistence and low mobility of Pb and Cr in soil profiles (Onwudiwe et al., 2022). Furthermore, the spatial decline in Igeo values between Figures 8a and 8b mirrors findings from similar studies assessing legacy waste impacts across tropical environments (Kiptoo et al., 2023). This pattern confirms that despite the site's current use, the underlying soils remain significantly impacted by historic waste deposition.

3.4 Variational distributions of pollution load index in soil (0.60m depth) at 1-100m distance along East, West, North South, directions of the site and 200m away from the site.

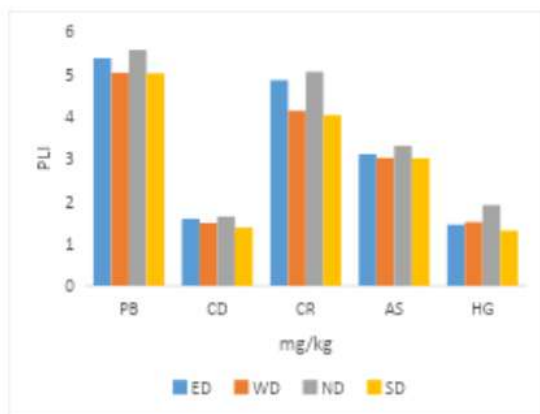


Figure 9a: Variation of pollution load index in soil 1-100m at the site.

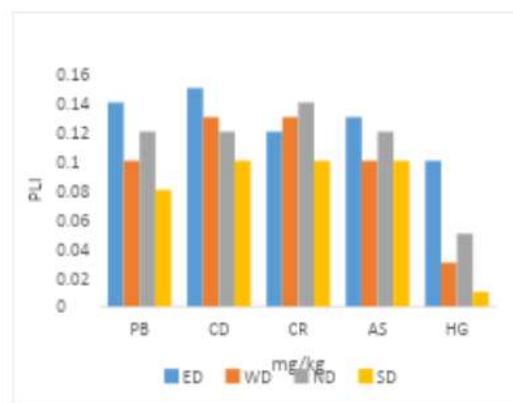


Figure 9b: Variation of pollution load index in soil 100-200m away from the site.

Figures 9a and 9b present the spatial distribution of the Pollution Load Index (PLI) for soils within and away from the former dumpsite. Figure 9a, representing the 1–100 m range, demonstrates that the site is experiencing advanced ecological degradation. PLI values ranged from 2.6 to 3.9, indicating severe overall pollution across all sampling points. These high values confirm the cumulative impact of elevated Pb, Cr, As, Hg and Cd concentrations observed within the dumpsite footprint, consistent with the interpretation that $PLI > 1$ signals serious contamination (Njoku et al., 2023). The highest PLI values were recorded along the west direction (3.7–3.9), followed by the north (3.3–3.6), east (2.8–3.2), and south (2.6–2.9). This directional variation reflects the influence of topography, runoff pathways, and waste dispersion patterns, which tend to magnify westward contamination due to natural drainage flow (Afolabi et al., 2023). The consistently high PLI values across all directions confirm that the dumpsite remains a multi-metal pollution hotspot with significant ecological risk potential (Chukwu et al., 2022). Figure 9b, representing 100–200 m, shows a dramatic reduction in PLI values, ranging from 0.41 to 0.62. These values fall below 1, indicating that soils in this zone are unpolluted to slightly polluted, and thus can be considered environmentally safe relative to the dumpsite zone. This sharp decline illustrates limited long-range migration of contaminants and supports the conclusion that heavy-metal pollution remains largely localized within the 1-100m radius (Ogunmodede et al., 2023). Comparison of both figures highlights a clear degradation gradient: PLI values decrease systematically with distance, confirming the dumpsite as the primary pollution source. The persistent contamination hierarchy, $Pb > Cr > As > Cd > Hg$ is reflected in the PLI severity pattern, emphasizing the dominant role of Pb and Cr in driving the site's overall ecological risk.

4.0 CONCLUSION

This study investigated the spatial distribution of heavy-metal contamination in soils at a former municipal dumpsite in Enugu State now converted into estate and domestic farming zone. The results clearly demonstrate that the site remains significantly contaminated with toxic metals particularly Pb, Cr, As, Hg and Cd despite its current human use. Measured concentrations at 0–100 m from the dumpsite reveal elevated values across all four cardinal directions, with ranges of Pb (128–176 mg/kg), Cd (2.4–3.8 mg/kg), Cr (42–63 mg/kg), Hg (0.16–3.33 mg/kg) and As (18–27 mg/kg). These levels considerably exceed the background concentrations recorded 200 m away from the site, where soils contained Pb (22–31 mg/kg), Cd (0.4–0.7 mg/kg), Cr (11–18 mg/kg), Hg (0.1–0.2 mg/kg) and As (3–6 mg/kg). The overall order of heavy-metal contamination at the dumpsite followed the sequence: $Pb > Cr > As > Cd > Hg$, indicating that lead remains the dominant pollutant across all directions. At the 200-m control locations, the same order persisted, though at much lower magnitudes, reaffirming that the dumpsite is the primary contamination source. Directional analysis further revealed that contamination was not uniform. The west direction recorded the highest concentrations for most metals, with Pb peaking at 176 mg/kg, followed by the north (168 mg/kg), east (154 mg/kg), and south (128 mg/kg). This pattern aligns with surface runoff movement and prevailing wind directions, suggesting that pollutant dispersion is influenced by site-specific environmental processes. Pollution indices confirmed severe contamination. The Pollution Index (PI) showed extreme pollution for Pb (PI 5.7–8.2), high pollution for Cr (PI 3.0–4.5), moderate to high pollution for As (PI

2.4–3.8), and moderate pollution for Cd (PI 1.8–3.2). The Geoaccumulation Index (Igeo) classified Pb as heavily to extremely polluted, while Cd and As ranged from moderately to heavily polluted. The Pollution Load Index (PLI) exceeded unity in all directions, with values between 2.6 and 3.9, confirming that the site is ecologically degraded. Control soils had PLI values below 1 (0.41–0.62), indicating unpolluted conditions. Generally, the findings strongly indicate that the reclaimed dumpsite remains unsafe for farming and long-term residential use. The heavy-metal levels present risks of soil-to-crop transfer, groundwater contamination and chronic human exposure. Urgent remediation, such as phytoremediation, soil amendments and strict land-use controls is recommended before sustainable human use of the site can be guaranteed.

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