Heavy Metal Concentrations and Ecological and Human Health Risks in Soils Around Osubi and Aladja Waste Dumpsites, Delta State, Nigeria

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Abstract
Open dumping of municipal solid waste can introduce potentially toxic metals into surrounding soils and may create long-term environmental and public-health concerns. This study assessed the concentrations, contamination status, ecological risk and potential human health risks of selected heavy metals in soils around active municipal waste dumpsites at Osubi (Okpe LGA) and Aladja DSC (Udu LGA), Delta State, Nigeria. Soil samples were collected using established field procedures, and cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), copper (Cu) and arsenic (As) were determined using Atomic Absorption Spectrophotometry (AAS). Soil contamination and ecological risk were assessed using the geo-accumulation index (Igeo), contamination factor (CF), degree of contamination (Cdeg), modified degree of contamination (mCd), pollution load index (PLI), ecological risk factor (Er) and potential ecological risk index (RI). Pearson correlation analysis was used to examine relationships among the metals, while non-carcinogenic and carcinogenic risks for adults and children were estimated using the hazard quotient (HQ), hazard index (HI) and lifetime cancer risk (LCR). Nickel and arsenic recorded the highest mean concentrations, whereas cadmium had the lowest. Copper and chromium showed a statistically significant positive correlation ($r = 0.534$, $p = 0.049$), suggesting a possible common source or similar behaviour in the soil. Although some localized enrichment was observed, particularly for lead and nickel, all Igeo values were negative and classified the soils as practically uncontaminated. The combined contamination and ecological-risk indices also indicated low contamination and low ecological risk. Based on the reported concentrations, HQ and HI values were below 1 for both adults and children, while the estimated cancer risks were below the stated negligible-risk level. Nevertheless, the continued occurrence of arsenic and nickel indicates the need for preventive monitoring and improved waste-management practices. The study recommends routine soil monitoring, improved waste segregation and recycling, engineered landfill development, and stronger enforcement of environmental regulations around the dumpsites.

Keywords: *Soil contamination; Heavy metals; Municipal solid waste dumpsites; Pollution indices; Ecological risk; Human health risk.*

Introduction

Open dumping remains a common method of municipal solid-waste disposal in many Nigerian communities. Household refuse, market waste, scrap metal, used batteries and other discarded materials are frequently deposited together on bare ground. As waste decomposes and rainfall infiltrates the waste mass, a liquid known as leachate is generated and can migrate into the underlying soil (Kjeldsen et al., 2002). Soil is therefore one of the first environmental compartments exposed to contaminants released from poorly managed waste dumps. Heavy metals are of particular concern because, unlike many organic pollutants, they do not readily degrade. They can bind to clay minerals, organic matter and iron oxides and may remain in soil for long periods (Alloway, 2013; Wuana & Okieimen, 2011). Depending on soil conditions, metals may be retained near the surface, taken up by plants, transported as dust, ingested through direct soil contact, or mobilised into groundwater. Previous studies of dumpsite-affected soils in Nigeria have reported enrichment of metals such as lead, cadmium, copper and nickel (Anikwe & Nwobodo, 2002; Essien et al., 2019; Omoboriowo, 2018).

The Warri–Effurun area of Delta State is a major commercial and industrial centre, and municipal waste from the surrounding communities is disposed of at several open dumpsites, including those at Osubi and Aladja. The Osubi dumpsite is located near vehicle and machinery repair activities, while the Aladja site is close to the Delta Steel Company. Steel-making residues such as slag, dust and mill scale can contain metals and may contribute to the metal burden of wastes generated in industrial settings (Natalia et al., 2015). The surrounding terrain is generally flat and sandy, with agricultural activities occurring in nearby areas. An earlier investigation reported heavy-metal contamination at the Osubi dumpsite (Okumoko & Izeze, 2020), but recent comparative information covering both Osubi and Aladja, including topsoil and subsoil and associated ecological and human-health risk indices, remains limited. The objectives of this study were to: (i) determine the concentrations of Cu, Cr, Cd, Pb, As and Ni in topsoil and subsoil from the Osubi and Aladja dumpsites and a control site; (ii) assess contamination using the geo-accumulation index, contamination factor, degree of contamination, modified degree of contamination, pollution load index and potential ecological risk index; (iii) examine relationships among the metals using correlation analysis to identify possible common sources or associations; and (iv) estimate non-carcinogenic and carcinogenic risks to adults and children associated with soil exposure.

Materials and Methods

Study Area

The Osubi (Ugolo) dumpsite is located off Osubi Road, Effurun, in Okpe LGA (approximately 5°34.6′N, 5°48.1′E), while the Aladja dumpsite is located near the Delta Steel Company in Udu LGA (approximately 5°28.4′N, 5°45.9′E). Each study area covers approximately 100 m × 100 m. Both sites receive mixed municipal waste from the Warri metropolitan area. According to the 2006 census, Okpe and Udu LGAs had a combined population of approximately 312,000 (NPC, 2006). The sites are situated on the Niger Delta plain and are underlain by loose Quaternary sands associated with the Benin Formation. The terrain is relatively flat, generally less than 20 m above sea level, and characterised by high rainfall and permeable sandy soils (Abam & Nwankwoala, 2020; Ekwok et al., 2024).

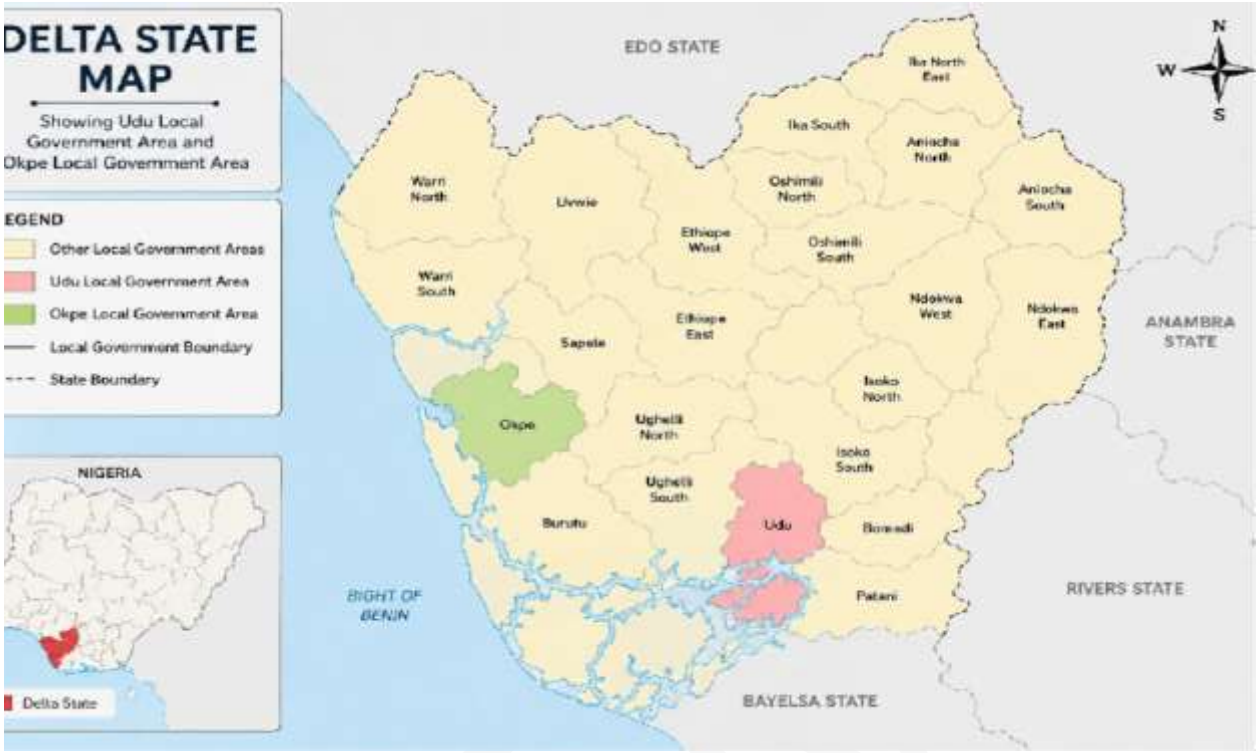


Figure 1: Delta State Showing LGA'S

Field Investigation and Sampling Collection

Sampling locations were selected to provide coverage of the study areas. Soil sampling was undertaken during the rainy season between September and October 2025. Samples were collected from designated locations within the Osubi and Aladja study areas, and geographic coordinates were recorded using a Garmin Global Positioning System (GPS) device. Fourteen soil samples were included in the final dataset.



Figure 2: Sample collection points at Aladja study area Udu LGA Delta State.

The sample-density classification approach described by Salminen (2008) was adopted as a guide for field sampling. The approach is applicable to environmental and geochemical investigations and recognises that sampling density should be sufficient to capture the spatial

variation of the contaminants under investigation.

Soil Sample Collection

A regular grid-based sampling network was used to obtain representative soil samples across the study areas. The base map was divided into square grid cells, and each cell was assigned an alphanumeric code for field identification and subsequent laboratory sample tracking.

Soil samples were collected at a depth of 15 cm using a clean stainless-steel soil auger. The auger was washed and rinsed with distilled water after each sampling operation to minimise cross-contamination. Samples were collected from the centre and edges of the designated grids and thoroughly mixed where composite sampling was required. The prepared samples were placed in clearly labelled polyethylene sample bags for laboratory analysis. Samples from both the Osubi and Aladja dumpsites, together with the control samples, were handled using metal-free collection containers and polyethylene bags to minimise contamination.



Figure 3: Soil sampling collection using Soil Auger

Laboratory Analysis of Soil Samples

Determination of Heavy Metals in Soil

The target metals analysed in the soil samples were cadmium, lead, chromium, arsenic, nickel and copper, as reported in the results tables. Heavy metals were extracted using a wet-oxidation digestion procedure. Soil samples were first air-dried at room temperature, gently disaggregated using a ceramic pestle and mortar, and sieved through a 2 mm mesh to remove

coarse materials and debris. Approximately 5 g of the dried soil was further ground and homogenised using an agate mortar, after which about 2 g was transferred into a 250 cm^3 acid-washed conical flask. The sample was digested using an acid mixture containing hydrofluoric acid (HF), hydrochloric acid (HCl) and nitric acid (HNO_3) in a 1:3:1 ratio. The digestion was carried out initially at room temperature and then continued on a hot plate in a fume cupboard at approximately 400 °C until digestion was complete. After cooling, the digest was filtered through Whatman No. 1 filter paper into a 50 mL volumetric flask, and the filtrate was stored in polyethylene bottles pending analysis. The same procedure was applied to blanks. Atomic Absorption Spectrophotometry (AAS) was used for the determination of the target metals. Sample solutions, standards and blanks were aspirated into the air–acetylene flame of a Varian Spectra Model 220 Fast Sequential AAS using the appropriate hollow cathode lamps for each metal. Samples were analysed in duplicate. Instrument calibration was checked in accordance with the manufacturer's specifications, and standard reference materials and blanks were included in each analytical batch as part of the quality assurance and quality control (QA/QC) procedures. Contact with metallic surfaces was avoided during sample handling to minimise the possibility of contamination.

Determination of Physical Properties of Soil

Selected physical properties of the soil, including moisture content, particle-size characteristics, bulk density, porosity, specific gravity and consistency limits, were determined to characterise the soils from the Osubi and Aladja dumpsites and the control site. Standard laboratory procedures based on ASTM D2216 and ASTM D422 were adopted, and tests were performed in triplicate where applicable to improve reproducibility.

Moisture content was determined by the oven-drying method. Approximately 30 g of fresh soil was weighed into a clean, pre-weighed moisture can and dried in a hot-air oven at 105 °C ± 5 °C for 24 hours, or until a constant weight was obtained. After cooling in a desiccator, the dry mass was recorded. Moisture content was calculated as the mass of water lost relative to the mass of dry soil, expressed as a percentage. Particle-size analysis was performed using a combination of dry sieving and hydrometer methods. A 500 g oven-dried soil sample was mechanically sieved through a nest of sieves ranging from 4.75 mm to 75 µm. For the fraction passing the 75 µm sieve, 50 g was dispersed in sodium hexametaphosphate solution and analysed by hydrometer at specified time intervals. The proportions of sand, silt and clay were determined, and the results were plotted on a particle-size distribution curve and classified using the USDA soil-texture classification system.

Bulk density was determined using the core-cutter method. An undisturbed soil core was collected using a cylindrical cutter of known volume. The core was trimmed, weighed and oven-dried to determine its dry mass. Bulk density was calculated as dry soil mass per unit volume. Porosity and void ratio were subsequently calculated from bulk density and specific gravity using standard equations. The specific gravity of the soil solids was determined using the pycnometer method. A known mass of oven-dried soil was placed in a calibrated pycnometer and filled with distilled water. The masses of the pycnometer containing the soil and water, and the pycnometer containing water alone, were recorded. Specific gravity was calculated from the mass of soil solids and the equivalent volume of water.

For the fine-grained fraction, the liquid limit was determined using the Casagrande apparatus, while the plastic limit was determined by rolling soil into threads of approximately 3 mm diameter until the threads crumbled. The plasticity index was calculated as the difference between the liquid limit and plastic limit. Plate 3.2 shows the researcher during laboratory air-drying of the samples.

Results

Metal concentrations

Nickel and arsenic recorded the highest mean concentrations in the soil samples, while cadmium had the lowest. Across the 14 samples, the mean concentrations followed the order Ni (0.043 mg/kg) > As (0.041 mg/kg) > Pb (0.034 mg/kg) > Cr (0.017 mg/kg) > Cu (0.016 mg/kg) > Cd (0.0005 mg/kg). Cadmium was below the detection limit in eight of the 14 samples. Lead showed the greatest variability, with a standard deviation of 0.042 mg/kg and concentrations ranging from not detected to 0.154 mg/kg at Osubi L2 topsoil.

Table 3. Heavy metal concentrations (mg/kg) in soils

Site / location / depth	Cu	Cr	Cd	Pb	As	Ni
Osubi L1, topsoil	0.0079	0.0069	ND	0.0260	0.0227	0.0200
Osubi L2, topsoil	0.0261	0.0074	ND	0.1543	0.0253	0.0230
Osubi L3, topsoil	0.0251	0.0052	ND	0.0870	0.0923	0.0220
Osubi L4, topsoil	0.0099	0.0063	ND	0.0233	0.0285	0.0300
Osubi L1, subsoil	0.0105	0.0035	ND	0.0201	0.0162	0.0303
Osubi L5, subsoil	0.0213	0.0082	0.0006	0.0251	0.0223	0.0602
Aladja L1, topsoil	0.0244	0.0489	0.0009	0.0242	0.0244	0.0722
Aladja L2, topsoil	0.0069	0.0124	ND	ND	0.0246	0.0200
Aladja L6, topsoil	0.0164	0.0138	ND	0.0079	0.0733	0.0922
Aladja L1, subsoil	0.0325	0.0599	0.0008	0.0239	0.0233	0.0632
Aladja L2, subsoil	0.0027	0.0097	ND	ND	0.0902	0.0233
Aladja L6, subsoil	0.0204	0.0148	0.0014	0.0067	0.0324	0.0723
Control, topsoil	0.0080	0.0188	ND	0.0092	0.0222	0.0500
Control, subsoil	0.0128	0.0213	0.0028	0.0670	0.0822	0.0234
Mean (n = 14)	0.0161	0.0169	0.0005	0.0339	0.0414	0.0430
SD	0.0090	0.0168	0.0008	0.0424	0.0288	0.0246
Average shale (Turekian & Wedepohl, 1961)	45	90	0.3	20	13	68

ND = not detected.

The two dumpsites showed distinct metal profiles (Table 4). Mean chromium concentration at Aladja (0.0266 mg/kg) was approximately four times the Osubi value (0.0062 mg/kg), while mean nickel was almost twice as high at Aladja (0.0572 mg/kg) as at Osubi (0.0309 mg/kg). In contrast, mean lead was substantially higher at Osubi (0.0560 mg/kg) than at Aladja (0.0105 mg/kg). Copper concentrations were similar at the two sites. Across the dumpsite samples, lead was higher in topsoil than subsoil, whereas chromium, cadmium and nickel were slightly higher in subsoil. The two control samples did not consistently show lower concentrations than the dumpsite samples; the control subsoil contributed to relatively high arsenic, lead and cadmium values.

Table 4. Mean metal concentrations (mg/kg) by site and depth

Group	N	Cu	Cr	Cd	Pb	As	Ni
Osubi dumpsite	6	0.0168	0.0062	0.0001	0.0560	0.0346	0.0309
Aladja dumpsite	6	0.0172	0.0266	0.0005	0.0105	0.0447	0.0572
Control	2	0.0104	0.0200	0.0014	0.0381	0.0522	0.0367
Dumpsite topsoil	7	0.0167	0.0144	0.0001	0.0461	0.0416	0.0399
Dumpsite subsoil	5	0.0175	0.0192	0.0006	0.0152	0.0369	0.0499

Geo-accumulation index

All calculated Igeo values were negative, ranging from −7.33 to −15.24 (Table 5). On the basis of the adopted classification, the soils fall within Class 0 (practically uncontaminated) for the six metals. The least negative values were recorded for cadmium in the control subsoil (−7.33), lead at Osubi L2 topsoil (−7.60), and arsenic at Osubi L3 topsoil (−7.72) and Aladja L2 subsoil (−7.76).

Table 5. Geo-accumulation index (Igeo) of metals in soils

Site / location / depth	Cu	Cr	Cd	Pb	As	Ni
Osubi L1, topsoil	−13.06	−14.26	BDL	−10.17	−9.75	−12.32
Osubi L2, topsoil	−11.34	−14.16	BDL	−7.60	−9.59	−12.11
Osubi L3, topsoil	−11.39	−14.66	BDL	−8.43	−7.72	−12.18
Osubi L4, topsoil	−12.74	−14.39	BDL	−10.33	−9.42	−11.73
Osubi L1, subsoil	−12.65	−15.24	BDL	−10.54	−10.23	−11.72
Osubi L5, subsoil	−11.63	−14.01	−9.55	−10.22	−9.77	−10.73
Aladja L1, topsoil	−11.43	−11.43	−8.97	−10.28	−9.64	−10.46
Aladja L2, topsoil	−13.26	−13.41	BDL	BDL	−9.63	−12.32
Aladja L6, topsoil	−12.01	−13.26	BDL	−11.89	−8.06	−10.11
Aladja L1, subsoil	−11.02	−11.14	−9.14	−10.29	−9.71	−10.66
Aladja L2, subsoil	−14.61	−13.76	BDL	BDL	−7.76	−12.10
Aladja L6, subsoil	−11.69	−13.16	−8.33	−12.13	−9.23	−10.46
Control, topsoil	−13.04	−12.81	BDL	−11.67	−9.78	−10.99
Control, subsoil	−12.36	−12.63	−7.33	−8.81	−7.89	−12.09

BDL = metal below detection limit; Igeo not calculated.

Contamination factor, pollution load and ecological risk

The other contamination and ecological-risk indices also indicated low levels of contamination (Table 6). The CF values were all well below 1, with the highest recorded for arsenic at Aladja (3.4×10^{-3}). The degree of contamination ranged from 0.0067 to 0.0116, while the modified degree of contamination ranged from 0.0011 to 0.0019. PLI values were below 0.001, and the potential ecological risk index (RI) ranged from 0.055 at Osubi to 0.194 at the control site, remaining within the low-risk category. Cadmium and arsenic made the largest relative contributions to ecological risk because of their higher toxic-response factors.

Table 6. Contamination factor (CF), ecological risk factor (E_r) and combined indices

Index	Osubi	Aladja	All dumpsite	Control
CF Cu	3.7×10^{-4}	3.8×10^{-4}	3.8×10^{-4}	2.3×10^{-4}
CF Cr	6.9×10^{-5}	3.0×10^{-4}	1.8×10^{-4}	2.2×10^{-4}
CF Cd	3.3×10^{-4}	1.7×10^{-3}	1.0×10^{-3}	4.7×10^{-3}
CF Pb	2.8×10^{-3}	5.2×10^{-4}	1.7×10^{-3}	1.9×10^{-3}
CF As	2.7×10^{-3}	3.4×10^{-3}	3.0×10^{-3}	4.0×10^{-3}
CF Ni	4.5×10^{-4}	8.4×10^{-4}	6.5×10^{-4}	5.4×10^{-4}
Degree of contamination (Cdeg)	0.0067	0.0072	0.0069	0.0116
Modified degree of contamination (mCd)	0.0011	0.0012	0.0012	0.0019
Pollution load index (PLI)	5.5×10^{-4}	8.2×10^{-4}	7.8×10^{-4}	1.0×10^{-3}
E_r Cd	0.010	0.052	0.031	0.141
E_r As	0.027	0.034	0.030	0.040
Potential ecological risk index (RI)	0.055	0.095	0.075	0.194
Class	Low	Low	Low	Low

Correlation between metals

Copper and chromium were the only metal pair showing a statistically significant positive correlation ($r = 0.534$, $p = 0.049$; Table 7). Positive but non-significant relationships were observed for Cr–Ni ($r = 0.480$), Cu–Pb ($r = 0.472$), Cu–Ni ($r = 0.432$) and Cr–Cd ($r = 0.378$). Lead and nickel showed a weak negative correlation ($r = -0.377$), which is consistent with the different spatial patterns observed at Osubi and Aladja. Arsenic did not show a clear relationship with the other metals.

Table 7. Pearson correlation matrix of metals in soils (n = 14)

Metal	Cu	Cr	Cd	Pb	As	Ni
Cu	1					
Cr	0.534*	1				
Cd	0.219	0.378	1			
Pb	0.472	−0.153	0.073	1		
As	−0.111	−0.183	0.198	0.130	1	
Ni	0.432	0.480	0.149	−0.377	−0.133	1

*Significant at $p < 0.05$ (two-tailed).

Human health risk

Based on the measured concentrations, estimated health risks associated with soil contact were low for both adults and children (Tables 8 and 9). The total hazard index was 3.8×10^{-4} for adults and 2.1×10^{-3} for children, both well below the reference value of 1. Arsenic contributed the largest share of the total HI in both groups. The children's HI was approximately six times the adult value, reflecting the greater relative exposure associated

with soil ingestion during childhood. The total estimated lifetime cancer risk was 3.3×10^{-8} for adults and 7.8×10^{-8} for children, both below the stated negligible-risk level of 10^{-6}.

Table 8. Hazard quotients (HQ) and hazard index (HI) from soil (mean of all samples)

Metal	Adult HQ ing.	Adult HQ derm.	Adult HI	Child HQ ing.	Child HQ derm.	Child HI
Cu	5.5×10^{-7}	2.1×10^{-8}	5.7×10^{-7}	5.1×10^{-6}	1.7×10^{-8}	5.2×10^{-6}
Cr	7.7×10^{-6}	4.4×10^{-6}	1.2×10^{-5}	7.2×10^{-5}	3.5×10^{-6}	7.6×10^{-5}
Cd	6.4×10^{-7}	7.3×10^{-7}	1.4×10^{-6}	5.9×10^{-6}	5.8×10^{-7}	6.5×10^{-6}
Pb	1.3×10^{-5}	1.0×10^{-6}	1.4×10^{-5}	1.2×10^{-4}	8.1×10^{-7}	1.3×10^{-4}
As	1.9×10^{-4}	1.6×10^{-4}	3.5×10^{-4}	1.8×10^{-3}	1.3×10^{-4}	1.9×10^{-3}
Ni	3.0×10^{-6}	1.2×10^{-7}	3.1×10^{-6}	2.8×10^{-5}	1.0×10^{-7}	2.8×10^{-5}
Total			3.8×10^{-4}			2.1×10^{-3}

ing. = ingestion; derm. = dermal contact. HI < 1 means no significant non-cancer risk.

Table 9. Lifetime cancer risk (LCR) from soil ingestion

Metal	Adult	Child
Cr	4.0×10^{-9}	9.3×10^{-9}
Cd	8.3×10^{-11}	1.9×10^{-10}
Pb	1.4×10^{-10}	3.2×10^{-10}
As	2.9×10^{-8}	6.8×10^{-8}
Total	3.3×10^{-8}	7.8×10^{-8}

LCR < 1×10^{-6} is considered negligible.

Discussion

The metal concentrations measured in this study were low in absolute terms and considerably lower than values reported in several other dumpsite and landfill studies. Rezapour et al. (2018), for example, reported 35–67 mg/kg copper and 54–95 mg/kg lead in soils affected by landfill leachate, while Ahmad et al. (2021) reported 73.8 mg/kg copper and 57.9 mg/kg chromium in soils near a landfill in Punjab, Pakistan. Beinabaj et al. (2023) reported 0.86 mg/kg copper and 1.02 mg/kg lead in soils around a Tehran landfill. The mean concentrations measured in the present study are substantially lower than those reported in these investigations. Several factors may help explain the relatively low concentrations observed. The dumpsites appear to receive predominantly municipal household waste, while the surrounding soils are sandy and relatively well drained. High rainfall in the Niger Delta may promote downward movement of dissolved constituents rather than their retention in surface soil (Abam & Nwankwoala, 2020). Sandy soils also generally provide fewer clay and organic surfaces for strong metal retention than finer-grained soils (Alloway, 2013).

However, these factors do not fully explain the magnitude of the reported concentrations. All samples, including the control, were well below the average shale values used for comparison (Turekian & Wedepohl, 1961). This raises an important analytical consideration: incomplete digestion, recovery effects or a unit-conversion issue could potentially contribute to the unusually low absolute values. The concentrations should therefore be interpreted cautiously,

particularly when comparing them with regional background values. The relative differences among sites, depths and metals remain useful for identifying patterns within the present dataset, but the absolute concentrations would benefit from confirmation through independent analytical quality checks.

Different signatures at the two dumps

The two sites showed different metal profiles that are broadly consistent with their surrounding land-use settings. Aladja recorded higher chromium and nickel concentrations. Both elements are associated with steel production and alloy manufacture, and steel slag, dust and mill scale from industrial activities may contribute metals to the local waste stream (Natalia et al., 2015). Osubi, in contrast, recorded higher lead concentrations. Its proximity to a vehicle and machinery repair area provides plausible sources such as spent lead-acid batteries, used lubricating oils and old paint (Wuana & Okieimen, 2011). These source interpretations should, however, be regarded as plausible explanations rather than confirmed source apportionment. Lead concentrations were approximately three times higher in dumpsite topsoil than in subsoil. Lead commonly has a strong affinity for organic matter and iron oxides and can therefore be retained near the soil surface (Alloway, 2013). The relatively high value at Osubi L2 topsoil (0.154 mg/kg) may represent a localized input rather than a uniform condition across the site. Chromium, nickel and cadmium were slightly higher in the subsoil, suggesting that some downward redistribution may occur; however, the present dataset does not by itself establish the mechanisms responsible for vertical movement.

What the correlations suggest

The significant positive relationship between copper and chromium suggests that the two metals may have a common source or may respond similarly to the same soil processes. The weaker positive relationships involving chromium and nickel are also consistent with some degree of shared source or behavior. The weak negative relationship between lead and nickel largely reflects the contrasting site patterns, with lead higher at Osubi and nickel higher at Aladja. Arsenic showed no clear correlation with the other metals, indicating that its distribution may be controlled by a different source or by different geochemical processes. Correlation alone, however, cannot establish a definitive source.

Pollution indices

The pollution indices consistently indicated low measured contamination and low ecological risk. Igeo values were strongly negative, while CF, Cdeg, mCd, PLI and RI remained within their lowest categories. Other studies using similar indices have reported considerably higher contamination levels. For example, Chonokhuu et al. (2019) reported PLI values of 0.94–1.83 in urban soils in Mongolia, while Ahmad et al. (2021) reported Igeo values corresponding to moderate to heavy contamination around a landfill in Pakistan. It is important to recognize that these indices depend on the measured concentrations and selected background values. Consequently, the indices support the low values observed in this dataset but do not provide an independent check on the analytical measurements. Cadmium and arsenic contributed relatively more to the calculated ecological risk because their toxic-response factors are higher than those assigned to several of the other metals considered (Håkanson, 1980; Ali et al., 2019). Their contribution therefore reflects both their measured concentrations and the weighting built into the ecological-risk methodology.

Human health risk

Using the measured concentrations, estimated soil-exposure risks were low for both adults

and children. The children's HI was about six times the adult value, which is consistent with the greater relative exposure of children to soil through ingestion and their lower body weight (Chonokhuu et al., 2019). Arsenic was the principal contributor to both non-carcinogenic and carcinogenic risk estimates. Because the risk calculations are directly dependent on the measured concentrations, confirmation of the unusually low analytical values would strengthen confidence in the resulting risk estimates.

Conclusion

The soils sampled at the Osubi and Aladja dumpsites contained low measured concentrations of copper, chromium, cadmium, lead, arsenic and nickel. The geo-accumulation, contamination, pollution-load and ecological-risk indices consistently classified the soils within their lowest reported categories, while the estimated non-carcinogenic and carcinogenic risks were below the stated reference levels for both adults and children. The two dumpsites nevertheless showed different metal patterns: chromium and nickel were higher at Aladja, while lead was higher at Osubi. Lead was more concentrated in topsoil, and copper and chromium showed a significant positive correlation. Overall, the results indicate low measured contamination at the time of sampling, but continued monitoring remains necessary because waste inputs, rainfall and site conditions can change the distribution of metals over time.

Recommendations

i. The Delta State Ministry of Environment should establish a routine monitoring program for physicochemical properties and heavy metals in soils around active dumpsites. Monitoring should be repeated at defined intervals to identify changes in contaminant concentrations throughout the operational life of the sites.

ii. Open dumping should progressively be replaced with engineered landfill facilities designed with appropriate liners and leachate-collection and management systems to reduce the release and accumulation of contaminants in surrounding soils.

iii. Source separation of municipal waste should be strengthened to reduce the amount of potentially hazardous materials entering dumpsites. Recycling, reuse and material-recovery programmes should also be expanded to reduce the volume of waste requiring final disposal.

iv. Agricultural activities and children's play should be discouraged on and immediately around active dumpsites, particularly in areas where localised lead enrichment has been identified.

v. Environmental regulatory agencies, including the relevant state environmental authorities and the Delta State Waste Management Board (DSWMB), should strengthen inspection, monitoring and enforcement of applicable waste-management requirements and environmental standards.

vi. Local governments and community organisations should sustain public-awareness programmes on proper waste disposal, environmental sanitation, groundwater protection and the potential environmental and health consequences of indiscriminate dumping.

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