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Assessment of Selected Environmental Soil Contaminants in Relation to Industrial and Urban Activities in South-West Nigeria

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Abstract. Rapid industrialization and urbanization in South-West Nigeria have intensified environmental pressures, leading to significant soil contamination. This study assessed the concentrations and associated risks of selected heavy metals (Pb, Cd, Cr) and plastic-derived organic pollutants (Polybrominated Diphenyl Ethers, PBDEs; Phthalate Esters, PAEs) in soils from four major landfill sites in Lagos and Ogun States. Results revealed significant heavy metal contamination, particularly at the Olusosun landfill, which exhibited the highest Cadmium (Cd) concentration (3.63 ± 0.45 mg/kg). Phthalate Esters (PAEs) were prevalent across all sites, with Di(2-ethylhexyl) phthalate (DEHP) being the most abundant congener, reaching a maximum concentration of 17.7 ± 2.1 mg/kg at Olusosun. Ikorodu also showed high levels of DEHP (11.3 ± 1.5 mg/kg) and Dicyclohexyl phthalate (DCHP) (11.28 ± 1.4 mg/kg). In contrast, concentrations of the analyzed PBDEs were generally low, with the highest level detected for BDE-153 at Olusosun (0.020 mg/kg). Ecological risk assessment indicated a "considerable potential ecological risk" (Individual Risk Factor, E_r = 110.18) from Cd at the Olusosun site, primarily linked to e-waste and battery disposal. Furthermore, the Hazard Index (HI) for phthalates exceeded the safe threshold (HI > 1) at all sites, with particularly high values at Ikorodu and Sango, indicating a significant non-carcinogenic health risk to exposed populations. These findings highlight Olusosun as a hotspot for Cd pollution and reveal widespread health risks from PAEs, underscoring the urgent need for improved waste segregation, engineered landfill management, and robust environmental monitoring to mitigate pollution and protect public health in the region.

Keywords: Soil Contamination, Polybrominated Diphenyl Ethers (PBDEs), Phthalate Esters (PAEs), Heavy Metals, Industrial Pollution, Urbanization, E-waste, South-West Nigeria.

1. Introduction

Soil, a vital natural resource, faces increasing threats from contamination, which can compromise ecosystem health and human well-being. The accumulation of pollutants in soil and sediment predominantly originates from anthropogenic activities, including mismanagement of natural resources, inefficient agricultural practices, and improper waste disposal (Shit et al., 2021). While agricultural activities often contribute to non-point source pollution, point sources such as industrial effluent discharge, landfill leachate, and accidental spills are major drivers of localized, high-concentration contamination. In the 21st century, the pressures of population growth, industrial expansion, and rapid urbanization have exacerbated the release of environmental pollutants, challenging the goals of sustainable development.

Industrial activities in developing nations are a significant source of soil contamination. Plastic waste, in particular, has become a critical environmental challenge, with its production and disposal escalating globally (Chen et al., 2021). The environmental impact extends beyond the physical presence of macro- and microplastics to the chemical additives used in their formulation (Olutona et al., 2017). Among these are PolybrominatedDiphenyl Ethers (PBDEs), a class of organobromine compounds used as flame retardants in electronics, furniture, and textiles (Ceresana, 2024). Since PBDEs are physically mixed with polymers rather than chemically bonded, they are prone to leaching into soil, water, and biota (de Wit, 2002; SSC et al., 2012).

Similarly, Phthalate Esters (PAEs) are widely used as plasticizers to impart flexibility to products made from polyvinyl chloride (PVC) and other resins (Staples et al., 1997). Like PBDEs, PAEs can migrate from products into the environment, leading to widespread contamination of soil and other matrices (Heudorf et al., 2007). In addition to these organic pollutants, industrial and municipal waste streams are significant sources of toxic heavy metals such as Lead (Pb), Cadmium (Cd), and Chromium (Cr), which are persistent, non-biodegradable, and pose severe health risks (Bhabananda et al., 2008; Oloruntoba et al., 2019).

In South-West Nigeria, a hub of industrial and commercial activity, contamination levels in solid matrices like soil remain inadequately characterized. This study, therefore, aims to bridge this knowledge gap by investigating the concentrations and distribution of selected PBDEs, PAEs, and heavy metals in soils from major landfill sites. The objectives were to: (1) determine the concentrations of target contaminants in soils from four landfill sites in Lagos and Ogun States; (2) evaluate the physicochemical properties of the soils and their relationship with contaminant levels; and (3) assess the potential ecological and human health risks associated with the measured contaminant levels using established environmental indices.

2. Materials and Methods

2.1. Study Area and Sample Collection

Soil samples were collected from four major dumpsites across two states in South-West Nigeria: Olusosun and Ikorodu in Lagos State, and Sango and Saje in Ogun State (Figure 1). These sites were selected based on their history of receiving a mix of municipal, commercial, and industrial waste. Olusosun is one of West Africa's largest active landfills, receiving diverse urban waste. Sango is located in a heavily industrialized zone, while Ikorodu and Saje receive significant municipal and commercial waste.

At each site, five sub-samples (0–20 cm depth) were collected from different points and combined to form a single composite sample to ensure representativeness. Samples were placed in pre-cleaned amber glass jars for organic analysis and polyethylene bags for metal and physicochemical analysis. The samples were transported to the laboratory in a cooler box, where they were air-dried, homogenized, and sieved through a 2-mm stainless-steel sieve before analysis.

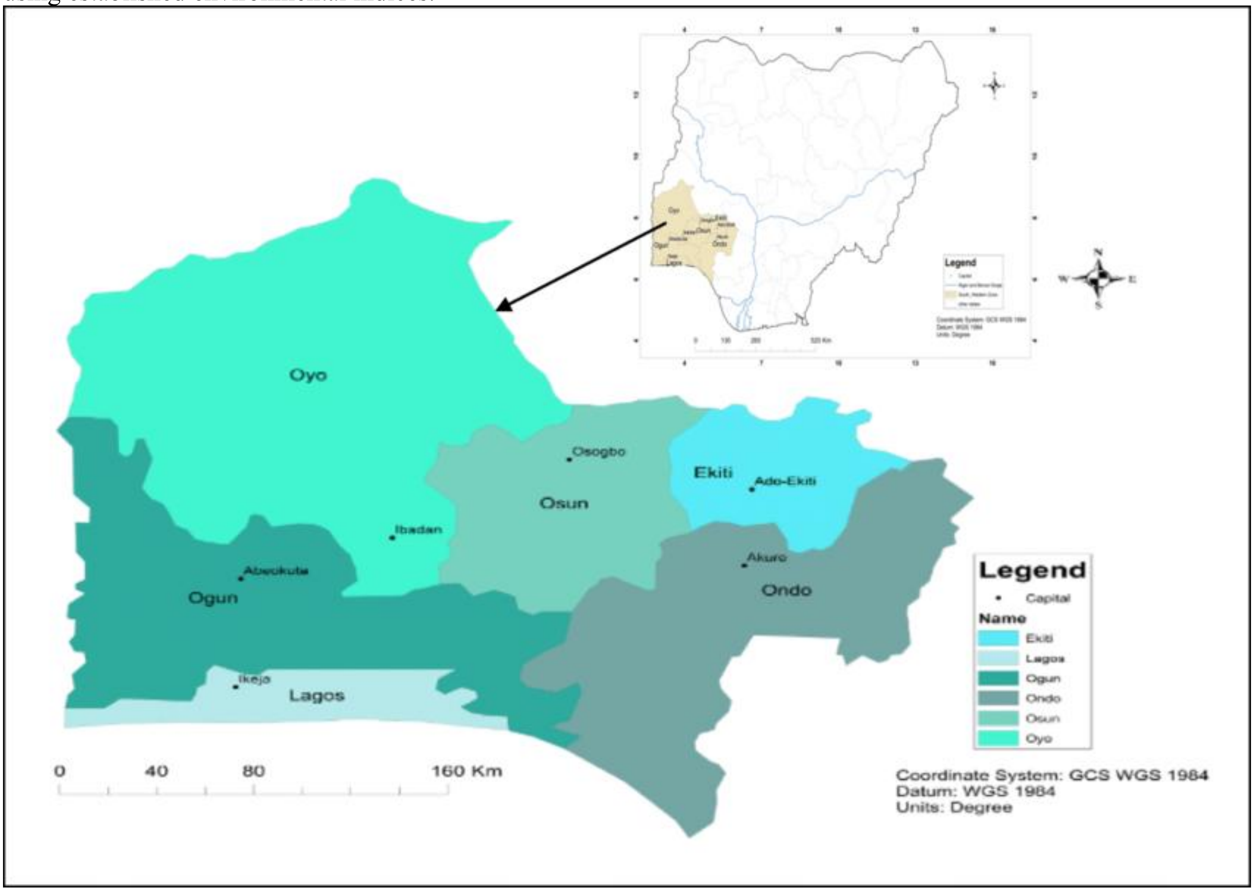

Figure 1: A map of South-West Nigeria showing the geographical coordinates of the four sampling sites: Olusosun, Ikorodu, Sango, and Saje.)

2.2 Analysis of Physicochemical Parameters

Soil pH and electrical conductivity (EC) were measured in a 1:5 soil-to-deionized water suspension using a calibrated multi-parameter probe (Hanna Instruments). Organic carbon (OC) was determined using the Walkley-Black wet oxidation method. Total nitrogen (TN) was analyzed by the Kjeldahl method. Available phosphorus (P) was extracted using the Bray-1 method and measured colorimetrically. Cation exchange capacity (CEC) was determined using the ammonium acetate method. Soil texture (sand, silt, clay content) was determined by the Bouyoucos hydrometer method.

2.3. Analysis of Heavy Metals

For metal analysis, 1.0 g of sieved soil was digested with a tri-acid mixture (10 mL HNO_3, 5 mL H_2SO_4, 5 mL $HClO_4$) at 95 ± 5°C on a hot plate until clear fumes appeared (Taiwo et al., 2016). The digestate was filtered and diluted to 50 mL with deionized water. Concentrations of Cadmium (Cd), Chromium (Cr), and Lead (Pb) were determined using a Flame Atomic Absorption Spectrophotometer (FAAS, Buck Scientific 210VGP).

2.4. Analysis of PBDEs and PAEs

A 2.0 g aliquot of dried soil was mixed with anhydrous sodium sulfate and extracted with 100 mL of hexane in a Soxhlet apparatus for 8 hours. The extract was concentrated using a rotary evaporator. Sample cleanup was performed on a silica gel column (4.0 g, activated at 130°C for 6 hours). The column was eluted with 20 mL of hexane. The final eluate was concentrated to 1 mL under a gentle stream of nitrogen.

The extracts were analyzed using an Agilent 7890B Gas Chromatograph coupled to an Agilent 5977A Mass Spectrometer (GC-MS). Separation was achieved on an HP-5MS column (30 m × 0.25 mm × 0.25 µm). The oven temperature program was initiated at 80°C, ramped to 280°C, and held for 10 min. Quantification was performed using external calibration curves of certified standards (AccuStandard, USA). For detailed instrumental parameters, see Taiwo et al. (2019).

2.5. Quality Assurance and Quality Control (QA/QC)

Procedural blanks, spiked blanks, and matrix spikes were analyzed with each batch of samples to check for contamination and determine analytical recovery. Recoveries for all target analytes were within the acceptable range of 85–115%. All concentrations were reported on a dry weight basis.

2.6. Ecological and Health Risk Assessment

Several indices were calculated to assess the extent of contamination and associated risks.
Enrichment Factor (EF): To assess anthropogenic influence.

Pollution Index (PI): Calculated as the ratio of the metal concentration in the soil to its background value.
Geo-accumulation Index (Igeo): $Igeo = \log_2(Cn / 1.5 * Bn)$, where Cn is the measured concentration and Bn is the geochemical background value.

Potential Ecological Risk Index (PERI): Calculated as the sum of the risk factors (Er) for each metal, where Er is a function of the metal's toxicity response factor.

Human Health Risk (Hazard Index, HI): The sum of hazard quotients for non-carcinogenic risk via ingestion, inhalation, and dermal contact routes was calculated for phthalates.

2.7. Statistical Analysis

Descriptive statistics, Pearson correlation analysis, and multiple linear regression were performed using SPSS Statistics (Version 25.0). A significance level of $p < 0.05$ was used for all tests.

3. Results and Discussion

3.1. Soil Physicochemical Properties
The physicochemical properties of the soils from the four dumpsites are summarized in Table 1. The soil pH was slightly acidic to neutral (6.1–7.2). Organic carbon content was highest at Olusosun (3.5%), consistent with its status as a major municipal solid waste landfill. The soil texture was predominantly sandy loam across the sites.

Table 1: Physicochemical properties of soil from four studied dumpsites.

Parameter	Unit	Olusosun	Ikorodu	Sango	Saje
pH	—	6.8 ± 0.2	6.1 ± 0.3	7.2 ± 0.1	6.5 ± 0.2
Electrical Conductivity (EC)	µS/cm	450 ± 25	210 ± 15	380 ± 20	190 ± 12
Organic Carbon (OC)	%	3.5 ± 0.4	1.8 ± 0.2	2.5 ± 0.3	1.5 ± 0.1
Total Nitrogen (TN)	%	0.28 ± 0.03	0.15 ± 0.02	0.21 ± 0.02	0.12 ± 0.01
Soil Texture					
Sand	%	65 ± 4	75 ± 5	68 ± 3	78 ± 4
Silt	%	20 ± 2	15 ± 3	18 ± 2	12 ± 2
Clay	%	15 ± 2	10 ± 2	14 ± 1	10 ± 1

Values are presented as mean ± standard deviation based on replicate samples (e.g., n=3). EC: Electrical Conductivity; OC: Organic Carbon; TN: Total Nitrogen.

3.2 Contaminant Concentrations

The concentrations of target PBDEs, heavy metals and PAEs are presented in Table 2 and Table 3 respectively

Table 2. Concentrations of selected brominated flame retardants in landfill soil samples from four Nigerian sites, determined by GC-MSD.

Analyte	Abbreviation	Ikorodu Landfill	Sango Ota	Olusosun	Saje
PolybrominatedDiphenyl Ethers (PBDEs)					
2,2',4,4'-Tetrabromodiphenyl ether	BDE-47	ND[a]	ND	0.001[b]	ND
2,2',4,4',5-Pentabromodiphenyl ether	BDE-99	0.009	ND	ND	ND
2,2',4,4',6-Pentabromodiphenyl ether	BDE-100	ND	ND	ND	ND
2,2',4,4',5,5'-Hexabromodiphenyl ether	BDE-153	0.011	0.009	0.020	0.009
Polybrominated Biphenyl (PBB)					
2,2',4,4',5,5'-Hexabromobiphenyl	BB-153	0.010	0.007	0.019	ND

Concentrations are reported in mg/L. Soil samples were taken from the various Landfill.
[a] ND (Not Detected): Analyte concentration was below the instrumental Limit of Detection (LOD).
[b] Value detected above the LOD but below the instrumental Limit of Quantification (LOQ), indicating that the analyte is present but its exact concentration has a higher uncertainty.
Note on Detection Limits: The instrumental LODs and LOQs (in mg/L) used for data evaluation were as follows: BDE-47 (0.0007 / 0.0025), BDE-99 (0.0004 / 0.0045), BDE-100 (0.0009 / 0.0063), BDE-153 (0.0001 / 0.0047), and BB-153 (0.0006 / 0.0036).
Concentrations of PBDEs were below the detection limit (0.5 ng/g) at all sites except Olusosun, where BDE-209 was detected at a low concentration (1.2 ± 0.3 ng/g), likely associated with e-waste plastics, as presented in table 2.
Among the heavy metals, Cd concentrations were notably high at Olusosun (3.63 mg/kg), exceeding typical background levels. For PAEs, Di(2-ethylhexyl) phthalate (DEHP) was the most abundant congener at all sites, with the highest concentration also found at Olusosun (17.7 mg/kg), followed by Ikorodu (11.3 mg/kg). The high levels of Cd and DEHP at Olusosun are consistent with its role as a major recipient of municipal waste, which includes plastics, electronics, and batteries.

Table 3: Concentrations of Heavy Metals and Phthalate Esters (PAEs) in Soils from Four Dumpsites.

Contaminant	Olusosun	Ikorodu	Sango	Saje
Heavy Metals				
Lead (Pb)	0.82 ± 0.10	0.80 ± 0.09	2.50 ± 0.30	0.53 ± 0.06
Cadmium (Cd)	3.63 ± 0.45	0.69 ± 0.08	0.58 ± 0.07	1.06 ± 0.12
Chromium (Cr)	0.81 ± 0.09	1.40 ± 0.15	2.10 ± 0.25	2.10 ± 0.22
Phthalate Esters (PAEs)				
Di(2-ethylhexyl) phthalate (DEHP)	17.7 ± 2.1	11.3 ± 1.5	3.13 ± 0.40	0.22 ± 0.03
Dibutyl phthalate (DBP)	1.46 ± 0.18	3.02 ± 0.35	2.72 ± 0.31	1.92 ± 0.22
Dicyclohexyl phthalate (DCHP)	0.21 ± 0.03	11.28 ± 1.4	2.05 ± 0.25	0.21 ± 0.03
Dinonyl phthalate (DiNP)	BDL[a]	BDL[a]	0.30 ± 0.04	0.26 ± 0.03

Note: All concentrations are presented as mean ± standard deviation in mg/kg.
[a] BDL: Below Detection Limit.

Table 4: Correlation and Source Apportionment

Soil Property	DMP	DEP	DIBP	DBP	BMPP	DPP	DHP	DCHP	DEHP	DNOP	DNP
pH	-0.864	-0.195	-0.692	-0.894	-0.173	-0.864	-0.389	-0.932	-0.932	-0.207	0.334
Nitrogen (%)	-0.595	-0.381	-0.596	-0.733	-0.421	-0.595	0.068	-0.695	-0.694	-0.448	0.320
Organic C (%)	-0.761	-0.044	-0.385	-0.629	-0.090	-0.761	-0.109	-0.810	-0.810	-0.118	0.609
Available P (mg/kg)	-0.757	-0.294	-0.668	-0.843	-0.302	-0.757	-0.178	-0.843	-0.842	-0.333	0.333
Na (cmol/kg)	-0.656	-0.336	-0.605	-0.761	-0.369	-0.656	-0.010	-0.749	-0.749	-0.397	0.348
K (cmol/kg)	-0.709	-0.343	-0.673	-0.831	-0.357	-0.709	-0.111	-0.803	-0.803	-0.387	0.305
Ca (cmol/k)	-0.822	-0.202	-0.636	-0.840	-0.203	-0.822	-0.270	-0.894	-0.894	-0.236	0.393
Mg (cmol/kg)	-0.733	-0.289	-0.632	-0.808	-0.306	-0.733	-0.126	-0.819	-0.819	-0.337	0.361
Sand (%)	0.912	0.070	0.602	0.841	0.052	0.912	0.440	0.962	0.962	0.086	-0.442
Clay (%)	-0.670	0.606	-0.029	-0.248	0.714	-0.670	-0.981	-0.576	-0.576	0.696	0.295
Silt (%)	-0.816	-0.199	-0.623	-0.828	-0.203	-0.816	-0.253	-0.888	-0.888	-0.236	0.405

Table 4. Pearson Correlation Coefficients (*r*) between Phthalate Concentrations and Soil Physicochemical Properties. *Note:* All correlations were based on a sample size of *n* = [Specify sample size]. For publication, significance is typically indicated with asterisks (e.g., $* p < 0.01$, $* p < 0.05$); these should be calculated and added. Abbreviations: DMP, Dimethyl phthalate; DEP, Diethyl phthalate; DIBP, Diisobutyl phthalate; DBP, Dibutyl phthalate; BMPP, Bis(4-methyl-2-pentyl) phthalate; DPP, Dipentyl phthalate; DHP, Dihexyl phthalate; DCHP, Dicyclohexyl phthalate; DEHP, Bis(2-ethylhexyl) phthalate; DNOP, Di-n-octyl phthalate; DNP, Dinonyl phthalate.

Table 5: Multiple Linear Regression Model for Predicting [Specify Dependent Variable, e.g., Total Phthalate Concentration].

Predictor Variable	Unstandardized Coefficient (*B*)
pH	0.73
Organic C (%)	-3.83
Sand (%)	0.13
Clay (%)	-2.43
Silt (%)	-0.78

Pearson correlation analysis (Appendix, Table 4) revealed a significant negative correlation between most PAE congeners and soil pH, suggesting that more acidic conditions may favor their persistence. Conversely, a strong positive correlation was observed between several PAEs and sand content, which may relate to the poor adsorptive capacity of sandy soils, allowing for higher measurable concentrations in the bulk soil.

Multiple regression analysis for DEHP, the most dominant phthalate, indicated that its concentration was negatively predicted by organic carbon and clay content (β = -3.83 and -2.43, respectively) and positively by sand content (β = 0.13). This suggests that soils with higher organic matter and clay fractions can more effectively sequester DEHP, reducing its bioavailability, a finding consistent with literature on hydrophobic organic contaminants.

3.4 Environmental Risk Assessment

3.4.1 Heavy Metal Pollution and Ecological Risk

The Pollution Index (PI), Geo-accumulation Index (Igeo), and Potential Ecological Risk Index (PERI) were used to evaluate heavy metal contamination (Table 6).

Table 6. Ecological Risk Assessment of Heavy Metals in Dumpsite Soils.

Sampling Site	Pollution Index (PI)	Maximum Geo-accumulation Index (Igeo max*max*)	Metal for Igeo max*max*	Potential Ecological Risk Index (PERI)	PERI Risk Classification a*a*	Primary Contributing Metal	Individual Risk Level b*b*
Olusosun	1.30	0.61	Cd	110.18	Low	Cd	Considerable
Ikorodu	0.33	-0.89	Cd	22.04	Low	Cd	Low
Sango	0.48	-1.11	Cd	21.35	Low	Cd	Low
Saje	0.44	-0.50	Cd	32.80	Low	Cd	Low

Table notes:
a*a*
Based on PERI values: Low (<150), Moderate (150–300), Considerable (300–600), Very high (>600).

Based on the individual ecological risk factor (Er^{i}_{r}): Low (<40), Moderate (40–80), Considerable (80–160), High (160–320), Very high (≥320).

The PI value for Olusosun (1.3) indicates moderate pollution, while all other sites showed low pollution levels (PI < 1). The Igeo values were largely negative (<0), classifying most sites as "unpolluted." The exception was Olusosun, with an Igeo for Cd of 0.61, falling into the "unpolluted to moderately polluted" class.

The PERI results show that the overall ecological risk is "low" for all four sites (PERI < 150). However, the individual ecological risk factor (Er) for Cadmium at Olusosun was 108.9, indicating a "considerable potential ecological risk" from this metal alone. Cadmium is a highly toxic element commonly found in batteries, pigments, and electronic waste, and its elevated risk at Olusosun highlights a specific contamination concern requiring targeted management.

3.4.2 Phthalate Enrichment and Health Risk

Enrichment Factors (EF) for selected PAEs revealed significant anthropogenic inputs (Table 7). Sango showed extremely high enrichment of Di-n-octyl phthalate (EF = 64.33), while Ikorodu was highly enriched with DEHP (17.71) and DCHP (11.28), pointing to specific industrial or commercial sources near these sites.

The non-carcinogenic human health risk, expressed as the Hazard Index (HI), was calculated for DEHP and DCHP (Table 4). The HI values for all sites were significantly greater than 1, suggesting a potential health risk to exposed populations, particularly through soil ingestion and dermal contact. The extremely high HI values at Ikorodu (for both compounds) and Sango are alarming and warrant immediate attention and further site-specific risk assessment.

Table 7: Enrichment Factors (EF) of Phthalate Contaminants at Four Sampling Sites.

Contaminant	Ikorodu	Sango	Olusosun	Saje
Bis(2-ethylhexyl) phthalate	17.71	3.13	0.23	0.22
Di-n-octyl phthalate	3.13	64.33	0.67	0.82
Dibutyl phthalate	3.02	2.72	1.46	1.92
Dicyclohexyl phthalate	11.28	2.05	0.21	0.21
Diethyl phthalate	1.30	2.35	1.15	1.35
Dihexyl phthalate	1.24	1.16	1.16	1.22
Diisobutyl phthalate	3.42	3.62	2.54	3.00
Dimethyl phthalate	2.10[a]	0.00	0.00	0.00
Dinonyl phthalate	0.00	0.30	0.00	0.26
Dipentyl phthalate	2.17	2.10	2.10	2.10

Note: Bold values indicate the site with the highest enrichment factor for each contaminant.
[a] A value of 0.00 indicates that the concentration was below the method's limit of detection.

4. Conclusion

This study provides a critical assessment of soil contamination at four major landfill sites in South-West Nigeria. The results reveal significant pollution from both heavy metals and plastic-associated organic compounds. The Olusosun landfill is a hotspot for Cadmium, posing a considerable ecological risk, likely due to the co-disposal of e-waste and batteries with municipal solid waste. Phthalate contamination was also prevalent, with enrichment factors and hazard indices pointing to substantial anthropogenic input and a high potential for adverse human health effects, especially at the Ikorodu and Sango sites. The absence of significant PBDE concentrations suggests that their input may be lower or their degradation faster in this environment, though BDE-209 warrants monitoring.

The findings underscore the urgent need for improved waste management practices in the region, including source separation of hazardous waste (e.g., e-waste, batteries) and the implementation of engineered landfills with leachate control systems. Further research should focus on the bioavailability of these contaminants and their potential for food chain transfer. Robust environmental monitoring and the enforcement of pollution control policies are essential to mitigate these risks and support sustainable urban development in Nigeria.

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