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Comprehensive Evaluation of the Physicochemical Properties and Contaminant Load of Oluku Dumpsite Leachate in Edo State, Nigeria

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ABSTRACT

Rapid urbanization and poor waste management across sub-Saharan Africa have intensified the environmental threat posed by open dumpsites, where leachate migration contaminates soil and groundwater. In Nigeria, the absence of engineered landfill systems allows toxic effluents from decomposing waste and electronic residues to infiltrate surrounding environments, yet little is known about their chemical complexity or ecological impact. This study presents a comprehensive assessment of the physicochemical properties, heavy metal burden, and brominated flame-retardant residues in leachate from the Oluku dumpsite in Edo State, Nigeria. Leachate samples collected from six points were analyzed using standard APHA procedures, Atomic Absorption Spectrophotometry, and GC-FID to quantify inorganic and organic contaminants. Results revealed a chemically aggressive leachate with extreme electrical conductivity (8,333 µS/cm), high total dissolved solids (5,500 mg/L), and severe exceedances of NESREA limits for BOD, COD, nitrate, and chloride. Heavy metals followed the order Zn > Fe > Cr > Pb > Cd > Cu > Ni, with cadmium (0.39 mg/L) and lead (0.59 mg/L) driving a very high ecological risk (PERI = 1214.14). Brominated flame retardants, particularly PBB-153 and BDE-153, exceeded EU Environmental Quality Standards by tens of thousands of times, confirming the presence of persistent organic pollutants in Nigerian leachate for the first time. These findings demonstrate synergistic contamination from ionic, metallic, and organic species, posing serious threats to ecosystem and public health. It is recommended that engineered liners, leachate treatment, continuous monitoring, and strict e-waste management be prioritized to prevent further degradation.

1. INTRODUCTION

Solid waste mismanagement remains one of the most pressing environmental challenges in developing countries, particularly across sub-Saharan Africa where open dumpsites are still the dominant waste disposal method (Akindele *et al.*, 2023; Tovide *et al.*, 2024). Globally, the World Bank estimates that more than 2 billion tonnes of municipal solid waste are generated annually, and this figure is expected to rise by over 70 percent by 2050 if current disposal practices persist (World Bank, 2023). In Nigeria, rapid urbanization, population growth, and weak waste

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management systems have intensified the accumulation of mixed solid waste materials including plastics, metals, electronic scraps, and industrial residues that readily release contaminants into surrounding environments (Essien *et al.*, 2022; Oguche *et al.*, 2021).

When rainfall percolates through these decomposing wastes, it generates leachate, a chemically complex liquid containing dissolved organic matter, nutrients, heavy metals, and synthetic organic compounds. The percolation of leachate into soil and groundwater modifies physicochemical properties such as pH, electrical conductivity (EC), total dissolved solids (TDS), and dissolved oxygen (DO), thereby impairing water quality and posing risks to aquatic life and human health (Afolabi *et al.*, 2021; Nubi *et al.*, 2020). In the humid regions of southern Nigeria, where annual rainfall often exceeds 2000 millimeters, high infiltration rates make dumpsites major sources of soil and groundwater contamination.

Several Nigerian studies have investigated the chemical composition and pollution potential of dumpsite leachates. Essien *et al.* (2022) assessed heavy metal distribution in landfill leachates and receiving waters in Uyo and employed pollution indices such as the Contamination Factor and Potential Ecological Risk Index to quantify ecological threat. Tovide *et al.* (2024) evaluated physicochemical and toxicological parameters of leachates and nearby groundwater in Lagos, finding elevated levels of iron, lead, zinc, and cadmium that exceeded regulatory limits. Both studies demonstrated the environmental burden of poorly managed dumpsites but primarily addressed inorganic pollutants. In contrast, emerging contaminants such as brominated flame retardants (BFRs), widely used in plastics, foams, textiles, and electronic components, remain largely unstudied in Nigerian leachate systems. These compounds are persistent, bioaccumulative, and capable of long-range transport, making them a growing concern in environmental chemistry.

The Oluku dumpsite in Edo State, southern Nigeria, exemplifies an unmanaged disposal facility that receives domestic, industrial, and electronic waste without engineered liners or leachate control systems. Continuous leachate seepage from such sites may introduce toxic substances into nearby soil and water bodies, threatening ecological balance and public health.

This study aims to quantitatively characterize the physicochemical properties, heavy metal concentrations, and brominated flame retardant residues in leachate samples from the Oluku dumpsite in Edo State, Nigeria. The analysis integrates statistical descriptors (range, mean ± standard deviation) with quantitative pollution and ecological risk indices, including the Contamination Factor (CF), Geoaccumulation Index (Igeo), Pollution Load Index (PLI), and Potential Ecological Risk Index (PERI). Through this integrated approach, the study provides a detailed understanding of contaminant dynamics in open dumpsite leachate and establishes a technical basis for risk mitigation and environmental management in Nigeria's rapidly urbanizing regions.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

The study was carried out at the Oluku dumpsite, located in Egor Local Government Area, Benin City, Edo State, Nigeria. Geographically, the site lies between latitude 6°19′30″N and 6°19′50″N and longitude 5°44′40″E and 5°45′00″E, about 8 km northwest of the Benin City centre, along the Benin-Lagos expressway. The area falls within the humid tropical rainforest belt of southern Nigeria, characterized by two

distinct seasons: a wet season (April-October) and a dry season (November-March). The mean annual rainfall ranges between 2,000 and 2,200 mm, while average temperature varies between 25 and 31 °C with relative humidity above 70% during the wet season (Akinbile *and* Yusoff, 2011).

The geology is dominated by the Benin Formation, consisting mainly of coarse sandstones and lateritic soils, which encourage leachate infiltration and migration. The dumpsite covers about 10 hectares and receives municipal, industrial, electronic, and agricultural wastes without any engineered liner or leachate collection system. Surrounding the site are residential areas, farmlands, and drainage channels leading to the Ogba River, a surface water body that supports irrigation and domestic use. This proximity heightens concern about contaminant migration and makes the site representative of unregulated urban dumpsites in Nigeria's South-South region.

2.2 Study Design

A descriptive and analytical design was adopted to assess the physicochemical properties, heavy metal levels, and brominated flame retardants (BFRs) in dumpsite leachate. Sampling was done during the dry season, when minimal rainfall produces the most concentrated leachate. Six (6) composite samples were collected from defined sampling points across the dumpsite, representing different zones (central, periphery, slope base, lowland, and boundary areas). Composite sampling reduced local variation due to waste heterogeneity and leachate flow differences.

2.3 Sample Collection and Preservation

Leachate samples were collected from surface pools and drainage channels at six points (PT-1 to PT-6). About 1 L of leachate was collected at each point using pre-cleaned amber glass bottles with Teflon-lined caps. Bottles were rinsed with dichloromethane and deionized water, followed by sample rinsing before filling.

In situ parameters, pH, temperature, electrical conductivity (EC), and dissolved oxygen (DO), were measured using a portable multi-parameter probe (Hanna Instruments, USA). Samples for metal analysis were acidified immediately to pH < 2 with ultrapure nitric acid, while samples for organic analysis were left unacidified to prevent analyte loss. All samples were stored in ice-packed coolers at 4 °C and transported to the laboratory within 24 hours. Field duplicates and trip blanks were collected at 10% frequency to ensure precision and detect contamination.

2.4 Sampling points, coordinates, and dominant waste types at Oluku dumpsite.

Table 1: Sampling Locations, Coordinates, and dominant waste types

Point	Location description	Coordinates (Lat/Long)	Dominant waste type
PT-1	Central waste heap	N 6°19′46.23″, E 5°44′55.91″	Mixed domestic and industrial
PT-2	Periphery near access road	N 6°19′34.14″, E 5°44′48.77″	Predominantly domestic
PT-3	Near open burning site	N 6°19′41.71″, E 5°44′48.01″	Domestic and plastics
PT-4	Base of waste slope	N 6°19′37.46″, E 5°44′47.76″	Organic waste

PT-5	Adjacent to lowland	N 6°19′41.89″, E 5°44′49.64″	Domestic and scrap metal
PT-6	Near boundary fence	N 6°19′41.91″, E 5°44′49.70″	Domestic and small-scale industrial

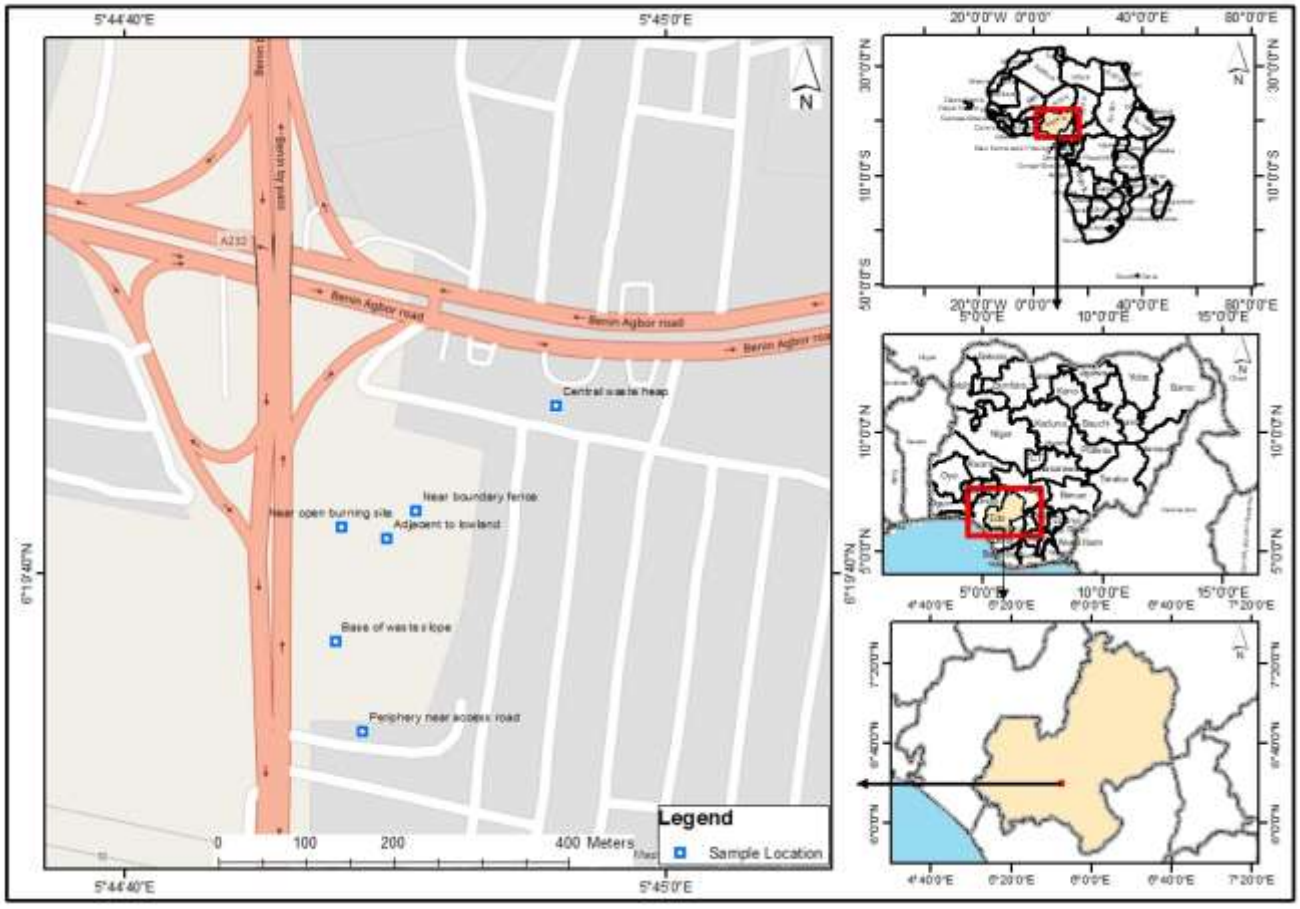


Figure 1: Schematic site map of Oluku dumpsite with contamination hotspots and site features.

2.5 Physicochemical Analysis

Physicochemical parameters were analyzed using standard methods prescribed by APHA (2017). All determinations were made in triplicate, and results are presented as range and mean ± standard deviation.

i. pH, Electrical Conductivity (EC), and Temperature: Measured in situ using a calibrated multi-parameter meter.

ii. Total Dissolved Solids (TDS): Derived from EC and validated gravimetrically.

iii. Dissolved Oxygen (DO): Determined by the Winkler titrimetric method.

iv. Biochemical Oxygen Demand (BOD_5): Measured as the oxygen depletion after 5-day incubation at 20 °C in the dark.

v. Chemical Oxygen Demand (COD): Determined by the closed reflux dichromate method with spectrophotometric detection at 600 nm.

vi. Total Suspended Solids (TSS): Determined gravimetrically by filtration through pre-weighed glass fibre filters (0.7 µm).

vii. Turbidity: Measured using a nephelometric turbidimeter and reported in NTU.

viii. Nutrients:

   a. Nitrate (NO_3^-): Cadmium reduction method.

   b. Phosphate (PO_4^{3-}): Ascorbic acid method.

   c. Sulfate (SO_4^{2-}): Turbidimetric method.

   d. Chloride (Cl^-): Determined by argentometric titration.

2.6 Heavy Metal Analysis

For heavy metals, acidified samples were digested using a 3:1 mixture of nitric acid (HNO_3) and hydrochloric acid (HCl) until the solution became clear. After cooling, the digest was filtered and made up to volume with deionized water. Concentrations of Fe, Zn, Cu, Cr, Ni, Mn, Cd, Pb, As, and V were determined using Atomic Absorption Spectrophotometry (AAS) (PerkinElmer AAnalyst 400).

Calibration used multi-element certified standards, and procedural blanks and reference materials were included for accuracy and precision control. Quality control criteria required correlation coefficients (R^2) ≥ 0.995 for all calibration curves.

2.7 Brominated Flame Retardant Analysis

The analysis of brominated flame retardants (BFRs), the key novelty of this study, followed solid-phase extraction (SPE) and gas chromatography-mass spectrometry/flame ionization detection (GC-MS/FID) techniques.

i. Extraction and Clean-up: Five hundred millilitre aliquots of filtered leachate were extracted using C18 SPE cartridges (Supelco, USA) preconditioned with dichloromethane, methanol, and deionized water. Cartridges were washed with ultrapure water, dried under vacuum, and eluted with 10 mL dichloromethane. Extracts were concentrated under a gentle nitrogen stream to about 1 mL and cleaned on silica gel columns to remove humic interferences.

ii. Instrumental Analysis: BFRs were quantified using a Thermo Scientific Trace GC Ultra fitted with a DB-5MS capillary column (30 m × 0.25 mm × 0.25 µm) and connected to both mass spectrometer (MS) and flame ionization detector (FID). Helium was used as carrier gas at a flow rate of 1.2 mL min^{-1}. Injection volume was 1 µL (splitless mode, 280 °C). The oven was programmed from 90 °C (2 min hold) to 320 °C at 10 °C min^{-1}, held for 10 min. Identification was achieved by comparing retention times and spectral patterns with authentic standards and the NIST library, while quantification used FID responses and external calibration with PBDE and PBB standards (BDE-47, -99, -153, -209, PBB-153, TBBPA).

2.8 Pollution and Ecological Risk Indices

To evaluate the degree of contamination and potential ecological risk posed by heavy metals in Oluku dumpsite leachate, four quantitative indices were computed: the Contamination Factor (CF), Geoaccumulation Index (Igeo), Pollution Load Index (PLI), and Potential Ecological Risk Index (PERI). Calculations were based on mean metal concentrations obtained from this study and the NESREA effluent limits (mg/L) serving as background values, ensuring unit consistency for leachate analysis. All computations were done in SPSS v26 and Microsoft Excel (2021).

2.8.1 Treatment of Non-Detects and Data Integrity

Vanadium was not detected (0.00 mg/L) and was therefore excluded from index computations.

Other nondetects, if present, were treated as half the method detection limit (0.5 × MDL) to avoid

bias. All indices were computed using consistent units (mg/L), and results were cross-checked for

arithmetic precision. The approach ensures reproducibility and compliance with water-quality risk

assessment standards.

2.9 Quality Assurance and Quality Control

Strict QA/QC measures were implemented throughout sampling and analysis. Field blanks, trip blanks, and procedural blanks were analyzed alongside samples. Matrix spikes and surrogate recoveries were included for every batch, with recovery ranges between 78 % and 110 %, meeting international validation criteria. Replicate analyses were performed on at least 10 % of samples, with relative standard deviations (RSD) kept below 15 %.

Method Detection Limits (MDL) ranged from 0.05-0.2 µg L^{-1}, and Limits of Quantification (LOQ) were three times the MDL. Instrument calibration was verified every ten injections.

2.10 Data Analysis

All results are presented as range and mean ± standard deviation. Data were subjected to descriptive and inferential statistics using SPSS v26 and GraphPad Prism.

i. Comparative analyses: One-way ANOVA tested spatial differences among sampling points.

ii. Correlation: Pearson correlation assessed relationships among physicochemical parameters, metals, and BFRs at $p < 0.05$.

iii. Pollution and risk indices:

   a. Contamination Factor (CF)

   b. Geoaccumulation Index (Igeo)

   c. Pollution Load Index (PLI)

   d. Potential Ecological Risk Index (PERI)

Indices were calculated following standard equations (Hakanson, 1980; Varol, 2020), using regional background values and toxic-response factors from established sources.

3. RESULTS

Table 2: Physicochemical Properties of Oluku Dumpsite Leachate

Parameter	Range	Mean ± SD	NESREA Limit	Compliance*	Environmental Implication
pH	7.68 - 8.40	8.01 ± 0.14	6.0 - 9.0	✓	Slight alkalinity may enhance metal solubility and microbial degradation.
Temperature (°C)	29.8 - 31.8	30.68 ± 0.37	≤ 40	✓	Favors microbial activity but accelerates organic degradation.
Electrical Conductivity (µS/cm)	3500 - 13300	8333.33 ± 2117.65	-	✗	Indicates strong ionic mineralization and salinity.
Total Dissolved Solids (mg/L)	2100 - 7980	5500 ± 1278.1	2000	✗	Exceeds limit; risks groundwater salinization.
Total Suspended Solids (mg/L)	145 - 210	178.67 ± 12.61	10	✗	Indicates particulate load and surface clogging potential.
Dissolved Oxygen (mg/L)	0.00 - 1.36	0.74 ± 0.20	< 5	✗	Extremely low; shows oxygen depletion.
Biochemical Oxygen Demand (mg/L)	63 - 86	74.33 ± 4.65	20	✗	High organic load; indicates biodegradable pollutants.
Chemical Oxygen Demand (mg/L)	150 - 216	182.33 ± 13.32	40	✗	Strong chemical pollution, poor degradation potential.
Phosphate (mg/L)	55 - 80	67.00 ± 5.09	-	✗	Indicates nutrient enrichment, risk of eutrophication.
Sulphate (mg/L)	101 - 149	124.67 ± 9.59	100	✗	High levels promote corrosion, acidification risk.
Nitrate (mg/L)	43 - 69	55.83 ± 5.31	10	✗	High; may cause methemoglobinemia and eutrophication.
Chloride (mg/L)	1800 - 8700	5220.00 ± 1519.29	100	✗	Extreme saline condition, toxic to plants.
Turbidity (NTU)	141 - 198	168.67 ± 11.83	-	✗	Cloudy appearance; indicates poor quality.

Compliance: ✓ = within limit, ✗ = exceeds NESREA/FMEnv limit.

Table 3: Spatial Variation of Physicochemical Parameters (PT-1 to PT-6)

Parameter	**PT-1**	**PT-2**	**PT-3**	**PT-4**	**PT-5**	**PT-6**	**Mean ± SD**
pH	8.3	7.75	8.4	7.68	8.25	7.7	8.01 ± 0.14
Temperature (°C)	31.6	29.9	31.8	29.8	31.0	30.0	30.68 ± 0.37
Electrical Conductivity (µS/cm)	12900	3600	13300	3500	13000	3700	8333.33 ± 2117.65
TDS (mg/L)	7740	2160	7980	2100	7800	2220	5500 ± 1278.1
TSS (mg/L)	210	152	205	145	205	155	178.67 ± 12.61
DO (mg/L)	0.00	0.42	0.87	1.12	1.36	0.65	0.74 ± 0.20
BOD (mg/L)	83	64	86	63	85	65	74.33 ± 4.65
COD (mg/L)	208	153	216	150	212	155	182.33 ± 13.32
Phosphate (mg/L)	77	56	78	55	80	56	67.00 ± 5.09
Sulphate (mg/L)	143	104	149	101	146	105	124.67 ± 9.59
Nitrate (mg/L)	66	44	69	43	68	45	55.83 ± 5.31
Chloride (mg/L)	8500	1800	8700	1820	8650	1850	5220 ± 1519.29
Turbidity (NTU)	190	143	198	141	197	143	168.67 ± 11.83

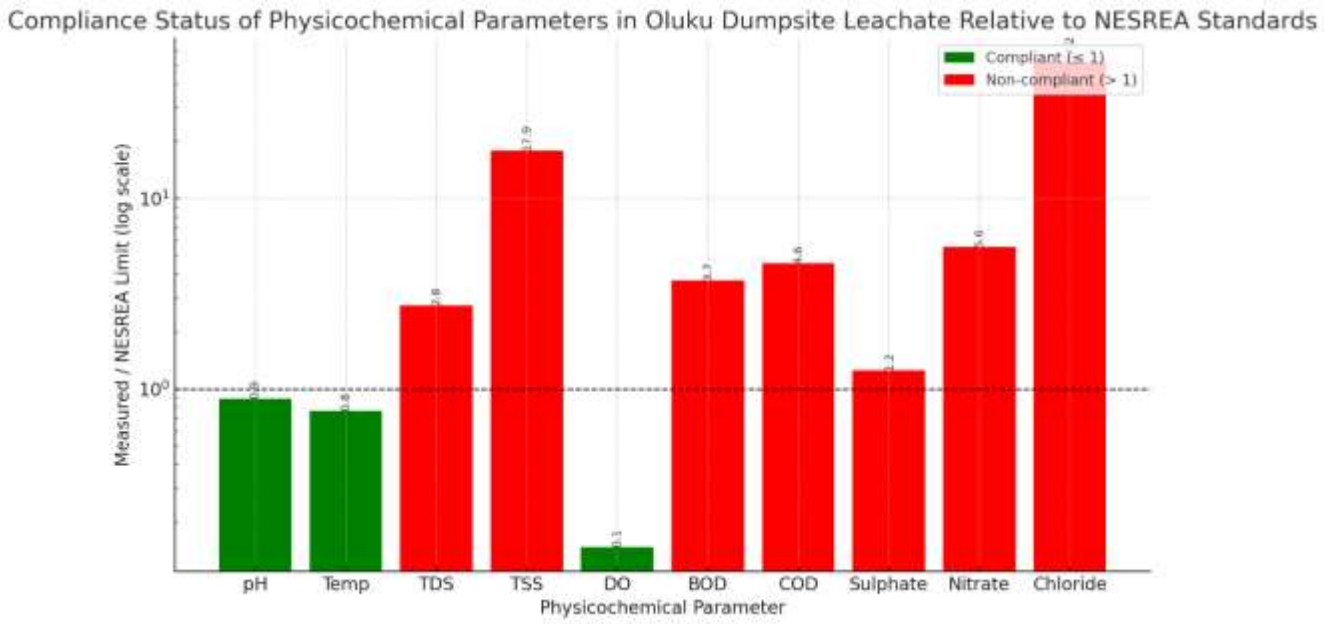


Figure 2: Compliance status of physicochemical parameters in Oluku dumpsite leachate relative to NESREA standards. While pH, temperature and Dissolved Oxygen (DO) are compliant, parameters such as Total Suspended Solids (TSS), TDS, BOD, COD, sulphate, Chloride and Nitrate show significant non-compliance, severely impacting leachate quality.

Table 4: Heavy Metal Concentrations in Oluku Dumpsite Leachate

Metal	Range (mg/L)	Mean ± SD	NESREA Limit	Compliance	Likely Source
Ni	0.09-0.29	0.19 ± 0.04	1.0	✓	Alloy, industrial waste
Cr	1.80-5.40	3.57 ± 0.78	2.0	✗	Electroplating, paints
Cu	0.52-1.35	0.93 ± 0.18	1.0	✓	Electrical components
Zn	4.30-15.70	9.89 ± 2.48	5.0	✗	Metal scrap, batteries
Fe	7.40-11.60	9.47 ± 0.91	20.0	✓	Corroded metal
Pb	0.24-0.95	0.59 ± 0.15	0.1	✗	Battery waste, solder
Cd	0.17-0.63	0.39 ± 0.10	0.01	✗	Plastic pigment, e-waste
Mn	0.06-0.15	0.11 ± 0.02	5.0	✓	Batteries, industrial dyes
As	0.01-0.05	0.03 ± 0.01	0.1	✓	Wood preservatives
V	0.00-0.00	0.00 ± 0.00	–	✓	Not detected

Table 5: Spatial Variation of Heavy Metals (mg/L) Across Sampling Points

Metal	PT-1	PT-2	PT-3	PT-4	PT-5	PT-6	Mean ± SD
Ni	0.28	0.09	0.29	0.09	0.27	0.10	0.19 ± 0.04
Cr	5.20	1.80	5.40	1.85	5.35	1.85	3.57 ± 0.78
Cu	1.30	0.52	1.35	0.53	1.32	0.54	0.93 ± 0.18
Zn	14.90	4.30	15.70	4.35	15.60	4.40	9.89 ± 2.48
Fe	11.50	7.40	11.60	7.45	11.55	7.50	9.47 ± 0.91
Pb	0.94	0.24	0.95	0.25	0.91	0.26	0.59 ± 0.15
Cd	0.61	0.17	0.63	0.18	0.60	0.19	0.39 ± 0.10
Mn	0.14	0.06	0.15	0.07	0.14	0.08	0.11 ± 0.02
As	0.05	0.01	0.05	0.01	0.04	0.01	0.03 ± 0.01
V	0.00	0.00	0.00	0.00	0.00	0.00	0.00 ± 0.00

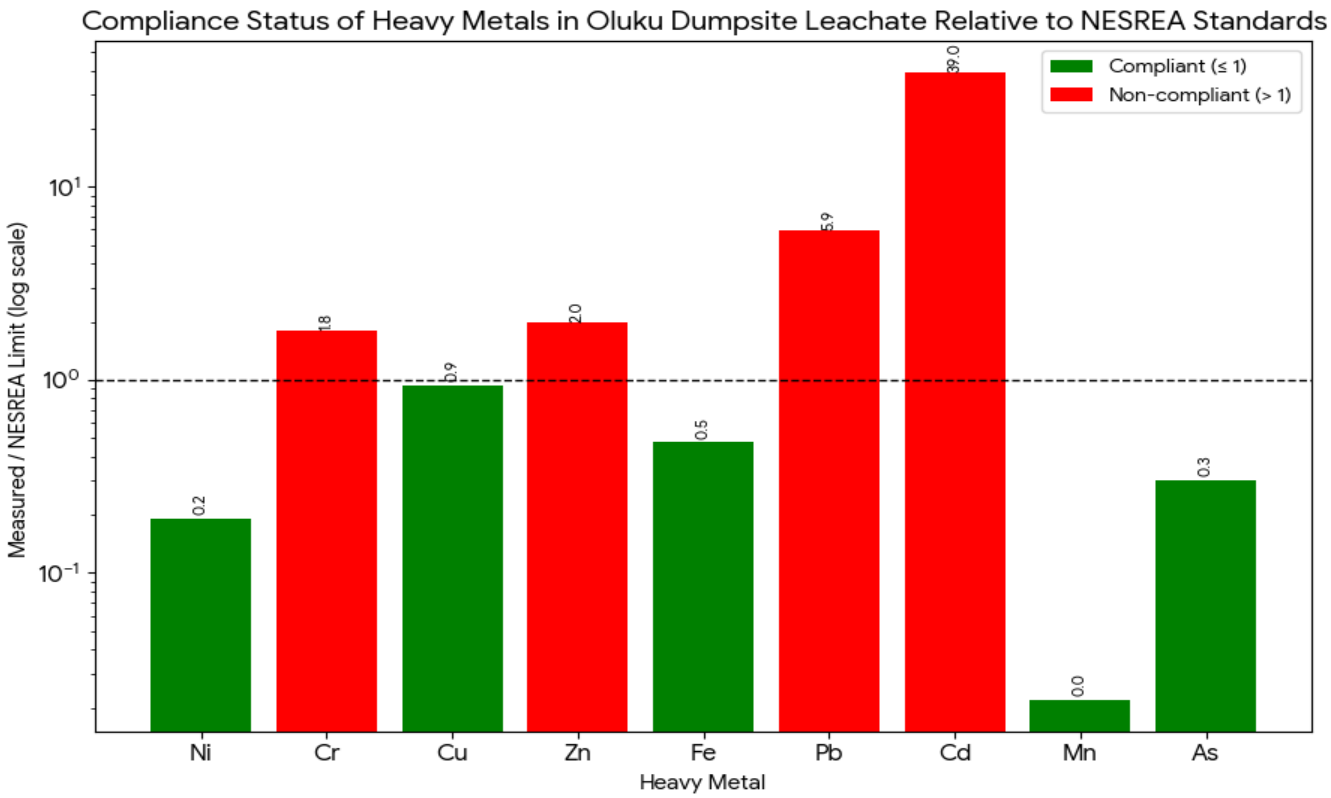


Figure 3: Compliance status of heavy metals in Oluku dumpsite leachate relative to NESREA standards. The leachate exhibits severe non-compliance for lead (Pb), cadmium (Cd), and chromium (Cr), while metals like Nickel (Ni) and Manganese (Mn) show concentrations well below the regulatory limit.

Table 6: Pollution and Ecological Risk Indices for Heavy Metals (Mean Values)

Metal	**CF**	**Igeo**	**E_r**	**Risk Level (PERI scale)**	**Interpretation**
Ni	0.19	-2.98	0.95	Low	Within safe limit
Cr	1.78	0.25	3.57	Low	Moderate enrichment
Cu	0.93	-0.69	4.65	Low	Minimal risk
Zn	1.98	0.40	1.98	Low	Slight enrichment
Fe	0.47	-1.08	0.47	Low	Natural occurrence
Pb	5.90	5.06	29.50	Moderate	Strong anthropogenic impact
Cd	39.00	12.29	1170.00	Very High	Critical contamination
Mn	0.02	-6.09	0.02	Low	Negligible
As	0.30	-2.32	3.00	Low	Low enrichment
PLI = 0.915				*<1 = no overall pollution*	
PERI = 1214.14				*Very high ecological risk*	

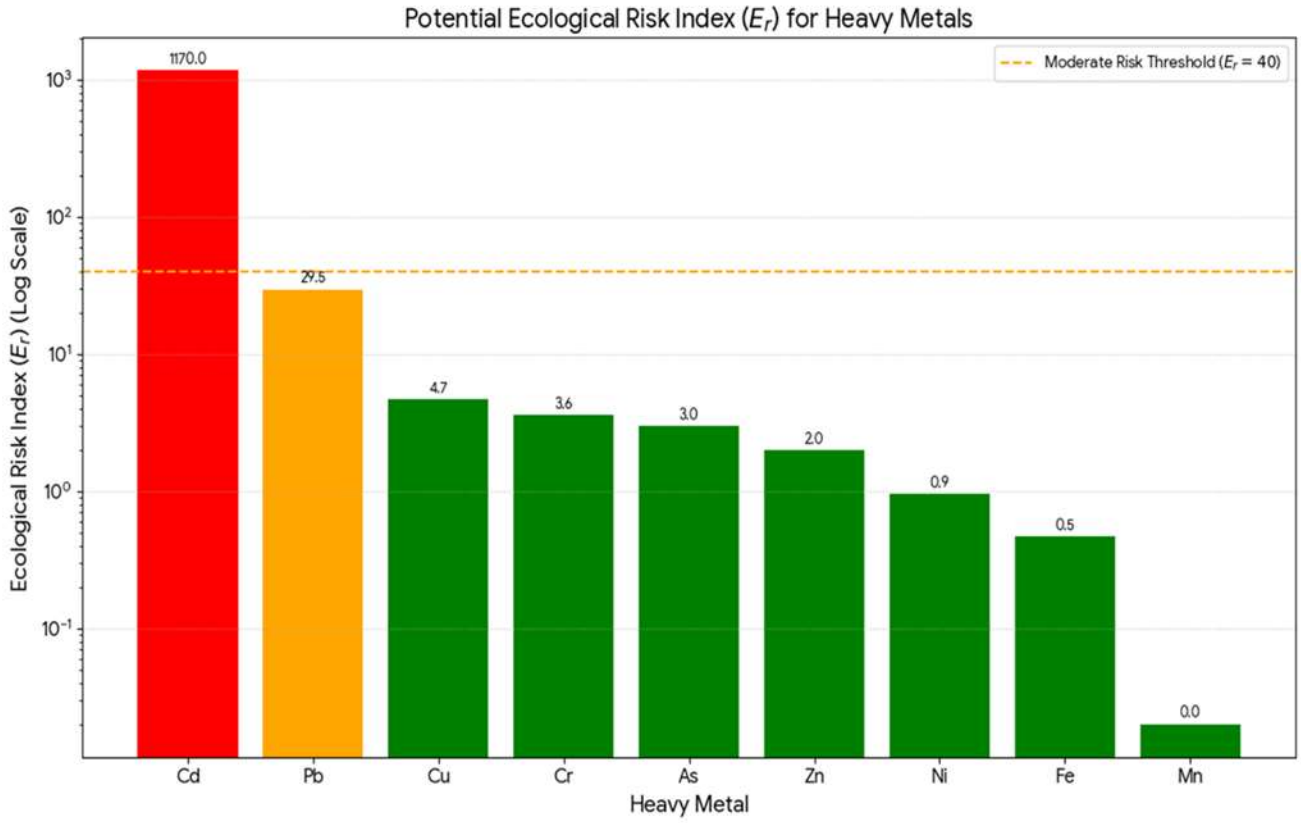


Figure 4: Potential Ecological risk Index (E_r) for heavy metals. Cadmium (Cd) presents an 'Extreme' ecological risk (E_r = 1170.0), vastly exceeding the moderate threshold (E_r = 40), while Lead (Pb) poses a 'Moderate' risk. All other heavy metals fall into the 'Low' risk category.

Table 7: Flame Retardant Concentrations in Leachate

Compound	**Range (µg/L)**	**Mean ± SD**	**EU EQS (µg/L)**	**Compliance**	**Likely Source**
BDE-47	0.0-2.0	0.7 ± 0.3	0.0005	✗	Electronic waste, plastics
BDE-100	0.0-1.0	0.2 ± 0.2	0.0005	✗	Industrial polymers
BDE-99	0.0-1.0	0.2 ± 0.2	0.0005	✗	Flame-treated furniture
PBB-153	10.3-60.0	31.0 ± 8.7	0.0005	✗	Plastic resins, e-waste
BDE-153	3.5-25.0	12.1 ± 3.9	0.0005	✗	Textile, circuit boards

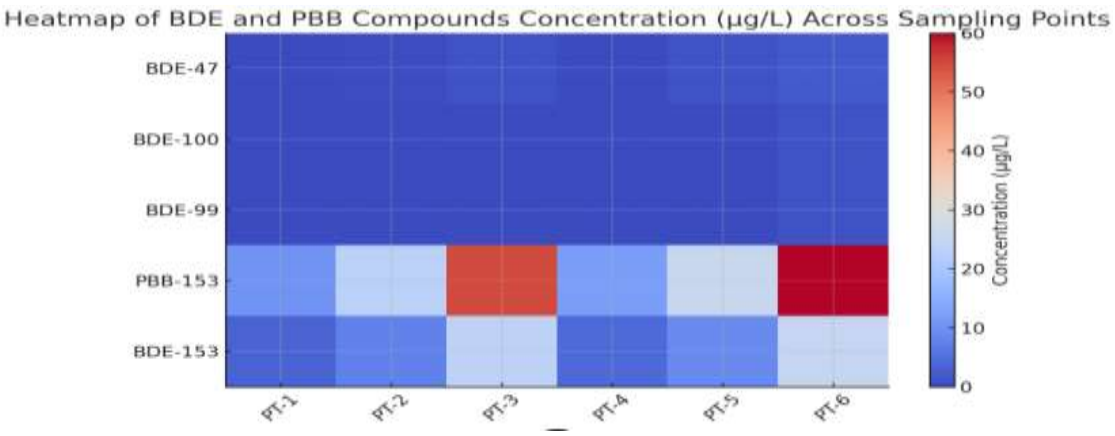


Figure 5: Flame retardants in lecheate across sampling points in Oluku dumpsite. Elevated concentrations of PBB-153 and BDE-153 are localized, with high-concentration hotspots observed at sampling points PT-3 and PT-6. This suggests heterogeneous pollutant input or varying attenuation across the dumpsite.

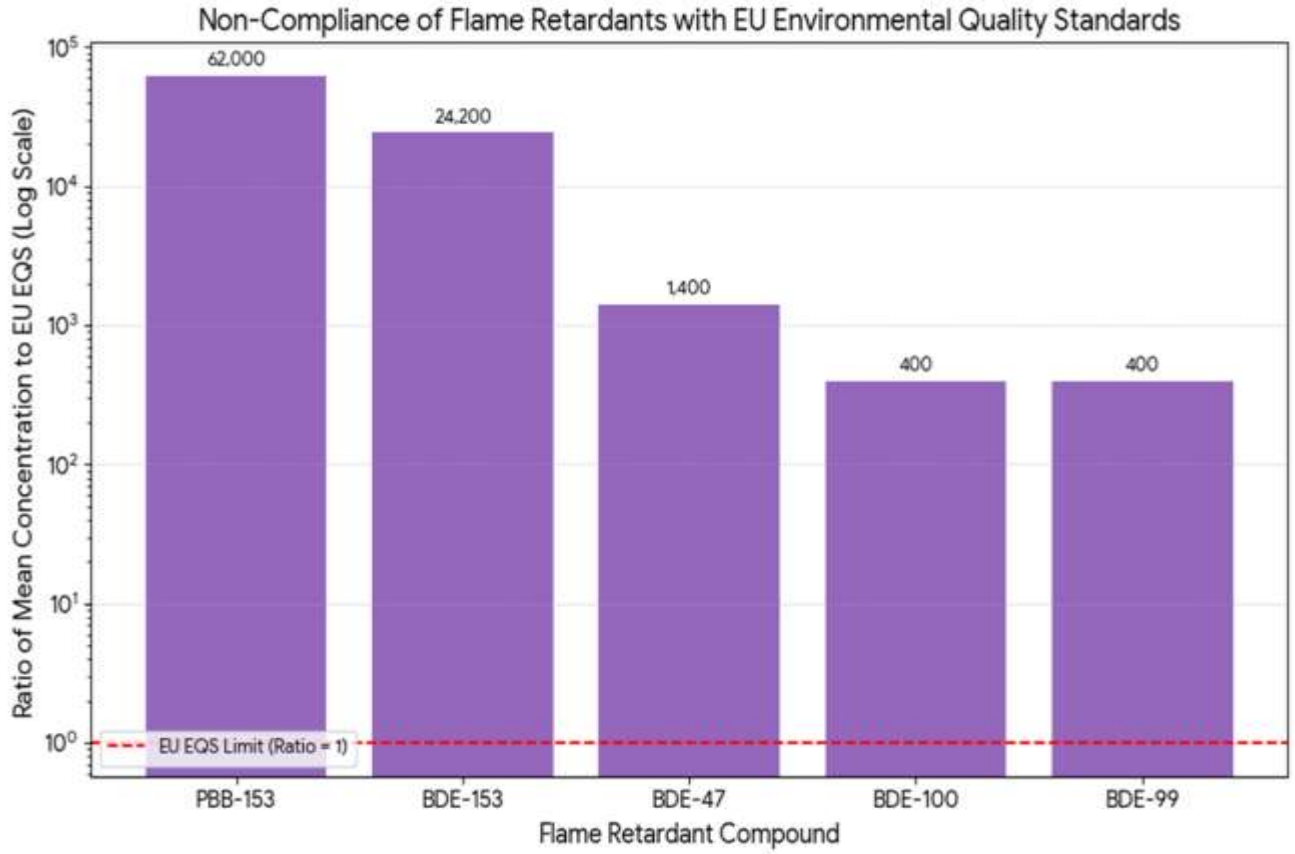


Figure 6: Ratio of Mean Concentration to EU Environmental Quality Standards (EQS) for Selected Flame Retardant Compounds. All analyzed flame retardants significantly exceed the EU EQS. PBB-153 shows the most severe non-compliance by far, with its mean concentration being 62,000 times the EQS limit, followed by BDE-153 at 24,200 times the limit.

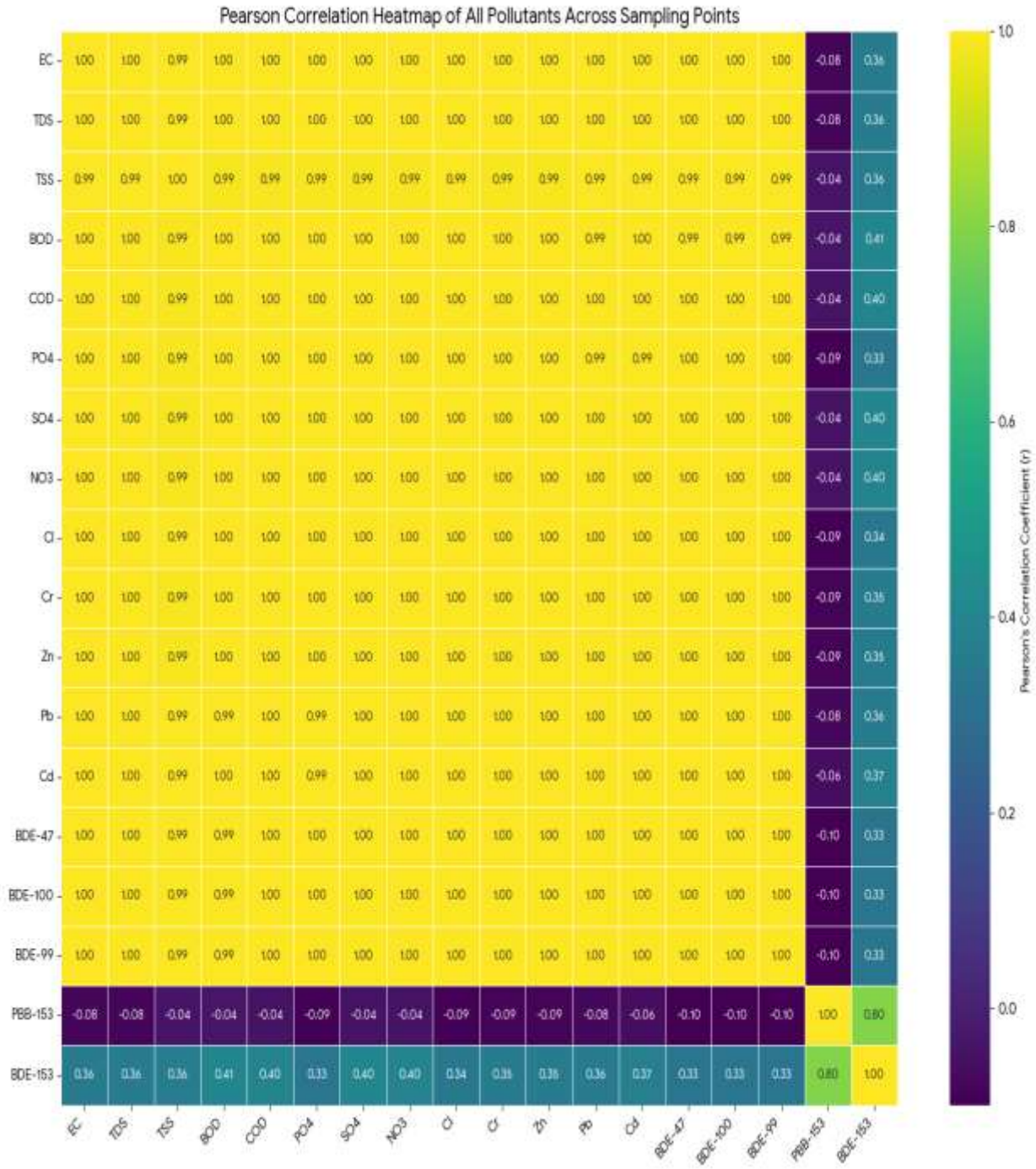


Figure 7: Intercorrelation Matrix of Physicochemical Parameters, Heavy Metals, and Flame Retardants in Leachate Samples. The data reveal two distinct groups: a large cluster of highly correlated parameters (physicochemical parameters and heavy metals) and a separate group of flame retardants (PBB-153 and BDE-153) that exhibit a high correlation with each other (r = 0.80) but a negligible or negative correlation with the main pollutant body.

4. DISCUSSION

4.1 Physicochemical parameters

The physicochemical analysis of the Oluku dumpsite leachate reveals a complex matrix of organic, inorganic, and ionic pollutants typical of open, unengineered waste disposal systems. The general non-compliance across major parameters confirms the leachate's high contamination potential, consistent with findings at similar sites across Nigeria (Adegoke *et al.*, 2022; Ogundele *et al.*, 2023; Tovide *et al.*, 2024).

pH and Temperature

The leachate exhibited a slightly alkaline (8.01 ± 0.14) placing it within the range associated with the methanogenic stabilization phase of waste decomposition, where initial acidic conditions have transitioned to bicarbonate buffering (Ogundele *et al.*, 2023). This alkaline nature is significant because it enhances the solubility and mobility of heavy metals, particularly Pb, Zn, and Cd (which were found to be non-compliant), increasing their risk of migration into groundwater and soil (Onwughara *et al.*, 2020).

The moderate temperature (30.68 ± 0.37) suggests active, intense microbial degradation of the organic load. Such warm conditions accelerate decomposition, gas production, and the potential volatilization of certain contaminants. Prolonged exposure to warm, alkaline leachate can also destabilize soil chemistry and impact the microbial communities critical for natural attenuation (Enekwechi *et al.*, 2022).

Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

The values for Electrical Conductivity (8333.33) and TDS (5500) were orders of magnitude above safe thresholds, confirming strong mineralization and high ionic strength. These levels arise from extensive leaching of inorganic salts, likely originating from dumped materials such as batteries, saline industrial effluents, and other high-salt wastes (Akinbile *and* Yusoff, 2011). The exceeding of the TDS limit (2000) by more than double indicates a high risk of groundwater salinization in the vicinity. High ionic strength not only impairs aquatic life through osmotic stress but also acts as a key driver in increasing the mobility of toxic heavy metals across the saturated zone (Etim *et al.*, 2021).

Total Suspended Solids (TSS) and Turbidity

The TSS (178.67 ± 12.61) and Turbidity (168.67±11.83) drastically exceeded regulatory benchmarks, pointing to a heavy particulate load. This load is characteristic of dumpsites where open burning, soil disturbance, and surface runoff introduce fine debris, ash, and settleable organic matter (Oni *et al.*, 2021). High turbidity impedes light penetration in surface waters, inhibiting photosynthesis and depressing dissolved oxygen regeneration (Enekwechi *et al.*, 2022). Crucially, suspended solids act as adsorptive carriers for pollutants like heavy metals and hydrophobic organic compounds (including some flame retardants), which are later deposited into sediments, prolonging the contamination cycle upon remobilization.

Dissolved Oxygen (DO), BOD, and COD

The leachate is highly anaerobic, demonstrated by the very low DO (0.74) coupled with significantly high organic pollutant indicators: BOD (74.33) and COD (182.33). The BOD/COD ratio (~ 0.4) suggests the organic content is partially biodegradable, typical for leachate from mixed-waste sites containing persistent, recalcitrant compounds like plastics (Ahmed *et al.*, 2020). This oxygen depletion poses an

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immediate threat to aquatic biota near discharge points. Furthermore, the anaerobic environment fosters the production of greenhouse gases (CH_4) and toxic reduced species (H_2S), contributing to both localized ecological shifts and regional atmospheric pollution (Tovide *et al.*, 2024).

Nitrate, Phosphate, Sulphate, and Chloride

The concentrations of inorganic ions and nutrients highlight the leachate's capacity to cause both nutrient pollution and chemical corrosion. Nitrate (55.83) and Phosphate (67.00) vastly exceed limits, pointing to inputs from decomposing food waste and detergents. Nitrates pose a serious human health hazard, specifically the risk of methemoglobinemia in infants consuming contaminated groundwater (WHO, 2022). Elevated phosphate drives eutrophication in receiving waters (Ukah *et al.*, 2020).

The Sulphate (124.67) levels, slightly above the 100 benchmark, contribute to leachate corrosivity and can increase soil acidity upon infiltration. Finally, the extreme Chloride concentration (5220) over 50 times the standard, is a strong signature of high inputs from PVC materials and industrial salts. As discussed, this high salinity significantly amplifies the mobility of heavy metals, directly compounding the toxicity risks associated with Pb and Cd.

Heavy Metals and Pollution Indices

The heavy metal profile of the Oluku dumpsite leachate reflects a complex mixture of contamination arising from poorly segregated municipal and electronic waste (e-waste). Although the average Pollution Load Index (PLI = 0.92) suggests moderate overall pollution, the Potential Ecological Risk Index (PERI = 1214.14) reveals that the leachate poses a very high ecological threat (Hakanson, 1980). This contrast emphasizes that the risk is driven not by the general load of contaminants, but by the presence of a few highly toxic, non-compliant metals that dominate the environmental hazard landscape.

Cadmium (Cd)

Cadmium recorded a mean concentration of 0.39 exceeding the NESREA effluent limit of 0.01 by nearly forty-fold. Its high Contamination Factor (and exceptionally high-risk factor (E_r = 1170) unequivocally identify it as the chief ecological pollutant (Essien *et al.*, 2022). This extreme Cd concentration is consistent with the high e-waste burden across the region, aligning with findings from sites heavily impacted by battery and electronic waste (Iwegbue *et al.*, 2020). The alkaline pH further enhances Cd's mobility in soil and groundwater (Onwughara *et al.*, 2020). Cd readily bioaccumulates in plants and aquatic organisms, disrupting microbial balance and threatening biodiversity. From a health perspective, chronic human exposure via contaminated water or food crops poses severe risks, including renal dysfunction, "Itai-itai" disease (skeletal fragility), and cardiovascular problems (WHO, 2022).

Lead (Pb)

Lead exhibited a mean concentration of 0.59 exceeding its regulatory limit 0.1 by almost sixfold. This resulted in a CF of 5.9 and an E_r of 29.5 denoting a considerable ecological risk (Moderate category). Lead's presence is typical of battery waste, paints, and soldered materials, with concentrations comparable to those found in other high-salinity Nigerian leachates (Etim *et al.*, 2021). Though less soluble than Cd, Pb's strong affinity for organic matter ensures its persistence, where it inhibits soil enzyme activity and bioaccumulates in the food chain. Health-wise, chronic Pb exposure is a potent neurotoxin, causing neurological impairment and cognitive decline, particularly in children

(WHO, 2022). The high contribution from Cd and Pb largely accounts for the overall elevated PERI score.

Chromium (Cr) and Zinc (Zn)

Both Chromium (3.57) and Zinc (9.89) displayed concentrations above their NESREA standards, confirming a moderate pollution profile (Osazee *et al.*, 2021). The Pearson Correlation Heatmap (Figure 7) revealed a near-perfect positive correlation ($r \geq 0.98$) among Cr, Zn, Pb, and Cd, which provides statistical evidence that these metals are co-released and co-transported by the same principal leachate flow mechanism (Akinbile *and* Yusoff, 2011). The Cr concentration confirms input from non-compliant industrial waste (e.g., metal plating); Cr can inhibit microbial respiration, while excess Zn disrupts microbial processes and can inhibit plant growth. Health-wise, Cr, particularly the hexavalent form $Cr^{6+}$is a known human carcinogen, while chronic high Zn ingestion can interfere with the metabolism of other essential elements (WHO, 2022).

Copper (Cu) and Nickel (Ni)

Copper 0.93 and Nickel 0.19 recorded mean concentrations within permissible limits, with minimal ecological risk scores (Er<1) (Ukah *et al.*, 2022). Though compliant, these metals can accumulate in sediments; excess Cu can affect aquatic respiration and enzyme balance. Chronic Ni exposure is associated with dermatological issues and respiratory irritation (WHO, 2022).

Iron (Fe), Manganese (Mn), and Arsenic (As)

Iron (9.47) Manganese (0.11) and Arsenic (0.03) all remained below their respective NESREA standards. Environmentally, high Iron levels can alter the leachate's oxidation-reduction dynamics, influencing the solubility of other, more hazardous metals; Arsenic, even at trace levels, is ecologically significant due to its pervasive toxicity. Chronic Manganese ingestion is linked to neurological disorders, while Arsenic exposure is associated with skin lesions and carcinogenesis (WHO, 2022).

Vanadium (V)

The absence of Vanadium (V) (mean = 0.00) is noteworthy. Since V is often linked to the combustion of heavy fossil fuels, its non-detection suggests that the Oluku dumpsite has a limited historical input of oil-based industrial or power generation waste, differentiating it from sites located near heavy industrial complexes.

4.3 Flame Retardants in Oluku Dumpsite Leachate

The analysis of the leachate confirms substantial contamination by brominated flame retardants (BFRs), with concentrations many orders of magnitude above the EU Environmental Quality Standard (EQS) of (0.0005) (European Commission, 2013). This contamination confirms the site's status as a major hotspot for persistent organic pollutants originating from electronic, plastic, and municipal waste streams, with the overall pollution intensity rivalling dedicated industrial e-waste zones (Zhang *et al.*, 2022).

PBB-153

PBB-153 showed the highest concentration (310 ± 8.7) exceeding the EQS by over 60000-fold. This compound, used widely in legacy plastics and circuit boards, suggests a massive influx of older electronic waste (Tang *et al.*, 2023). PBB-153 is highly persistent, with a half-life exceeding 10 years in sediments. Its strong lipophilicity means it poses significant bioaccumulation and biomagnification risks up the food chain, representing the most significant long-term ecological hazard at the site. Furthermore, its

toxicity is linked to hepatocellular damage, immunosuppression, and neurobehavioral deficits in humans and animals (Tang *et al.*, 2023). Spatially, it exhibited high heterogeneity, suggesting contamination tied to specific waste accumulation zones (PT-6 being the peak at 55.0). Critically, its concentration showed only a moderate correlation ($r \approx 0.3$ to 0.6) with the core leachate indicators (Cl, CDS, Cd) in the Figure 7. This finding suggests its transport is largely decoupled from the bulk aqueous flow that mobilizes metals and ions, instead being dominated by sorption onto organic matter or suspended solids, resulting in a complex, particle-assisted transport pathway (Zhang *et al.*, 2022).

BDE-153

BDE-153 exhibited a high average concentration of 12.1±3.9 exceeding the EQS by over 24000-fold. This congener is less volatile but extremely persistent, with elevated levels indicating the aging and fragmentation of polymer-bound BFRs in discarded electronics and foams. The ecological persistence of BDE-153 means it readily adsorbs onto the high load of Total Suspended Solids (TSS), facilitating its entry into sediments where it can bioaccumulate in aquatic organisms. Chronic human exposure to this compound has been associated with endocrine disruption, impaired lipid metabolism, and reproductive toxicity (Rahman ets al., 2022). Similar to PBB-153 the statistical evidence of its moderate correlation with bulk contaminants further supports the hypothesis that its transport is governed by sorptive processes rather than simple aqueous dissolution.

BDE-47

BDE-47 recorded a mean concentration of 0.7±0.3. Its detection at multiple sampling points confirms its environmental mobility and aligns with previous findings from open dumpsites in Lagos and Accra (Asante *et al.*, 2019; Ogunjimi *et al.*, 2020). This congener is semi-volatile and highly mobile, tending to partition between aqueous and gaseous phases (Zhang *et al.*, 2022). Despite its relatively lower concentration, its persistence means that long-term bioaccumulation in soil biota and fish is certain if leachate infiltrates adjacent water bodies. BDE-47 is classified as a potent endocrine disruptor, known to interfere with thyroid hormone regulation and fetal neurodevelopment (Rahman *et al.*, 2022).

BDE-99 and BDE-100

Both BDE-99 and BDE-100 were detected at low mean concentrations of 0.2 ± 0.2 representing an EQS exceedance by over 400-fold. Their concurrent presence suggests thermal decomposition of octa- and deca-BDE mixtures, which points to evidence of open-burning practices within the dumpsite (Adegoke *et al.*, 2021). These lower-brominated congeners are highly bioavailable, and their long-term presence contributes to chronic groundwater contamination. Studies show that BDE-99 and BDE-100 induce oxidative stress and developmental toxicity in biological systems, and chronic exposure can impair hepatic and cognitive function (Chen *et al.*, 2021; Rahman *et al.*, 2022).

5. CONCLUSION

This study revealed that the Oluku dumpsite leachate is a chemically aggressive mixture with severe exceedances of regulatory limits for salinity, organic load, and nutrients, indicating strong mineralization, oxygen depletion, and high contamination potential. Heavy metals, particularly cadmium and lead, were identified as the dominant pollutants, driving a very high ecological risk index (PERI = 1214.14). Cadmium alone presented extreme ecological and health

risks, while lead and chromium added significant neurotoxic and carcinogenic burdens. The detection of exceedingly high brominated flame retardants (notably PBB-153 and BDE-153) marks one of the first reports of such contaminants in Nigerian dumpsite leachate, highlighting serious long-term bioaccumulation and ecological threats.

Based on these findings, it is recommended that immediate containment and treatment measures be implemented at the Oluku dumpsite. Priority should be given to installing engineered liners, leachate collection and treatment units employing oxidation, adsorption, or membrane filtration systems. Continuous monitoring of both inorganic and emerging organic pollutants should be institutionalized to track remediation efficiency. At the policy level, strict enforcement of e-waste management, waste segregation, and recycling regulations is essential to curb contaminant input. Finally, integrating ecological risk mapping, groundwater surveillance, and public awareness programs will strengthen long-term environmental protection and public health safety in the Oluku region and other similar unregulated dumpsites in Nigeria.

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