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CHARACTERIZATION OF TOXIC METALS AND FLAME RETARDANTS IN PRINTED CIRCUIT BOARDS FROM ELECTRONIC WASTE

ONUCHUKWU, S.C., UDOUSORO, I.I.* AND UMOREN, I.U.
Department of Chemistry, University of Uyo, Akwa Ibom State, Nigeria
***CORRESPONDENCE:** imaobong2i@yahoo.com (https://orcid.org/0000-0003-3227-7656)

ABSTRACT
The rapid growth of e-waste from advancing technology raises urgent environmental and health concerns, driven largely by printed circuit boards. This study evaluated toxic metals (As and Cd) and flame retardants (ΣPBDEs) in waste printed circuit boards (WPrCBs), soil, and borehole water from a dumpsite. WPrCBs exhibited the highest As (10.63 mg/kg) and Cd (10.05 mg/kg) levels, while ΣPBDEs reached 69.91 ng/g. Topsoil had elevated As and Cd levels compared to subsoil, reflecting surface accumulation; while borehole water mean concentrations were within permissible limits but posed potential health risks. Pollution indices confirmed significant Cd contamination, particularly in topsoil near the dumpsite. Health risk assessments showed higher non-carcinogenic exposure risks for children than adults, although total hazard quotients were below 1. Findings underscore the environmental impact of improper e-waste disposal and call for urgent remediation strategies to protect ecosystems and human health.

KEYWORDS: Waste Printed circuit boards (WPrCBs), Toxic metals, Flame retardants (ΣPBDEs), Soil and water contamination, Health risk assessment.

INTRODUCTION
The global proliferation of electronic waste (e-waste) has emerged as a significant environmental and public health issue. Defined broadly as Waste Electrical and Electronic Equipment (WEEE), e-waste includes any device dependent on electricity or batteries for operation and is deemed non-functional or obsolete (Faluyi *et al.*, 2023; Ghosh *et al.*, 2016). According to the Global E-waste Monitor 2024, approximately 62 million metric tons (Mt) of e-waste were generated worldwide in 2022, and this volume is projected to reach 82 million metric tons (32% rise) by 2030 due to rapid technological advancements, shorter product life cycles, and increasing digital dependence (https://unitar.org/about/news-stories/press/global-e-waste-monitor-2024-electronic-waste-rising-five-times-faster-documented-e-waste-recycling). Major regional contributors to this rise in e-waste in 2019 include Asia, America, and Europe which generated 24.9 Mt, 13.1 Mt and 12 Mt, respectively; while African countries generated the least (0.5 Kg of e-waste/capita). China alone generated 10.1 Mt (19% of global e-waste generation) and recycled 1546 kt of e-waste (https://emew.com/blog/global-e-waste-statistics). However, only 17.4% of this e-waste was formally collected and recycled, with the remaining waste often ending up in informal or unregulated dumping grounds (Widmer *et al*., 2005; Purchase *et al*., 2020).

Global e-waste management is critical due to its environmental and social impacts. Frameworks like the Basel Convention, RoHS Directive, and the Stockholm Convention aim to regulate hazardous waste, reduce toxic substances, and promote responsible recycling. However, inconsistent enforcement and inadequate recycling infrastructure limit effective management, especially in many regions (Oloruntoba *et al.*, 2022).

Prominent e-waste sites, such as Guiyu in China and Agbogbloshie in Ghana (Moeckel *et al.*, 2020), have become infamous for the hazardous disposal and processing practices that dominate these areas. In Agbogbloshie, for example, workers, including children, frequently dismantle electronic devices under unsafe conditions, releasing hazardous chemicals into the environment and exposing the community to toxic substances. These practices have led to the leaching of heavy metals and toxic chemicals, including lead, cadmium, and polybrominated flame retardants, into surrounding ecosystems. Such compounds pose severe health risks, including respiratory issues, neurodevelopmental damage, and even cancer, to the individuals directly handling the waste and communities living nearby (Perkins *et al*., 2014; Shamim *et al*., 2015).

Printed circuit boards (PrCBs) are integral to nearly all electronic devices and are a major source of toxic elements and chemicals within e-waste (Li *et al.*, 2004; Das *et al*., 2009). The rising global volume of PCBs typically contain significant concentrations of toxic metals like alumimium, arsenic, cadmium, copper, mercury, lead, zinc; and flame retardants (FRs), specifically polybrominated diphenyl ethers (PBDEs), designed to reduce flammability but known for their environmental persistence and bioaccumulative properties (Manikkampatti *et al.*, 2022). When improperly disposed of, these components release pollutants that can persist in the environment, contaminating air, soil, and groundwater, causing chromosomal damage and micronuclei formation, resulting in genetic instability in those exposed (Creamer *et al.*, 2006; Rimantho and Nasution, 2016).

While some studies have addressed the environmental contamination resulting from various types of e-waste disposal (Nnorom *et al.*, 2010; Yu *et al.*, 2017; Priya and Hait, 2018; Oloruntoba *et al.*, 2022), there remains limited comprehensive data on the precise composition of toxic metals and flame retardants in waste PCBs (WPrCBs) across varying electronic devices. This research aims to fill this gap by analyzing the chemical and elemental composition of WPrCBs sourced from TVs and mobile phones. Such

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characterization is essential to understanding the potential environmental and health risks associated with e-waste disposal, and recycling as well as encouraging safer e-waste management practices.

MATERIALS AND METHODS

Study area

The study area, Uyo Village Road Dumpsite in Akpayak Community near Wellington Bassey Road in Uyo Capital City of Akwa Ibom State, which is located in the South-South part of Nigeria. The city has a population of 427,873 according to the 2006 Nigerian Census. The coordinates of the sample locations are presented in Table 1.

Table 1: GPS location coordinates of samples

Sample type `	Sample code	Latitude (ºN)	Longitude (ºE)
WPrCBs	ETD	5.04511	7.93704
	EMP	5.04511	7.93704
Soil	Bs1* and 2º	5.04511	7.93704
	Ds1* and 2º	5.05014	7.9353
Borehole water	Aw	5.04761	7.937048
	Bw	5.05034	7.93671

1 = Topsoil (0 – 30 cm), 2º = Subsoil (100 – 120 cm)*

Samples collection and preparation

Waste printed circuit board (WPrCB) of various types, brands, manufacturers, years of manufacture, and sizes of e-waste were collected at Uyo village road dumpsite (Fig. 1). The samples were air-blown and washed with deionized water to remove sand particles and other particles before being dismantled and separated into different components. WPrCBs (Fig. 2b) were cut and ground in a heavy-duty stainless mill after sorting out the various components and passed through a 2 mm mesh sieve to ensure the desired particle size. The crushed samples were stored in Ziploc bags and aluminum foils prior to analysis.

Soil samples were taken at two depths (0-30 cm and 100-120 cm). The samples were air-dried and homogenized, sieved through a 2 mm mesh size, and then placed in the proper containers (Ziploc bags for metals and aluminum foil for FRs) until further analysis was performed. Water samples were collected from different boreholes around the dumpsite area with polyethylene bottles (1.0 L plastic bottles for metals and 250 mL Amber bottles for FRs). The water samples were stored in an ice-chest box and transported to the laboratory for analysis.

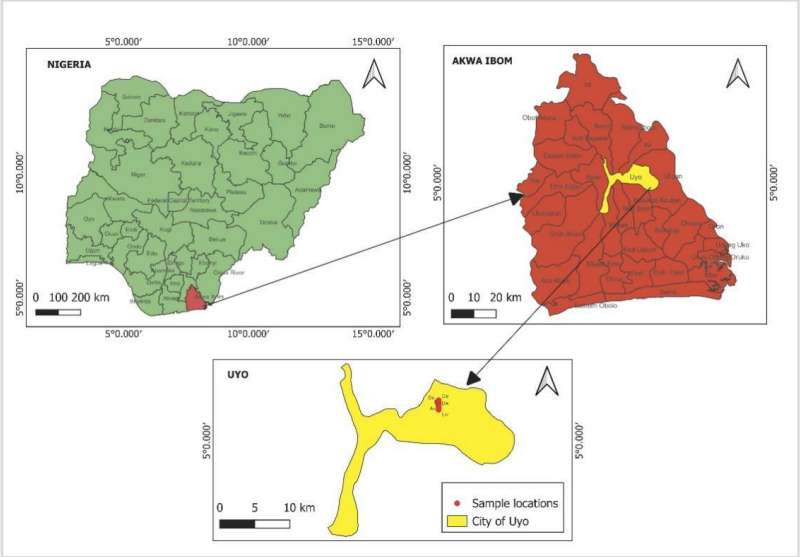

Fig. 1: Sample locations around the Uyo Village Road Dumpsite

A B

Fig. 2: Waste printed circuit boards (WPrCBs) before (A) and after (B) cleaning and separation

Digestion WPrCBs, soil and borehole water samples

A representative sub-sample (0.5 g) from thoroughly crushed WPrCBs sample was digested according to EPA Method 3050B (EPA, 1996) and Nnorom *et al.* (2010). The method was used with slight modifications (especially with respect to refluxing and duration of heating). The digest was filtered into 50 mL volumetric flasks and diluted with deionized water. A 0.3 g soil sample was digested based on EPA Method 3050. Finally, the sample digest was filtered into a 50 mL volumetric flask and diluted to volume with de-ionized water. A 50 mL of borehole water sample was digested based on EPA Method 600/4-79/020. The digest was filtered into 50 mL volumetric flasks and diluted with deionized water. Blank samples were analysed using the same procedure but without the sample. All sample digests were analyzed for toxic metals using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES).

Extraction, clean-up and analysis of flame retardants (FRs)

Approximately 1 g of each solid sample (soil and WPrCBs) and 5 mL of water sample was transferred into a 20 mL glass centrifuge tube. 10 mL and 5 mL of chloroform was added to the solid samples and the liquid samples, respectively. Chloroform was used in the study due to its superior eluting power compared to other organic solvents (dichloromethane, methanol, hexane etc.). The solid samples were centrifuged at 250 r/min for an hour (Centrifuge Model SM90, Surgfield Medical, England), while liquid samples underwent solvent extraction. Supernatants were then transferred to glass micro-columns packed with a 1:1 mixture of silica gel and anhydrous sodium sulphate. Flame retardants in the sample extracts were eluted using chloroform and analyzed using an Agilent 5890 Series II Gas Chromatographic system with a flame ionization detector (GC-FID). Chromatographic conditions are detailed as follows: Type of column (Capillary), Diameter (0.25 mm), Thickness (0.1 mm), Oven temperature (50°C), Injection mode (Split less), Injector temperature (260°C), Carrier gas (Helium), and Flow rate (1.5 mL/min).

Quality Control and Quality Assurance Protocol

Accurate results were guaranteed through quality control. Glass and plastic items were cleaned with 5% HNO_3, rinsed with deionized water, and stored appropriately. Reagent of analytical quality (AnalaR grade) were employed and analyses were in triplicate. By performing spiked recovery studies on the samples with known concentrations of the standard solutions, analytical processes were verified (Udousoro *et al.*, 2018). The percentage recoveries of elements in samples were computed using equation 1 and ranged from 90.8% to 100% (Table 2):

$$\text{Recovery (\%)} = \frac{C_{\text{spiked}} - C_{\text{unspiked}}}{C_{\text{spiked}}} \times 100 \quad (1)$$

Linearity and precision were assessed using six dilutions of standard PBDE mixtures in isooctane (1–50 ng/mL). Blank and low-spiked samples were analyzed to determine detection and quantification limits, with a minimum signal-to-noise ratio of 3. Spiked sample recoveries exceeded 80%. Calibration curves, constructed for each analysis sequence, showed strong linearity ($R^2 > 0.99$) based on peak area versus PBDE concentration (Table 3).

Table 2: Recovery studies for selected toxic metals

	Elements	Spike Conc. (µg/mL)	Conc in Spiked Sample	Conc in Unspiked Sample	Recovery (%)
WPrCBs	As	2	4.21	2.26	97.9
	Cd	2	3.36	1.36	100
Soil	As	2	3.40	1.40	100
	Cd	2	4.02	2.12	95
Borehole water	As	2	3.46	1.46	100
	Cd	2	1.83	0.01	90.8

Table 3: LOD, LOQ, R^2 and recovery for selected flame retardants

PBDEs	LOD (ppm)	LOQ (ppm)	R^2	Recovery (%)
2,4'-DB	0.109	0.3633	0.99697	92
2,2',4-TB	0.0054	0.0179	0.99983	95

PBDEs = Polybrominated diphenyl ethers, 2,4'-DB = 2,4'-Dibromodiphenyl ether, 2,2',4-TB = 2,2',4-Tribromodiphenyl ether, LOD = Limits of detection, LOQ = Limits of quantification

Risk Assessment Studies

Environmental assessment: Nemerow integrated pollution indices were used to assess the level of soil contamination. They were computed using equations 2 and 3.

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

$$\mathbf{I} = \sqrt{\frac{(PI)^2_{max} + (PI)^2_{min}}{2}} \quad (3)$$

Where **PI** represents the pollution index for a single element, $\mathbf{C_i}$ is the concentration of heavy metals in soil, **Si** is the standard concentration for heavy metals in soil. The

integrated pollution index **I** reflects the degree of overall soil contamination. The $\mathbf{S_i}$ (mg/kg) for Cd = **0.3** (Liu *et al.*, 2021) and **6.8** for As (Saha *et al.,* 2017). A **PI < 1** indicates no pollution, while **I < 3** signifies low contamination level.

Non-carcinogenic risk assessment*:* Using a heavy metal exposure assessment model, the study evaluated the average daily dosage (ADDing) from exposure pathways and its total hazard quotient (THQ) to determine the risk to human health. The exposure assessment model was computed using equations 4 and 5 (Ahmad *et al.*, 2021).

$$ADD_{ing} = C_{(mg/kg)} \times \frac{IngR \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (4)$$

$$THQ = \frac{ADD_{ing}}{RfD} \quad (5)$$

Where the parameters are defined as follows; C: concentration of TMs in mg/kg, IngR: ingestion rate given as 200 mg day^{-1} for children and 100 mg day^{-1} for adults, EF: exposure frequency as 180 day $year^{-1}$, ED: exposure duration as 6 years for children and 24 years for adult, BW: average body weight as 15 kg for children and 70 kg for adults, and AT: averaging time (for non-carcinogens, ED×365 days) (Ahmad *et al.,* 2021). RfD is the oral reference doses (mg/kg/day), for Cd=1.00E-03 (Udousoro *et al.,* 2018) and As = 3.00E-04 (Ahmad *et al.*,2021). THQ < 1 means there is no significant adverse effect on the exposed population, whereas THQ ≥1 implies potential health risk.

RESULTS AND DISCUSSION

Toxic metals in WPrCBs, soil and water

The study revealed variations in arsenic (As) and cadmium (Cd) concentrations across waste printed circuit boards (WPrCBs), soil, and borehole water. The highest mean concentrations were observed in WPrCBs (As: 10.6 mg/kg; Cd: 10.1 mg/kg), followed by topsoil (As: 6.14 mg/kg; Cd: 3.94 mg/kg) and subsoil (As: 1.92 mg/kg; Cd: 2.90 mg/kg), with borehole water recording the lowest levels (As and Cd: 0.01 mg/L) (Table 4). Comparatively, WPrCBs from India exhibited higher As (25 mg/kg) and Cd (646 mg/kg) concentrations (Priya and Hait, 2018; Table 5), reflecting regional variations influenced by e-waste import policies, manufacturing practices, and local geology (Baldé *et al.*, 2017; Liu *et al.*, 2021).

Higher As and Cd concentrations in topsoil indicate surface accumulation from WPrCB leachates, limited vertical mobility due to adsorption on organic matter and clay minerals, and potential uptake by plants. While As levels in soil were within agricultural safety limits (10–50 mg/kg; EC, 2006), Cd exceeded the threshold (1–3 mg/kg), posing risks to food security. Contamination levels were slightly higher than those reported in Alaba, Lagos (Table 5). Soil texture, organic matter, and climatic conditions influence heavy metal absorption with rainfall promoting leaching and metal transport into water bodies. Temperature variations can further affect microbial activity and chemical reactions in the soil, altering the speciation and mobility of these metals (Olusegun *et al.*, 2021).

Borehole water As levels met WHO (2017) limits (0.01 mg/L), while Cd was below permissible levels (0.005 mg/L), lower than Ghanaian reports (0.031 mg/L) (Cobbina *et al.*, 2013). Contamination is influenced by natural geology and anthropogenic activities, including industrial effluents (Nriagu and Pacyna, 1988). Heavy metals and brominated flame retardants leach into water through redox interactions, soil acidity, and hydrophobic properties (Segev *et al.*, 2009; Gupta and Nath, 2020; Medunić *et al.*, 2020).

Chronic As and Cd exposure is linked to carcinogenesis, kidney damage, and cardiovascular diseases (Singh *et al.*, 2007; Prakash and Verma, 2021; Fatoki and Badmus, 2022). In Nigeria, urgent policies are required to improve e-waste management and reduce environmental contamination. These findings underscore the need for monitoring, soil stabilization, and advanced treatment technologies to mitigate contamination risks.

Flame Retardants in WPrCBs, soil and water

The highest concentration of polybrominated diphenyl ether (ΣPBDEs) which is categorized as one of the popularly used FRs was found in WPrCBs (69.91 ng/g), followed by topsoil (8.29 ng/g), borehole water (3.97 ng/mL), and below detection limits (BDL) in subsoil (Table 4). The topsoil's elevated levels highlight its role as a primary sink due to limited pollutant mobility. Comparatively, WPrCBs in this study contained lower ΣPBDEs than reported in India (1.73×10^7 ng/g) for TV WPrCBs (Priya and Hait, 2018). Though the concentrations were below the EU Restriction of Hazardous Substances (RoHS) threshold of 1×10^6 ng/g (Table 5), appropriate waste management is essential to avoiding environmental degradation. At the dumpsite, there was higher concentrations of PBDE in the soil, with notable differences when compared to other areas. Top-soil concentrations aligned with lower values from Agbogbloshie (6.3-7,700 ng/g) and Kingtom (1.2-100 ng/g) in Ghana (Table 5).

In borehole water, ΣPBDEs exceeded the 5×10^{-7} ng/mL quality standard, posing health risks linked to neurotoxicity, endocrine disruption, and carcinogenicity. This emphasizes the need for improved water quality and monitoring. Effective e-waste management, eco-friendly recycling, and soil and water remediation are essential to mitigate environmental and health impacts, protect vulnerable populations, and ensure regulatory compliance.

Table 4: Concentrations of toxic metals (mg/kg; mg/L*) and flame retardants (ng/g, ng/L**) in samples

	Metals			Flame retardants		
Sample type	**Sample code**	**As**	**Cd**	**Sample code**	**2,4'-DB**	**2,2',4-TB**
WPrCBs	ETD	8.35±6.0	10.9±0.5	ETD	43.9	8.64
	EMP	12.9±1.2	9.25±0.4	EMP	14	3.37
	Mean	**10.6±3.2**	**10.1±1.1**	**Total**	**57.9**	**12.01**
Top-soil	Bs1 (0-30 cm)	4.94±3.4	5.15±0.4	Bs1 (0-30 cm)	BDL	BDL
	Ds1 (0-30 cm)	7.34±4.5	2.73±0.2	Ds1 (0-30 cm)	8.29	BDL
	Mean	**6.14±4.0**	**3.94±0.3**	**Total**	**8.29**	**BDL**
Sub-soil	Bs2 (100-120 cm)	BDL	4.14±0.29	Bs2 (100-120 cm)	BDL	BDL
	Ds2 (100-120 cm)	3.84±3.3	1.65±1.0	Ds2 (100-120 cm)	BDL	BDL
	Mean	**1.92±1.7**	**2.90±0.6**	**Total**	**BDL**	**BDL**
Borehole Water	Aw	BDL	0.01±0.00*	Aw	1.94**	1.15**
	Bw	0.02±0.0*	0.01±0.0*	Bw	0.88**	BDL
	Mean	**0.01±0.0***	**0.01±0.0***	**Total**	**2.82****	**1.15****

BDL = Below detection limit, 2,4'-DB = 2,4'-Dibromodiphenyl ether, 2,2',4-TB = 2,2',4-Tribromodiphenyl ether.

Table 5: Comparison of toxic metal and PBDE levels with previous studies and regulatory standards

Location	**Sample**	**As (mg/kg)**	**Cd (mg/kg)**	**PBDEs (ng/g)**	**References**
Uyo, Nigeria	WPrCBs	10.63±3.22	10.05±1.14	69.91	Present study
Patna, Bihar, India	TV WPrCBs	25±6	646±148		Priya and Hait, 2018
	PC WPrCBs	36±**8**	399±118		Priya and Hait, 2018
	Laptop WPrCBs	33±**4**	269±43		Priya and Hait, 2018
China	TV WPrCBs	-	-	1.7285E+07	Yu *et al.,* 2017
Threshold limit by RoHS	WPrCBs	-	-	1E+06	EU, 2011
Uyo, Nigeria	Top-soil	6.14±3.96	3.94±0.30	8.29	Present study
	Sub-soil	1.92±1.65	2.90±0.63	BDL	Present study
Alaba Lagos, Nigeria	Top-soil	-	3.6	-	Olusegun *et al.,* 2021
	Sub-soil	-	1.7	-	
Agbogbloshie, Ghana	Top-soil	-	-	6.3 - 7,700	Moeckel *et al.,* 2020
Kingtom, Ghana	Top-soil	-	-	1.2 - 100	Moeckel *et al.,* 2020
Permissible limit	Soil	10 – 50	1 – 3	-	EC, 2006
		(mg/L)	**(mg/L)**	**(ng/mL)**	
Uyo, Nigeria	Borehole water	0.01±0.01	0.01±0.00	3.97	Present study
Tinga, Ghana	Borehole water	-	0.031±0.02	-	Cobbina *et al.,* 2013
EQS	Surface water	-	-	5E-07	EU, 2013
Permissible limit	Drinking water	0.01	0.005	-	WHO (2017)

RoHS = Restriction of Hazardous Substances, WHO = World Health Organization, EC = European Commission, EQS = Environmental Quality Standard

Risk Assessment Studies

Pollution indices, soil contamination, and health risk assessment: The pollution indices (PI) for arsenic (As) and cadmium (Cd) were above 1 (PI > 1), meaning there is pollution from these elements, and further research is needed on the pollution indices of others. The degree of soil contamination was high (I > 3) around the dumpsite. Contamination levels (I) were elevated near the dumpsite (I > 3), while distant soils had lower contamination levels (I < 3). (Table 6). Elevated contamination near waste sites necessitates urgent remediation to protect vulnerable populations, particularly children, from long-term exposure. Essential measures include stricter hazardous waste regulations, enhanced public awareness, and improved waste management strategies. Nigeria faces challenges in e-waste management due to weak regulations and informal recycling, often involving unsafe practices like open burning. The Extended Producer Responsibility (EPR) framework and international collaborations have supported recycling efforts, but enforcement remains inadequate (Kang and Schoenung, 2004; Baldé *et al.*, 2017). A shift to a circular economy—emphasizing sustainable product design, remanufacturing, and efficient recycling—can mitigate environmental risks while fostering economic growth (Geissdoerfer *et al.*, 2017). Non-carcinogenic risks of As and Cd ingestion through soil and borehole water revealed higher average daily doses (ADDing) for children than adults, indicating greater exposure of children to the non-

carcinogenic risks. However, total hazard quotients (THQ) for both groups were below 1 (THQ < 1), indicating no significant adverse health effects from metal exposure via water and soil (Table 7). Generally, the findings indicate high contamination levels and no significant adverse health effects on the exposed population, and the dumpsite exhibits high pollution levels, and areas farther away demonstrate reduced contamination.

Table 6: Environmental assessment study on soil samples

Sample code/Depth	Parameters	SC	MC	PI	I
Bs1 (0 – 30 cm)	As	6.8	4.94±3.37	0.73	6.57
	Cd	0.3	5.15±0.35	17.17	5.16
Bs2 (100 – 120 cm)	As	6.8	0	0	0
	Cd	0.3	4.14±0.29	13.81	4.12
Ds1 (0 – 30 cm)	As	6.8	7.34±4.54	1.08	7.46
	Cd	0.3	2.73±0.25	9.10	2.68
Ds2 (100 – 120 cm)	As	6.8	3.84±3.30	0.56	4.28
	Cd	0.3	1.65±0.97	5.51	1.63

SC** = Standard Concentrations (mg/kg), **MC** = Mean Concentrations (mg/kg),* **PI** *= Pollution indices,* **I** *= Degree of soil contamination.* **PI < *1 *means no pollution and* **I < *3*** *means low level of combined pollution. SC values for As = 6.8 (Saha et al., 2017) and Cd = 0.3(Liu et al., 2021).*

Table 7: Non-carcinogenic risk assessment study on soil and water samples

Sample type	Code	Parameters	As	Cd
Borehole water	Aw	ADD_{ing} (children)	0	8.75E-08
		ADD_{ing} (adults)	0	9.37E-09
		THQ (children)	0	8.75E-05
		THQ (adults)	0	9.37E-06
	Bw	ADD_{ing} (children)	1.02E-07	7.52E-08
		ADD_{ing} (adults)	1.10E-08	8.06E-09
		THQ (children)	3.41E-04	7.52E-05
		THQ (adults)	3.66E-05	8.06E-06
Soil	Bs1 (0-30 cm)	ADD_{ing} (children)	3.25E-05	3.39E-05
		ADD_{ing} (adults)	3.48E-06	3.63E-06
		THQ (children)	1.08E-01	3.39E-02
		THQ (adults)	1.16E-02	3.63E-03
	Bs2 (100-120 cm)	ADD_{ing} (children)	0	2.72E-05
		ADD_{ing} (adults)	0	2.92E-06
		THQ (children)	0	2.72E-02
		THQ (adults)	0	2.92E-03
	Ds1 (0-30 cm)	ADD_{ing} (children)	4.82E-05	1.79E-05
		ADD_{ing} (adults)	5.17E-06	1.92E-06
		THQ (children)	1.61E-01	1.79E-02
		THQ (adults)	1.72E-02	1.92E-03
	Ds2 (100-120 cm)	ADD_{ing} (children)	2.53E-05	1.09E-05
		ADD_{ing} (adults)	2.71E-06	1.16E-06
		THQ (children)	8.42E-02	1.09E-02
		THQ (adults)	9.02E-03	1.16E-03
		RfD	3.00E-04	1.00E-03

ADD_{ing} = Average daily dosage for ingestion, THQ = Total hazard quotient, RfD = Oral reference dose. THQ < 1 means there is no significant adverse effect on the exposed population

CONCLUSION

This study assessed toxic metals and PBDE concentrations in soil, borehole water, and WPrCBs at the Uyo Village Road dumpsite in Akwa Ibom State, Nigeria, highlighted the environmental impact of unmanaged e-waste disposal. WPrCBs exhibited the highest concentrations of pollutants, with PBDE levels below RoHS guidelines. Significant contamination was observed in topsoil and borehole water, with Cd exceeding permissible limits, underscoring its role in soil pollution. Although borehole water met WHO safety

thresholds, its proximity to contamination sources raises concerns about long-term risks. Health risk assessments confirmed children's vulnerability to non-carcinogenic risks, emphasizing the need for immediate pollution control measures.

The study highlights critical gaps, including the absence of long-term monitoring data to assess temporal variations and the broader impacts of e-waste management in Uyo. Additionally, limited research on e-waste composition, accumulation, and handling within the dumpsite restricts a comprehensive understanding of environmental and health implications. Future research should focus on long-term monitoring, detailed compositional analysis of e-waste, and pathways of pollutant dispersion. Strengthening e-waste recycling practices, soil remediation, and water quality monitoring is essential to mitigating contamination risks and ensuring sustainable environmental management in the region.

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