



Environmental Assessment of Polybrominated Diphenyl Ethers (PBDEs) from Electronic Waste

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ABSTRACT

The rapid proliferation of electronic waste due to technological advancements poses significant environmental and public health risks, particularly from printed circuit boards (PrCBs), which contain persistent organic pollutants such as brominated flame retardants (BFRs). Among these, polybrominated diphenyl ethers (PBDEs) are of particular concern due to their environmental persistence and potential toxicity. This study assessed the levels of Σ PBDEs in waste printed circuit boards (WPrCBs), soil, and borehole water collected from the Uyo Village Road Dumpsite and its surrounding environment in Uyo, Akwa Ibom State, Nigeria. Quantitative analysis was conducted using gas chromatography coupled with a flame ionization detector (GC-FID). Results revealed that soil samples exhibited the highest Σ PBDE concentrations, ranging from 423.93 to 1420.06 ng/g in topsoil and 469.36 to 1568.45 ng/g in subsoil, followed by WPrCBs (22.56 to 824.23 ng/g) and borehole water (1.53 to 12.75 ng/mL). The highest contamination level was detected in subsoil beyond the dumpsite (Ds2: 1568.45 ng/g), whereas the lowest concentration was found in borehole water upstream of the dumpsite (Cw: 1.53 ng/mL). The elevated levels in subsoil indicate progressive accumulation and leaching, while the low borehole water concentrations suggest that groundwater contamination is still at an early stage. These findings stress the urgent need for effective e-waste management, soil remediation measures, and groundwater protection strategies to reduce environmental and health risks from improper e-waste disposal.

1. INTRODUCTION

E-waste is an alternative term for waste electrical and electronic equipment (WEEE). Although there is no universally recognized terminology for this category of waste, most nations and regions classify e-waste according to their own regulations and standards [1]. It encompasses electrical equipment approaching the end of its

operational lifespan, as well as any non-functional devices that operate on electricity or batteries [2].

Printed circuit boards (PrCBs), which are electrical circuit boards that interconnect components in electronic devices, present the most significant challenges in e-waste recycling due to

their complex designs, high metal content, and potential hazards. Typically, PCB composition consists of 40% ceramics, 30% plastic components, and 40% metals [3, 4]. Waste printed circuit boards (WPrCBs) contain organic substances, heavy metal components, and chemical residues that pose risks to human health and the environment when improperly disposed of in the ecosystem [5]. When WPrCBs are released into the air, water, or landfills, the hazardous pollutants within them induce chromosomal abnormalities and micronuclei formation, leading to genetic instability in exposed individuals [6, 7].

Flame retardants (FRs) are among the most crucial chemical compounds utilized in the manufacture of electronic devices. They function as protective materials to delay ignition, thereby reducing the flammability of combustible materials and enhancing safety for humans and property [8]. Many contemporary materials, particularly plastics, are inherently flammable due to their high carbon and hydrogen content, rendering them easily combustible [9]. Portable devices such as laptops and mobile phones may contain significant levels of flame retardants (FRs) in the electrical and electronics sector [10]. FRs can comprise various chemical substances, irrespective of their molecular composition or physicochemical characteristics. They can be incorporated as reactive FRs or added as additive FRs to impart flame-retardant properties to materials such as wood, plastics, appliances, computers, electrical cables, building supplies, fabrics, and upholstery [11]. One of the primary advantages of utilizing flame retardants in product design is their capacity to prevent small ignition events from escalating into larger fire scenarios. This property provides individuals with additional time to evacuate and emergency responders with extended response time [12]. FRs are among the waste chemicals that contribute significantly to organic pollutants emanating from electronic devices. As these organic pollutants are resistant to degradation by chemical, biological, and photolytic processes in the environment, they are classified as persistent organic pollutants (POPs). Examples of POP classes include polycyclic aromatic hydrocarbons (PAHs), polyhalogenated aromatic hydrocarbons (PHAHs), polychlorinated biphenyls

(PCBs), polybrominated biphenyls (PBBs), and polybrominated diphenyl ethers (PBDEs) [10, 13].

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>).

The global FR consumption reached over 2.4 million tons in 2019, representing a 4.9 percent increase in market size, which was projected to grow to a value of almost \$53 billion by 2024 [14, 15]. The world's largest consumer of FR, making up 26% of consumption, is China, followed by Western Europe (23%), North America (22%), Asia (18%), and Japan (6%). Five percent (5%) of global consumption is accounted for by the Middle East and Africa, Central and Eastern Europe, and Central and South America combined. More than 175 FR compounds are on the list and they are categorized according to their chemical constituents. Only one substance, aluminum trihydroxide ($\text{Al}(\text{OH})_3$) is the most consumed FR globally, accounting for 38% of all FRs consumed. Halogenated flame retardants (HFRs) come next (21%) which are composed of 17% brominated FRs and 4% chlorinated FRs, followed by organophosphorus (18%). Other classes, like metal-based FRs, account for 14% of the world's consumption, with FRs based on antimony oxides coming in next (9%) [15].

E-waste contains a variety of halogenated compounds, predominantly in the form of liquid crystals in LCDs, plastic casings, keyboards, chargers, and cables, as well as flame retardants (FRs) utilized in waste printed circuit boards (WPrCBs) [16]. Many of these compounds are persistent organic pollutants (POPs), which are regulated by the Stockholm Convention. These include, inter alia, the brominated flame retardant (BFR) group, which encompasses tetrabromobisphenol-A (TBBP-A), polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs), and hexabromocyclododecanes

(HBCDDs). Most liquid crystals in LCDs are composed of organic compounds, primarily carbon, hydrogen, oxygen, and fluorine [17]. BFRs, which constitute one of the principal manufactured halogenated flame retardants employed since the 1960s in products, have been a subject of concern for the past two decades due to their persistence, bioaccumulative properties, and toxicity characteristics [18]. Since the 1970s, PBDEs have been utilized as flame retardants in a wide range of consumer goods, including furniture, textiles, electronics, and car seats. PBDEs belong to the class of additive brominated flame retardants (BFRs), which are not covalently bonded to the products [19]. PentaBDE, octaBDE, and decaBDE are the three primary commercial mixtures of PBDEs that have been marketed; each mixture comprises numerous brominated diphenyl ether (BDE) congeners. A significant mechanism by which PBDEs are exported to developing nations such as Ghana, Nigeria, China, and India are through the importation of electronics [20, 21, 22, 23, 24]. PBDEs exhibit a high potential for long-range environmental transport, enabling them to deposit far from their source. They are also highly persistent in the environment and bioaccumulative in the food chain [25]. These compounds have been detected in humans as well as in increasing concentrations in various environmental matrices, such as air, water, soil, sediment, animals, and food, across all regions of the world [26]. Adverse effects that have been demonstrated to occur in both humans and wildlife include endocrine disruption, immunotoxicity, reproductive toxicity, impacts on fetal/child development, thyroid and neurologic function, and carcinogenicity [27, 28, 29, 30]. PBDEs can enter the environment through various pathways, including emissions from manufacturing processes, combustion from products in use, leaching from landfills, and recycling of e-waste [27]. The primary environmental receptors of chemical emissions from informal e-waste recycling are soil and dust. Consequently, soil has the potential to serve as secondary sources of PBDE emissions and can contaminate food, water, and air [25].

While numerous studies have addressed the environmental contamination resulting from various types of e-waste disposal [31, 32, 33, 34,

35], there remains a paucity of comprehensive data on the precise composition of flame retardants in waste PrCBs (WPrCBs) across diverse electronic devices. This research aims to address this knowledge gap by analyzing the chemical composition of WPrCBs sourced from various types of electronic devices. Such characterization is essential for understanding the potential environmental and health risks associated with e-waste disposal and recycling, as well as informing more effective e-waste management practices.

2. MATERIALS AND METHOD

2.1. Study Area

The study area, Uyo village road dumpsite, is located in Akpayak community near Barracks Road in Uyo city, Akwa Ibom State, situated in the South-Southern region of Nigeria. According to the Nigerian Census of 2006, the city has a population of 427,873 inhabitants. The coordinates of the sample locations are presented in Table 1.

Table 1: GPRS location of samples

Sample type	Sample code	Latitude (°N)	Longitude (°E)
WPrCBs	ETD	5.04511	7.93704
	EAP	5.04511	7.93704
	EMP	5.04511	7.93704
	ERS	5.04511	7.93704
	ECL	5.04511	7.93704
Soil	As	5.04742	7.93657
	Bs	5.04511	7.93704
	Cs	5.04899	7.93568
	Ds	5.05014	7.93530
Borehole water	Aw	5.047610	7.937048
	Bw	5.050340	7.936710
	Cw	5.052100	7.936991
	Dw	5.042990	7.937254
	Ew	5.040086	7.936995

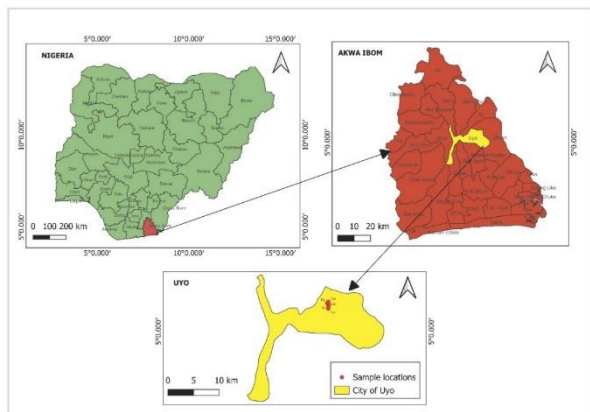


Figure 1: Map of Uyo showing the sample locations

2.2. Sample Collection and Preparation

About 30 kg of waste printed circuit boards (WPrCBs) of various types, brands, manufacturers, years of manufacture, and sizes of e-waste were collected at Uyo village road dumpsite. The samples were air-blown and washed with deionized water to remove sand particles and other contaminants before being dismantled and separated into plastics, motors/coils, ferrous and non-ferrous metals, circuit boards, batteries, and other materials. WPrCBs were cut and ground in a heavy-duty 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 aluminum foils prior to analysis.

Eight (8) soil samples (a composite of 10 samples each) were excavated at two depths (0-30 cm and 100-120 cm), four (4) samples at each depth. The samples were air-dried and homogenized, sieved through a 2 mm mesh size, and then placed in the proper containers (Aluminum foil) until further analysis were performed.

Five (5) borehole water samples were collected from different boreholes drilled around the dumpsite surroundings with sampling bottles (250 ml Amber bottles). The water samples were stored in an ice cooler and transported to the laboratory for analysis.

2.3. Sample Extraction and Clean-up

After samples were prepared, approximately 1 g

of each sample (soil and e-waste) and 5 mL of water sample was transferred into a 10 mL glass centrifugal tube. 10 mL of chloroform were added to the solid samples while 5 mL were added to the liquid sample given the ratio of 1:1. Chloroform was used in this study due to its high eluting power compared to other organic solvents (dichloromethane, methanol, hexane etc.). The solid sample solutions were centrifuged at 250 r/min for 1 hr (Centrifuge Model SM90, Surgfield Medical England). The liquid sample were extracted using solvent extraction method. After extraction, the supernatants were then transferred to a glass micro-column packed with 1:1 ratio mixture of silica gel and sodium sulphate anhydrous. FRs in the sample extract were eluted from the column by chloroform and concentrated to 10 mL.

2.4. Instrumental Analysis (GC-FID)

The sample extracts were analyzed for Polybrominated diphenyl ethers (PBDEs) using an Agilent 5890 Series II Gas Chromatographic system connected to flame ionization detector (GC-FID). The GC system was operated in split less injection mode, and the injector temperature was maintained at 260°C. A 15 m DB-5HT capillary column (0.25 mm i.d., 0.1 mm film thickness; J&W Scientific, USA) was used with helium as a carrier gas at a constant flow rate of 1.5 ml/min. The oven temperature program started at 50°C (held for 1 min), ramped to 220°C at 15 °C/min, and 300°C at 8 °C/min (held for 13 mins). Other gases employed in the GC-FID setup were hydrogen gas which serves as fuel gas for FIDs and compressed air which provides oxidant gas for detection.

2.5. Quality Control and Quality Assurance Protocol

Accurate results were ensured through rigorous quality control. 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 2).

Table 2: Limits of detection (LOD) and quantification (LOQ), R^2 and recovery of PBDEs

S/No	Components	LOD (ppm)	LOQ (ppm)	R^2	Recovery (%)
1.	2- BDE	0.00320	0.01060	0.99987	99.9
2.	3- BDE	0.00010	0.00030	0.99988	99
3.	4- BDE	0.05030	0.16770	0.99195	98
4.	2,4-Di BDE	0.00420	0.01390	0.99974	95
5.	2,4'-Di BDE	0.10900	0.36330	0.99697	92
6.	2,6-Di BDE	0.10200	0.33990	0.99440	96
7.	3,3'-Di BDE	0.00250	0.00610	0.99968	91
8.	3,4-Di BDE	0.04700	0.15670	0.99946	90
9.	3,4'-Di BDE	0.00090	0.00300	0.99932	93
10.	4,4'-Di BDE	0.00030	0.00100	0.99546	94
11.	2,2',4-Tri BDE	0.00540	0.01790	0.99983	95
12.	2,3',4-Tri BDE	0.00120	0.00400	0.99970	96
13.	2,4,4'-Tri BDE	0.00150	0.00530	0.99504	89
14.	2,4,6-Tri BDE	0.00130	0.00440	0.99410	96.5
15.	2,4',6-Tri BDE	0.00060	0.00200	0.99907	88
16.	2',3,4-Tri BDE	0.00080	0.00260	0.99410	97
17.	3,3',4-Tri BDE	0.00050	0.00160	0.99965	93
18.	3,4,4'-Tri BDE	0.00060	0.00210	0.99697	94
19.	2,2',4,4'-Tetradi BDE	0.00090	0.00300	0.99876	88
20.	2,2',4,5'-Tetra BDE	0.00070	0.00230	0.99932	95
21.	2,3',4,4'-Tetra BDE	0.00040	0.00130	0.99974	89
22.	2,3',4',6-Tetra BDE	0.00090	0.00310	0.99697	86
23.	2,4,4',6-Tetra BDE	0.00900	0.03100	0.99907	90
24.	3,3',4,4'-Tetra BDE	0.00700	0.02330	0.99546	94.5
25.	2,2',3,4,4'-Penta BDE	0.00090	0.00310	0.99983	95
26.	2,2',4,4',5-Penta BDE	0.00300	0.00980	0.99970	96
27.	2,2',4,4',6-Penta BDE	0.00600	0.01950	0.99504	98
28.	2,3,4,5,6-Penta BDE	0.00900	0.03600	0.99986	90
29.	2,3',4,4',5-Penta BDE	0.01210	0.03630	0.99980	89
30.	2,3',4,4',6-Penta BDE	0.02140	0.06300	0.99190	87
31.	3,3',4,4',5-Penta BDE	0.01210	0.03300	0.99934	91
32.	2,2',3,4,4',5'-Hexa BDE	0.01200	0.03300	0.99400	85
33.	2,2',4,4',5,5'-Hexa BDE	0.00320	0.00610	0.99901	93
34.	2,2',4,4',5,6'-Hexa BDE	0.00320	0.00630	0.99410	86
35.	2,2',4,4',6,6'-Hexa BDE	0.01100	0.03030	0.99985	89
36.	2,3,4,4',5,6-Hexa BDE	0.00910	0.02700	0.99667	88
37.	2,2',3,4,4',5,6-Hepta BDE	0.01200	0.03100	0.99975	98
38.	2,2',3,4,4',5',6-Hepta BDE	0.00920	0.02070	0.99898	98
39.	2,3,3',4,4',5,6-Hepta BDE	0.02210	0.06360	0.99945	98

BDE = Bromodiphenyl ether

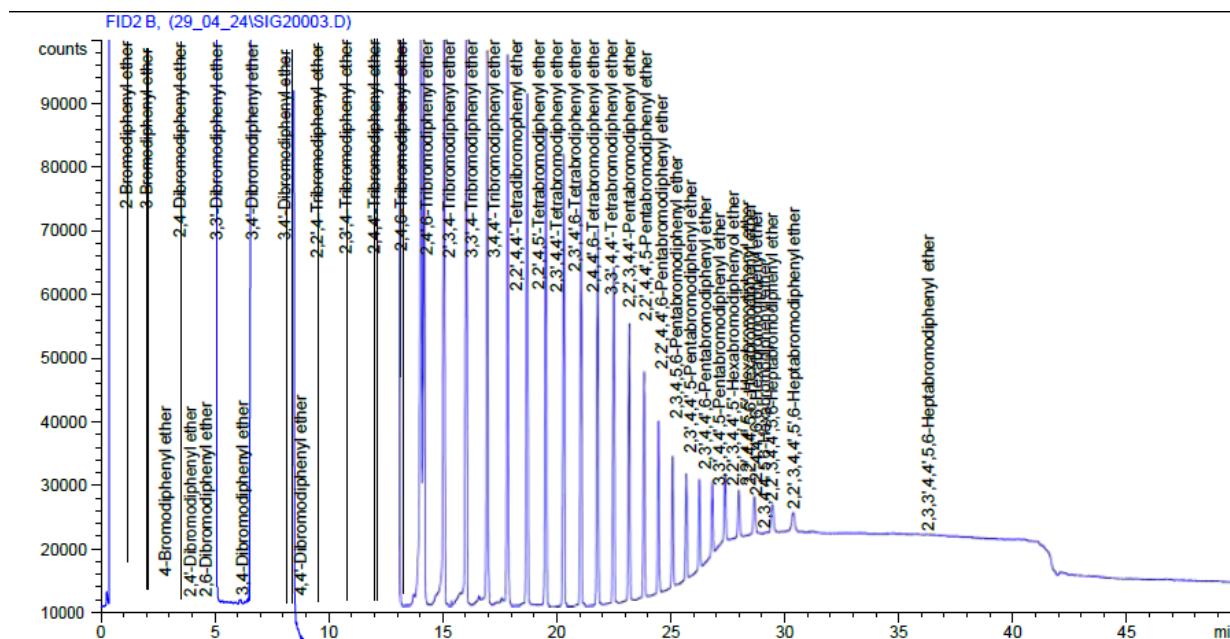


Figure 2: Showing the chromatograph of the PBDEs standard calibration

3. RESULTS AND DISCUSSION

3.1. PBDEs in WPrCBs Samples

The WPrCBs samples were categorized into five types of e-waste, including TV/DVD sets (ETD), Amplifiers (EAP), Mobile Phones (EMP), Radio sets (ERS), and Computers/Laptops (ECL). All the sample types were found to contain the PBDEs, which indicated a high frequency in the use of PBDEs in these electronic devices.

Previous studies also reported PBDEs were detected in 40% and 51% of all BFRs containing e-waste samples [36, 37]. The concentrations of PBDEs determined in WPrCBs samples are presented in table 3. Among all the WPrCBs samples, the ΣPBDEs concentration in ECL were higher than others, up to 824.23 ng/g, followed by ERS (683.51 ng/g), ETD (74.59 ng/g), EMP (28.99 ng/g) and EAP (22.56 ng/g) (Table 3). The trend for the ΣPBDEs concentrations was in the order: EAP < EMP < ETD < ERS < ECL.

Table 3: Concentrations of PBDEs (ng/g) in WPrCBs samples

S/N	Components	ETD	EAP	EMP	ERS	ECL
1.	2- BDE	BDL	BDL	0.15	BDL	BDL
2.	3- BDE	0.08	BDL	BDL	BDL	BDL
3.	4- BDE	2.43	BDL	BDL	BDL	BDL
4.	2,4-Di BDE	0.16	BDL	BDL	BDL	46.63
5.	2,4'-Di BDE	43.91	10.31	14.00	27.67	126.07
6.	2,6-Di BDE	BDL	BDL	BDL	12.25	BDL
7.	3,3'-Di BDE	BDL	BDL	BDL	0.07	0.26
8.	3,4-Di BDE	BDL	BDL	BDL	7.50	9.93
9.	3,4'-Di BDE	BDL	BDL	BDL	0.09	0.65
10.	4,4'-Di BDE	BDL	BDL	BDL	0.62	0.01
11.	2,2',4-Tri BDE	8.64	2.30	3.37	534.81	2.63
12.	2,3',4-Tri BDE	0.29	0.06	0.05	BDL	0.31
13.	2,4,4'-Tri BDE	0.17	0.06	BDL	BDL	28.56
14.	2,4,6-Tri BDE	0.14	BDL	0.06	BDL	12.84
15.	2,4',6-Tri BDE	BDL	BDL	BDL	51.27	2.75
16.	2',3,4-Tri BDE	14.42	4.98	7.74	3.28	67.17
17.	3,3',4-Tri BDE	2.07	0.83	1.26	BDL	7.89
18.	3,4,4'-Tri BDE	0.52	0.25	0.40	BDL	25.66

19.	2,2',4,4'-Tetra BDE	0.97	0.44	0.57	BDL	5.85
20.	2,2',4,5'-Tetra BDE	0.14	0.09	0.10	BDL	0.72
21.	2,3',4,4'-Tetra BDE	0.16	0.10	0.09	BDL	2.97
22.	2,3',4',6-Tetra BDE	0.09	0.08	0.12	BDL	4.14
23.	2,4,4',6-Tetra BDE	BDL	BDL	BDL	BDL	57.59
24.	3,3',4,4'-Tetra BDE	BDL	BDL	BDL	BDL	BDL
25.	2,2',3,4,4'-Penta BDE	BDL	BDL	BDL	5.28	421.59
26.	2,2',4,4',5-Penta BDE	BDL	0.21	BDL	6.06	BDL
27.	2,2',4,4',6-Penta BDE	0.16	0.45	0.52	9.91	BDL
28.	2,3,4,5,6-Penta BDE	0.25	0.58	0.38	2.21	BDL
29.	2,3',4,4',5-Penta BDE	BDL	0.74	0.19	7.13	BDL
30.	2,3',4,4',6-Penta BDE	BDL	0.30	BDL	5.91	BDL
31.	3,3',4,4',5-Penta BDE	BDL	0.47	BDL	1.56	BDL
32.	2,2',3,4,4',5'-Hexa BDE	BDL	0.15	BDL	3.91	BDL
33.	2,2',4,4',5,5'-Hexa BDE	BDL	0.09	BDL	1.51	BDL
34.	2,2',4,4',5,6'-Hexa BDE	BDL	0.06	BDL	0.67	BDL
34.	2,2',4,4',6,6'-Hexa BDE	BDL	BDL	BDL	0.42	BDL
36.	2,3,4,4',5,6-Hexa BDE	BDL	BDL	BDL	0.11	BDL
37.	2,2',3,4,4',5,6-Hepta BDE	BDL	BDL	BDL	0.43	BDL
38.	2,2',3,4,4',5',6-Hepta BDE	BDL	BDL	BDL	0.12	BDL
39.	2,3,3',4,4',5,6-Hepta BDE	BDL	BDL	BDL	0.72	BDL
	ΣPBDEs	74.59	22.56	28.99	683.51	824.23

BDE = Bromodiphenyl ether, ΣPBDEs = Sum of Total Polybrominated diphenyl ether, BDL = Below detection limit

According to “Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS)” directive by EU, there is an upper threshold limit (1×10^6 ng/g) for the concentration of PBDEs [34]. The ΣPBDEs of WPrCBs in this study did not exceed the RoHS threshold limit in this study. Comparatively, WPrCBs in this study contained lower ΣPBDEs than reported in China’s 4.251×10^7 ng/g for CRT TV/Printer/Copier WPrCBs [34], 1.7285×10^{10} for TV [38], Japan’s 4.5×10^9 for CRT TV [39],

Switzerland’s 5.4×10^7 and Austria’s 9.2×10^7 for small e-waste [18, 40] (Table 4). This observation indicates a reduction in the potential risks associated with PBDEs. It is important to note that reduced total quantities of PBDEs do not necessarily correlate with decreased environmental releases. However, improper treatment of these electronic waste materials may still result in significant environmental consequences.

Table 4: Comparison of PBDE Levels with other studies and standards

Location	Sample	PBDEs (ng/g)	References
Uyo, Nigeria	E-waste: WPrCBs	22.56 - 824.23	Present study
China	CRT, TV/Printer/Copier TV	4.251×10^7	[34]
	Small e-waste	1.7285×10^{10}	[38]
Switzerland	Small e-waste	5.4×10^7	[18]
Austria		9.2×10^7	[40]
	CRT TV		[39]
Japan		4.5×10^9	

Soil:			
Uyo, Nigeria	Topsoil	423.93 - 1420.06	Present study
	Subsoil	469.36 - 1568.45	Present study
Nigeria	Top/Subsoil	1.91 - 1.94	[35]
Lagos, Ibadan and Aba, Nigeria	Top/Subsoil	1.702 - 149770.560	[25]
Agbogbloshie,	Topsoil	6.3 - 7,700	[41]
Ghana	Topsoil	1.2 - 100	[41]
Kingtom, Ghana	Rural	0.065 - 12	[42]
UK and Norway	areas/woodlands	100	[43]
China	-		
Water:			
Uyo, Nigeria	Borehole water	1.53 - 12.75	Present study
South China	Pearl river	0.34 - 68	[32]
Shihwa, Korea	Artificial lake	0.16 - 11	[32]
EQS	Surface water	5E-07	[44]

Small e-waste, e.g. vacuum cleaner, toaster, iron, kettle, electric fan, electric toothbrush, etc.

3.2. PBDEs in Soil Samples

PBDEs were detected in soil samples with their concentrations varying over the sampling depths (Topsoil and Subsoil). The concentrations of PBDEs for topsoil and subsoil are presented in table 5 below. Σ PBDEs were in the range of 423.93 ng/g to 1420.06 ng/g for topsoil and 469.36 ng/g to 1568.45 ng/g for subsoil (Tables 5). Higher Σ PBDEs were generally observed in the topsoil opposite dumpsite (Cs1) and in the subsoil after the dumpsite (Ds2), while the lower Σ PBDEs in the top and subsoils before the dumpsite (As1/As2) (Tables 5). Comparatively, several studies have shown higher Σ PBDEs in soil and vegetation in Africa [35]. Moeckel and his co-investigators reported Σ PBDEs concentrations of topsoil in Agbogbloshie area of Ghana to range between 6.3 and 7,700 ng/g and Kingtom samples to range between 1.2 and 100 ng/g which aligns with the values from this study (Table 4). The concentrations at both sites were much higher than those reported for background areas in Kenya and Tanzania [41]. In rural areas and woodlands in UK and Norway, the Σ PBDEs concentrations ranged from 0.065 to 12 ng/g which is lower than that obtained in this study (Table 4). On a local scale the increase in the

PBDE levels were detected in flooded areas and in agricultural regions (up to several hundred ng/g), where the sewage sludge is used [45] or where the land is irrigated with treated effluents [42].

Several studies carried out in Nigeria reported that most of the PBDEs assessed were below detectable limits (<0.01 ng/g) except for Octa brominated diphenyl ether (OctaBDE-79) which were present at concentrations ranging from 1.91-1.94 ng/g [35]. Ohajinwa *et al.*, also reported that PBDE congeners were detected in all sampling sites studied across Lagos, Ibadan and Aba, with the Σ PBDEs concentration of 13 PBDE ranging from 1.702 to 149770.560 ng/g which indicates that PBDEs were widespread pollutants in the research area [25]. The most abundant PBDE congener in all the sites and samples was BDE-209, with concentrations ranging from 0.850 to 147,091.400 ng/g at e-waste dismantling sites in Lagos, Ibadan and Aba [25]. These findings were aligned with that from this study as we recorded Σ PBDEs concentrations within the ranges.

Table 5: Concentrations of PBDEs (ng/g) in soil profiles

S/N	Components	TS	SS	TS	SS	TS	SS	TS	SS
		As1	As2	Bs1	Bs2	Cs1	Cs2	Ds1	Ds2
1.	2- BDE	BDL	BDL	BDL	BDL	BDL	BDL	BDL	4.64
2.	3- BDE	BDL	BDL	BDL	BDL	BDL	0.06	0.07	2.28
3.	4- BDE	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4.	2,4-Di BDE	0.15	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5.	2,4'-Di BDE	BDL	BDL	BDL	BDL	BDL	BDL	8.29	BDL
6.	2,6-Di BDE	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
7.	3,3'-Di BDE	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
8.	3,4-Di BDE	5.23	BDL	BDL	BDL	BDL	BDL	BDL	8.18
9.	3,4'-Di BDE	0.11	0.16	BDL	BDL	BDL	BDL	BDL	0.11
10.	4,4'-Di BDE	BDL	0.01	BDL	BDL	BDL	BDL	BDL	BDL
11.	2,2',4-Tri BDE	BDL	2.93	BDL	BDL	BDL	BDL	BDL	BDL
12.	2,3',4-Tri BDE	BDL	0.06	BDL	BDL	BDL	BDL	BDL	BDL
13.	2,4,4'-Tri BDE	0.07	0.09	BDL	BDL	BDL	BDL	BDL	BDL
14.	2,4,6-Tri BDE	0.08	BDL	BDL	BDL	BDL	BDL	BDL	0.09
15.	2,4',6-Tri BDE	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
16.	2',3,4-Tri BDE	0.57	0.08	BDL	BDL	BDL	BDL	BDL	BDL
17.	3,3',4-Tri BDE	0.07	0.27	BDL	BDL	BDL	BDL	BDL	BDL
18.	3,4,4'-Tri BDE	0.14	BDL	BDL	BDL	BDL	BDL	0.16	BDL
19.	2,2',4,4'-Tetra BDE	BDL	BDL	200.48	BDL	0.08	BDL	BDL	0.44
20.	2,2',4,5'-Tetra BDE	BDL	BDL	13.73	1.41	BDL	0.36	0.16	1.77
21.	2,3',4,4'-Tetra BDE	BDL	BDL	18.83	BDL	BDL	BDL	BDL	BDL
22.	2,3',4',6-Tetra BDE	1.16	BDL	24.15	BDL	BDL	BDL	BDL	BDL
23.	2,4,4',6-Tetra BDE	BDL	BDL	5.99	BDL	BDL	BDL	BDL	BDL
24.	3,3',4,4'-Tetra BDE	BDL	BDL	30.53	BDL	BDL	BDL	BDL	BDL
25.	2,2',3,4,4'-Penta BDE	BDL	31.37	23.59	BDL	BDL	BDL	BDL	BDL
26.	2,2',4,4',5-Penta BDE	BDL	36.39	44.59	BDL	BDL	BDL	BDL	BDL
27.	2,2',4,4',6-Penta BDE	BDL	67.46	42.73	BDL	BDL	BDL	397.23	BDL
28.	2,3,4,5,6-Penta BDE	247.74	15.32	15.02	712.54	710.54	562.95	17.18	893.48
29.	2,3',4,4',5-Penta BDE	69.37	44.57	18.23	110.71	191.87	48.22	42.31	264.29
30.	2,3',4,4',6-Penta BDE	31.37	25.11	12.57	56.66	93.45	105.47	56.02	38.09
31.	3,3',4,4',5-Penta BDE	12.49	71.31	32.15	50.82	67.91	22.68	10.48	71.29
32.	2,2',3,4,4',5'-Hexa BDE	12.24	18.03	15.17	36.27	36.5	27.55	15.57	53.65
33.	2,2',4,4',5,5'-Hexa BDE	4.42	16.46	7.59	14.05	45.39	107.09	34.3	23.13
34.	2,2',4,4',5,6'-Hexa BDE	10.16	26.48	13.22	23.71	41.5	23.53	27.25	35.46
34.	2,2',4,4',6,6'-Hexa BDE	6.04	20.8	3.59	29.72	29.07	28.48	26.56	21.72
36.	2,3,4,4',5,6-Hexa BDE	4.10	7.9	6.73	25.54	25.49	7.38	18.46	41.47
37.	2,2',3,4,4',5,6-Hepta BDE	8.29	55.27	11.15	152.57	115.81	96.26	91.97	75.42
38.	2,2',3,4,4',5',6-Hepta BDE	4.29	13.6	9.32	16.4	47.11	15.53	20.13	21.75
39.	2,3,3',4,4',5,6-Hepta BDE	5.83	15.72	5.66	32.25	15.34	27.81	21.51	11.2
	ΣPBDEs	423.93	469.36	555.03	1262.65	1420.06	1073.36	787.66	1568.45

TS = Topsoil (0-30 cm), *SS* = Subsoil (100-120 cm), *BDE* = Bromodiphenyl ether, *ΣPBDEs* = Sum of Total Polybrominated diphenyl ether, *BDL* = Below detection limit

3.3. PBDEs in Borehole Water Samples

PBDEs were detected in borehole water samples from different boreholes drilled around the dumpsite surroundings with their concentrations varying over the sampling area. The concentrations of PBDEs detected in borehole water samples are presented in Table 6. Σ PBDEs in borehole water samples ranged from 1.53 to 12.75 ng/ml. The order of Σ PBDEs across the different locations were Cw < Bw < Ew < Aw < Dw (Table 6). Higher Σ PBDEs observed in the borehole water samples around the dumpsite were attributed to dumping and burning of large quantities of electronic wastes and other waste products which contains some number of organic pollutants (PBDEs) on the dumpsite. These activities could result in a burden of PBDEs on the surrounding dumpsite. The amount of each PBDEs congener will therefore depend on the percentage of its composition in the source materials and the rate at which such materials enter the water body. The levels of the individual PBDE congeners can also be influenced by the rate of photochemical or biological debromination of higher brominated congeners to lower ones under certain environmental conditions [46].

Globally, the published data on PBDEs in water was relatively limited. Concentrations of PBDEs in environmental water have been observed generally to be very low which varied from pg/L to ng/L. This could be attributed to the hydrophobic characteristics of PBDEs in which they tend to adsorb suspended solids in water bodies [32]. The comparison with other locations around the world showed that the range of Σ PBDEs in this study were higher. A study in South China reported the Σ PBDEs concentrations of Pearl River ranging from 0.34 to 68 ng/L but were comparable to the Σ PBDEs concentrations in water of the artificial Lake Shihwa (Korea) which ranged from 0.16 to 11 ng/L [32] (Table 4). Most of the Σ PBDEs concentrations reported in several regions around the world were mostly below 0.50 ng/L (Table 4) detected in water samples [47]. In borehole water, Σ PBDEs 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 6: Concentrations of PBDEs (ng/ml) in borehole water samples

S/N	Components	Aw	Bw	Cw	Dw	Ew
1.	2- BDE	BDL	BDL	BDL	BDL	BDL
2.	3- BDE	0.10	0.02	0.02	0.05	BDL
3.	4- BDE	5.40	BDL	0.36	2.02	0.40
4.	2,4-Di BDE	0.04	BDL	BDL	0.12	BDL
5.	2,4'-Di BDE	1.94	0.88	BDL	2.85	3.38
6.	2,6-Di BDE	0.73	BDL	BDL	1.84	BDL
7.	3,3'-Di BDE	0.08	BDL	BDL	0.15	BDL
8.	3,4-Di BDE	BDL	0.68	BDL	4.18	BDL
9.	3,4'-Di BDE	0.05	BDL	0.01	BDL	BDL
10.	4,4'-Di BDE	<0.01	BDL	BDL	BDL	<0.01
11.	2,2',4-Tri BDE	1.15	BDL	0.67	1.44	1.12
12.	2,3',4-Tri BDE	0.02	BDL	0.03	0.02	0.02
13.	2,4,4'-Tri BDE	0.02	BDL	0.01	0.01	0.02
14.	2,4,6-Tri BDE	0.03	BDL	0.04	0.01	BDL
15.	2,4',6-Tri BDE	0.01	BDL	0.03	BDL	BDL
16.	2',3,4-Tri BDE	0.01	BDL	BDL	BDL	0.02
17.	3,3',4-Tri BDE	0.05	BDL	0.03	BDL	0.11
18.	3,4,4'-Tri BDE	0.02	BDL	0.02	BDL	0.08
19.	2,2',4,4'-Tetradi BDE	0.02	BDL	0.03	0.04	0.04

20.	2,2',4,5'-Tetra BDE	BDL	BDL	0.02	0.02	BDL
21.	2,3',4,4'-Tetra BDE	0.03	BDL	BDL	BDL	BDL
22.	2,3',4',6-Tetra BDE	0.02	0.02	BDL	BDL	BDL
23.	2,4,4',6-Tetra BDE	0.02	BDL	BDL	BDL	BDL
24.	3,3',4,4'-Tetra BDE	0.07	BDL	BDL	BDL	BDL
25.	2,2',3,4,4'-Penta BDE	0.02	BDL	BDL	BDL	0.07
26.	2,2',4,4',5-Penta BDE	BDL	BDL	BDL	BDL	0.03
27.	2,2',4,4',6-Penta BDE	0.09	0.03	0.04	BDL	0.04
28.	2,3,4,5,6-Penta BDE	0.23	0.04	0.06	BDL	BDL
29.	2,3',4,4',5-Penta BDE	0.13	BDL	0.04	BDL	BDL
30.	2,3',4,4',6-Penta BDE	0.08	BDL	0.08	BDL	BDL
31.	3,3',4,4',5-Penta BDE	0.24	BDL	0.03	BDL	BDL
32.	2,2',3,4,4',5'-Hexa BDE	0.04	BDL	BDL	BDL	BDL
33.	2,2',4,4',5,5'-Hexa BDE	BDL	BDL	BDL	BDL	BDL
34.	2,2',4,4',5,6'-Hexa BDE	0.02	BDL	BDL	BDL	BDL
34.	2,2',4,4',6,6'-Hexa BDE	BDL	BDL	BDL	BDL	BDL
36.	2,3,4,4',5,6-Hexa BDE	BDL	BDL	BDL	BDL	BDL
37.	2,2',3,4,4',5,6-Hepta BDE	BDL	BDL	BDL	BDL	BDL
38.	2,2',3,4,4',5',6-Hepta BDE	BDL	BDL	BDL	BDL	BDL
39.	2,3,3',4,4',5,6-Hepta BDE	BDL	BDL	BDL	BDL	BDL
	ΣPBDEs	10.66	1.67	1.53	12.75	5.32

BDE = Bromodiphenyl ether, **ΣPBDEs** = Sum of Total Polybrominated diphenyl ether, **BDL** = Below detection limit

3.4. Comparison of PBDEs Concentration Among the Sample Matrices

The environmental concentrations of brominated flame retardants (PBDEs), a family of compounds used as flame retardants in a variety of products, can differ greatly depending on the sample type. Comparing the amounts of ΣPBDEs in soil, borehole water, and WPrCBs samples used for this study shows significant variations in the levels of pollution and their effects on the environment's health.

With a total ΣPBDEs concentration of 1633.88 ng/g (Figure 3), e-waste exhibits comparatively high levels of contamination when compared to water samples, but noticeably lower levels than soil samples. This is in line with the knowledge that because PBDEs are widely used in electronic devices, e-waste frequently has significant quantities of them [48]. When e-waste is improperly disposed of, PBDEs are known to leach into the environment and eventually endanger soil and water systems.

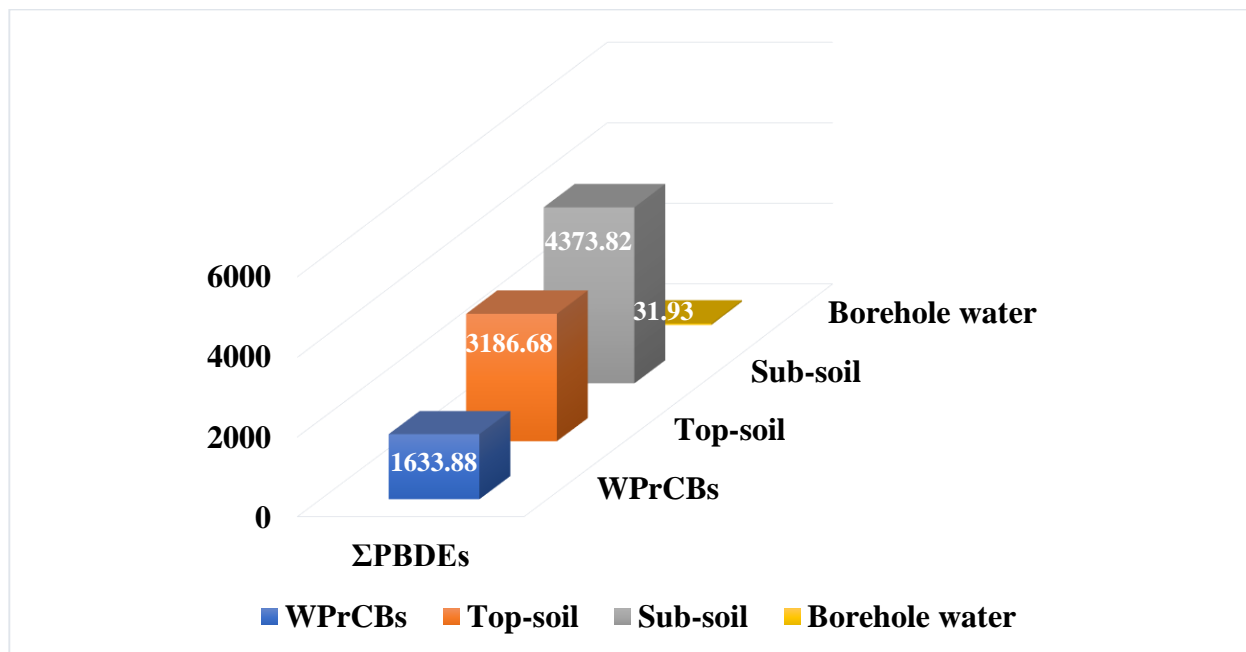
The highest levels of PBDE contamination among the three sample types are found in soil

samples, with a total ΣPBDEs concentration of 3186.68 ng/g for topsoil and 4373.82 ng/g for subsoil (Figure 3). The presence of PBDEs in the soil can be attributed to their historical use in a variety of products and their subsequent release from contaminated e-waste, or atmospheric deposition. The elevated concentration in question is indicative of the accumulation and persistence of PBDEs in the soil. Because PBDEs have an affinity for sticking to soil particles and linger in the environment, there is a high concentration of them in the soil. A study by Wang *et al.*, found that there can be a wide range of PBDE concentrations in soil, with values as high as 100 ng/g reported in some polluted sites [43]. The soil sample used for this study had higher concentration, which is elevated but typical for regions close to e-waste recycling facilities.

The lowest concentrations of PBDEs are found in borehole water samples with a total ΣPBDEs concentration of 31.93 ng/mL (Figure 3). This lower concentration is expected because PBDEs have a lower affinity for water than for soil and solid waste. Since PBDEs tend to adsorb onto particles and sediments, aqueous environments will typically have lower concentrations of

PBDEs; however, even lower concentrations can have significant ecological and health implications because PBDEs can accumulate in aquatic organisms and enter the food chain. These comparisons show how contamination levels vary significantly amongst various environmental

matrices. This discrepancy emphasizes the need for focused remediation strategies and cautious handling of materials containing PBDEs to lessen the harmful effects of these materials on the environment and public health.



Figures 3: Total ΣPBDEs among the sample matrices

4. CONCLUSION

The present study has shown the presence and levels of PBDEs in WPrCBs, soil and borehole water samples collected from Uyo village road dumpsite and its environs in Uyo Akwa Ibom State, Nigeria. Relatively, the highest concentration was found in soil samples. The observed high concentration from these sampling points may be attributed to PBDEs subsequent release from contaminated e-waste, or atmospheric deposition. The elevated concentration in question is indicative of the accumulation and persistence of PBDEs in the soil because PBDEs have an affinity for sticking to soil particles and linger in the environment. However, the concentration of PBDEs for all borehole water samples considered was the lowest, and this lower concentration is expected because PBDEs have a lower affinity for water

than for soil and solid waste. Effective e-waste recycling, soil remediation, and water quality monitoring are critical to safeguarding public health and ensuring environmental sustainability. Furthermore, intensive monitoring is required to acquire substantial data for characterization of the PBDEs profile. Future research should prioritize the establishment of long-term monitoring programs to track trends and impacts over time.

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Conflict of Interest Declaration

The author(s) declare that there are no conflicts of

interest regarding the publication of this paper.

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