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Concentration and Hazard Quotient Assessment of Flame Retardant in Different Electronic Debris in Selected Dumpsites in Warri, Southern Nigeria

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ABSTRACT

The rapid accumulation of electronic waste in developing regions has intensified the environmental burden of persistent organic pollutants, particularly polybrominated diphenyl ethers (PBDEs), which remain embedded in legacy electronic components and pose significant toxicological risks. This study quantified PBDE concentrations and evaluated associated human health risks in electronic debris collected from four major dumpsites in Warri, southern Nigeria. Electronic waste samples comprising mobile phones, laptops, and monitors were systematically collected, homogenized, and analyzed for eight PBDE congeners using Soxhlet extraction followed by gas chromatography–mass spectrometry. Total PBDE (ΣPBDE) concentrations ranged from 0.018 to 0.988 mg/kg, with the highest levels observed in laptop-derived materials, particularly at the Enerhen site. Congener distribution was dominated by BDE-47, BDE-154, and BDE-183, while BDE-209 remained below detection across all samples, indicating a predominance of legacy penta- and octa-BDE formulations. Spatial analysis revealed site-specific variability, with Enerhen and Deco exhibiting elevated contamination relative to PTI. Hazard quotient (HQ) assessment showed that all samples exceeded the safety threshold (HQ > 1), with several classified as high to very high risk, suggesting potential adverse health implications for exposed populations. The findings demonstrate that PBDE contamination in Warri is driven by both material composition and site-specific waste dynamics. It is recommended that formalized e-waste management systems, controlled dismantling practices, and targeted monitoring of high-risk device categories be implemented to mitigate exposure and environmental dispersion.

1. INTRODUCTION

The rapid expansion in the production and consumption of electrical and electronic equipment has resulted in a substantial increase in global electronic waste, which exceeded 62 million metric tonnes in 2022 (Forti *et al.*, 2023). A significant proportion of this waste stream contains brominated flame retardants, particularly polybrominated diphenyl ethers (PBDEs), incorporated into polymeric components to enhance fire

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resistance. Although effective in reducing flammability, PBDEs are persistent organic pollutants characterized by environmental stability, bioaccumulation potential, and capacity for long-range transport, thereby posing considerable ecotoxicological and human health concerns (Wang *et al.*, 2022).

PBDEs are structurally stable halogenated compounds that resist degradation and preferentially partition into particulate matter and organic-rich matrices. Their release into the environment occurs primarily during informal recycling activities such as manual dismantling, open burning, and uncontrolled material recovery. These practices are prevalent in many developing regions where regulatory oversight is limited, resulting in elevated environmental contamination (Alabi *et al.*, 2021). Consequently, PBDEs have been widely detected in soils, air, sediments, and biota, with established links to endocrine disruption, neurodevelopmental toxicity, immune dysfunction, and carcinogenic potential in humans (EFSA, 2021).

Sub-Saharan Africa has become a major destination for end-of-life electronics, often processed under poorly controlled conditions. Nigeria represents a key hub within this system, handling substantial volumes of both locally generated and imported e-waste. Informal recycling activities are concentrated in urban and peri-urban areas, where dismantling and material recovery occur with minimal environmental safeguards (Ogunseitan et al., 2022). Within the Niger Delta, Warri constitutes an important focal point due to its industrial character, high population density, and inadequate waste management infrastructure. Dumpsites such as Enerhen, PTI, Osubi, and Deco serve as major accumulation points for heterogeneous electronic debris, where continuous degradation and handling facilitate the release and redistribution of brominated contaminants into surrounding environmental media.

Despite growing awareness of e-waste-related pollution in Nigeria, quantitative data on PBDE concentrations within specific electronic components and across different dumpsite environments remain limited. In addition, the human health implications associated with direct exposure to PBDE-contaminated materials, particularly among informal waste handlers and nearby populations, have not been adequately characterized. Hazard quotient (HQ) assessment provides a pragmatic approach for evaluating non-carcinogenic risk by comparing measured exposure levels with established reference thresholds.

Against this backdrop, this study quantified PBDE concentrations in selected categories of electronic waste, including mobile phones, laptops, and monitors, collected from major dumpsites in Warri, southern Nigeria. It further evaluated spatial and compositional variations in PBDE distribution and assessed associated human health risks using hazard quotient modeling, with the aim of providing empirical evidence to support risk-informed e-waste management strategies in the Niger Delta region.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Warri, Delta State, Nigeria, within the Niger Delta region. Warri is characterized by intense urbanization, commercial activity, expanding population density, and inadequately regulated waste disposal systems. These conditions have encouraged the growth of informal dumpsites where mixed municipal and electronic wastes accumulate. Four major dumpsites with notable electronic waste burdens were selected for investigation: Enerhen, PTI, Osubi, and Deco. These locations function as active centers for informal e-waste storage, scavenging, dismantling, and material recovery.

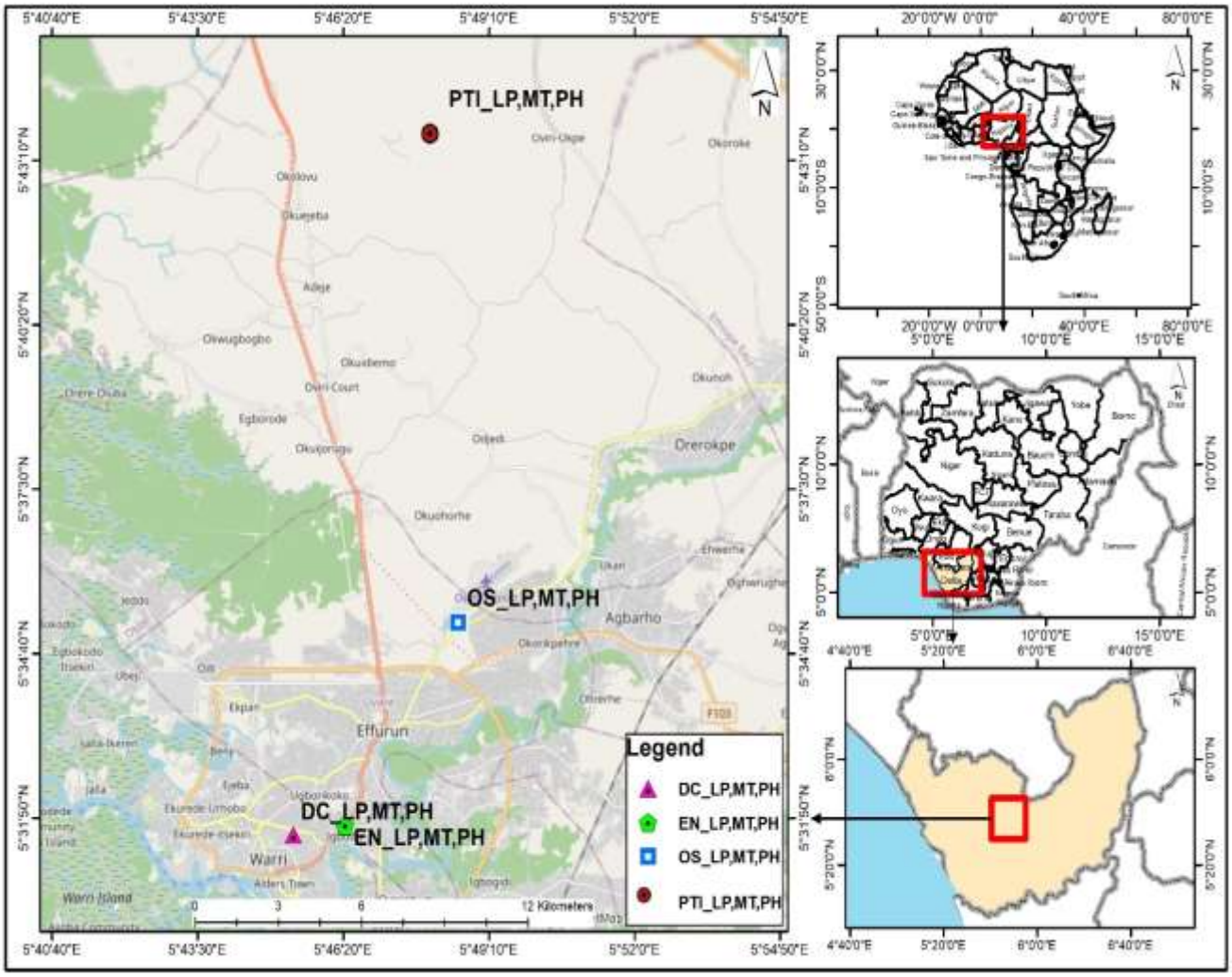

PTI_LP,MT,PH
OS_LP,MT,PH
DC_LP,MT,PH
EN_LP,MT,PH
Legend
DC_LP,MT,PH
EN_LP,MT,PH
OS_LP,MT,PH
PTI_LP,MT,PH
Effurun
Warri
Agbarho
Ogbe-Ijoh
Ekpan
Ubeji
Ugborikoko
Ekurede Urhobo
Ekurede-Ijaw
Warri Island
Adeje
Okuevbo
Okuokiti
Okuokpehre
Ofuoma
Ogharugha
Ifiwerhe
Ukuan
Jeddo
Egbokodo
Itsekiri
Jakpa
Ewhro
Ogbe-Ijoh
Ajamimo
Ajakpo
Ajamimo Island
Ajakpo Island
Ogbe-Ijoh Island
Ogbe-Ijoh Community
Okuokiti
Okuevbo

Table 1: Sampling Locations and Characteristics

Site Code	Location	Description of Activity	Dominant E-waste Stream
EN	Enerhen	Mixed municipal and electronic waste dumping with active scavenging	Household electronics
PTI	PTI	Institutional and industrial e-waste with dismantling activities	Office/industrial electronics
OS	Osubi	Moderate e-waste accumulation in semi-urban setting	Mixed consumer electronics
DC	Deco	High-intensity informal recycling and open handling	Commercial electronic debris

2.2 Study Design

A cross-sectional environmental assessment design was adopted to determine the occurrence, concentration, and potential health implications of PBDEs in discarded electronic materials. At each dumpsite, composite samples were prepared by combining multiple e-waste fragments collected within a 5–10 m radius. This approach reduced microscale heterogeneity and improved sample representativeness for complex waste matrices (USEPA, 2021).

Because of analytical cost and instrumentation constraints, one composite sample per device category per site was analyzed. Accordingly, the investigation represents a screening-level contamination and risk assessment intended to identify priority hotspots and device categories requiring intervention.

2.3 Sample Collection and Categorization

Electronic waste materials were manually collected from active dismantling and disposal zones. Samples were sorted into three major categories:

i. Mobile phones
ii. Laptops
iii. Monitors

Each sample was coded according to site and device type (e.g., ENPH = Enerhen Phone; PTILP = PTI Laptop). A total of twelve composite samples were obtained.

Metallic frames and obviously inert fractions were excluded, while PBDE-relevant materials such as plastic casings, insulated wires, laminated circuit boards, and polymeric internal components were retained. Samples were transferred into pre-

cleaned amber glass containers, transported under cooled conditions, and stored at approximately 4°C prior to extraction.

2.4 Target PBDE Congeners

Eight PBDE congeners commonly associated with historical commercial flame-retardant formulations were selected.

Table 2: Target PBDE Congeners

Congener	**Chemical Name**
BDE-28	2,4,4′-Tribromodiphenyl ether
BDE-47	2,2′,4,4′-Tetrabromodiphenyl ether
BDE-99	2,2′,4,4′,5-Pentabromodiphenyl ether
BDE-100	2,2′,4,4′,6-Pentabromodiphenyl ether
BDE-153	2,2′,4,4′,5,5′-Hexabromodiphenyl ether
BDE-154	2,2′,4,4′,5,6-Hexabromodiphenyl ether
BDE-183	2,2′,3,4,4′,5,6-Heptabromodiphenyl ether
BDE-209	2,2′,3,4,4′,5,5′,6,6′-Decabromodiphenyl ether

2.5 Sample Preparation and Mass Determination

Each sample collected was weighed before processing using an analytical balance to obtain initial mass. Samples were then mechanically pulverized to particle sizes below 1 mm to achieve homogeneity and maximize extraction efficiency.

The powdered fractions were reweighed after grinding to estimate mass loss during processing. This step was important because e-waste fragmentation may generate losses through dust formation, particle dispersion, or removal of coarse non-target fractions.

2.6 Extraction of PBDEs

PBDEs were extracted using Soxhlet extraction according to USEPA Method 3540C. Ten grams (0.010 kg) of homogenized material were extracted with n-hexane for 16 h. The extracts were concentrated using rotary evaporation and adjusted to a final volume of 2 mL prior to cleanup and instrumental analysis.

2.7 Extract Clean-Up

Extract purification was performed using a silica gel column to remove co-extracted matrix interferences. The column consisted of an upper anhydrous sodium sulfate layer for moisture removal and activated silica gel for adsorption of unwanted organic compounds. PBDEs were eluted using n-

hexane followed by n-hexane:dichloromethane (1:1, v/v). Final eluates were concentrated to 2 mL.

2.8 Instrumental Analysis (GC–MS)

PBDE congeners were quantified using gas chromatography–mass spectrometry (GC–MS). Separation was achieved on a DB-5MS capillary column (30 m × 0.25 mm × 0.25 µm). Helium was used as carrier gas at 1.0 mL/min. A 1 µL aliquot was injected in splitless mode. Electron ionization was performed at 70 eV.

The oven program commenced at 80°C (2 min), increased to 200°C at 20°C/min, then to 300°C at 5°C/min with a 10 min hold, and finally maintained at 320°C for 10 min. Detection was conducted in selected ion monitoring (SIM) mode for enhanced sensitivity.

2.9 Calibration and Quantification

External calibration was carried out using certified PBDE mixed standards over a multi-point concentration range. Calibration curves with coefficient of determination ($R^2 \geq 0.99$) were considered acceptable.

Individual congener concentrations were determined from corresponding calibration functions. Total PBDE concentration was calculated as:

Individual congener concentrations were determined from corresponding calibration functions. Total PBDE concentration was calculated as:

$$\Sigma PBDE = \sum_{i=1}^{n} C_i$$

where (Ci) is the concentration of each detected congener. The method detection limit for each analyte was 0.001 mg/kg.

2.10 Quality Assurance and Quality Control

Quality assurance procedures included procedural blanks, duplicate analysis, calibration verification, and recovery monitoring. Recoveries ranged from 70–120%, while analytical precision remained within ±15%. Values below detection limit (<0.001 mg/kg) were treated as non-detects.

2.11 Hazard Quotient Assessment

Potential non-carcinogenic health risk associated with exposure to PBDE-contaminated e-waste was evaluated using the Hazard Quotient (HQ) model. Estimated exposure concentration was based on measured ΣPBDE values in each sample. HQ was computed as:

$$HQ = \frac{ADD}{RfD}$$

where:

ADD = average daily dose (mg kg^{-1} day^{-1})

RfD = reference dose (mg kg^{-1} day^{-1})

Average daily dose was estimated using standard USEPA exposure assumptions:

$$ADD = \frac{C \times IR \times EF \times ED}{BW \times AT}$$

where:

C = ΣPBDE concentration in sample (mg/kg)

IR = intake/contact rate

EF = exposure frequency

ED = exposure duration

BW = body weight

AT = averaging time

HQ values were interpreted as follows:

i. HQ ≤ 1: negligible risk

ii. HQ > 1: potential non-carcinogenic concern

iii. Higher HQ values indicate progressively greater exposure significance.

2.12 Data Treatment and Statistical Analysis

PBDE concentrations were expressed in mg/kg. Descriptive statistics including mean, standard deviation, median, range, and coefficient of variation were computed. Site and device patterns were evaluated comparatively using ΣPBDE burdens and congener fingerprints. HQ values were ranked to identify high-risk dumpsites and electronic categories.

Given the composite sampling design and limited replication, inferential statistics were interpreted cautiously, with emphasis placed on robust pattern recognition, contamination ranking, and screening-level human health implications.

3. RESULTS

To evaluate the extent of material transformation during sample processing and its potential influence on contaminant distribution, the initial and post-grinding masses of the collected e-waste samples were compared alongside corresponding ΣPBDE concentrations (Table 3).

Table 3: Sample Mass Balance and Corresponding ΣPBDE

Sample	Location	Device	Initial (g)	Final (g)	Mass Loss (%)	ΣPBDE (mg/kg)
DCLP	Deco	Laptop	45.49	38.67	14.99	0.227
DCMT	Deco	Monitor	55.57	30.13	45.78	0.050
DCPH	Deco	Phone	26.17	14.43	44.86	0.499
ENLP	Enerhen	Laptop	86.12	63.44	26.33	0.988
ENMT	Enerhen	Monitor	50.49	39.38	21.99	0.018
ENPH	Enerhen	Phone	8.91	6.71	24.69	0.054

PTILP	PTI	Laptop	108.89	107.31	1.45	0.035
PTIMT	PTI	Monitor	171.94	30.92	82.02	0.032
PTIPH	PTI	Phone	11.64	7.53	35.31	0.033
OSLP	Osubi	Laptop	50.15	46.41	7.46	0.397
OSMT	Osubi	Monitor	76.50	53.06	30.64	0.068
OSPH	Osubi	Phone	62.28	18.91	69.63	0.054

Interpretation: Mass loss (1.45–82.02%) varied widely across samples and did not correspond proportionally with ΣPBDE levels, indicating that PBDE distribution is primarily influenced by intrinsic material composition rather than degree of physical reduction.

The congener-specific distribution of PBDEs across all sampled electronic waste matrices is presented in Table 4, providing a detailed quantitative basis for assessing compositional patterns and dominant flame retardant signatures.

Table 4: PBDE Congener Distribution in E-waste Samples (mg/kg)

Congener	**DCLP**	**DCMT**	**DCPH**	**ENLP**	**ENMT**	**ENPH**	**PTILP**	**PTIMT**	**PTIPH**	**OSLP**	**OSMT**	**OSPH**
BDE-28	0.004	<0.001	0.002	0.005	0.001	0.007	0.007	<0.001	<0.001	<0.001	<0.001	0.001
BDE-47	0.058	0.004	0.350	0.190	<0.001	<0.001	<0.001	0.001	0.004	0.245	0.019	0.005
BDE-99	0.001	<0.001	<0.001	0.012	<0.001	0.001	0.001	0.009	<0.001	0.050	<0.001	0.001
BDE-100	0.001	0.001	0.110	0.049	<0.001	<0.001	<0.001	<0.001	<0.001	0.037	0.005	<0.001
BDE-153	<0.001	<0.001	0.035	0.014	<0.001	<0.001	<0.001	<0.001	0.010	0.040	0.001	0.001

BDE-154	0.124	<0.001	0.005	0.468	0.017	0.021	0.007	0.019	0.004	0.008	0.024	0.004
BDE-183	0.039	0.045	0.002	0.250	<0.001	0.025	0.020	0.003	0.015	0.017	0.019	0.042
BDE-209	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
ΣPBDE	**0.227**	**0.050**	**0.499**	**0.988**	**0.018**	**0.054**	**0.035**	**0.032**	**0.033**	**0.397**	**0.068**	**0.054**

Interpretation: PBDE occurrence is characterized by dominance of BDE-47, BDE-154, and BDE-183, while BDE-209 was consistently below detection, suggesting minimal contribution from deca-BDE formulations or possible environmental transformation.

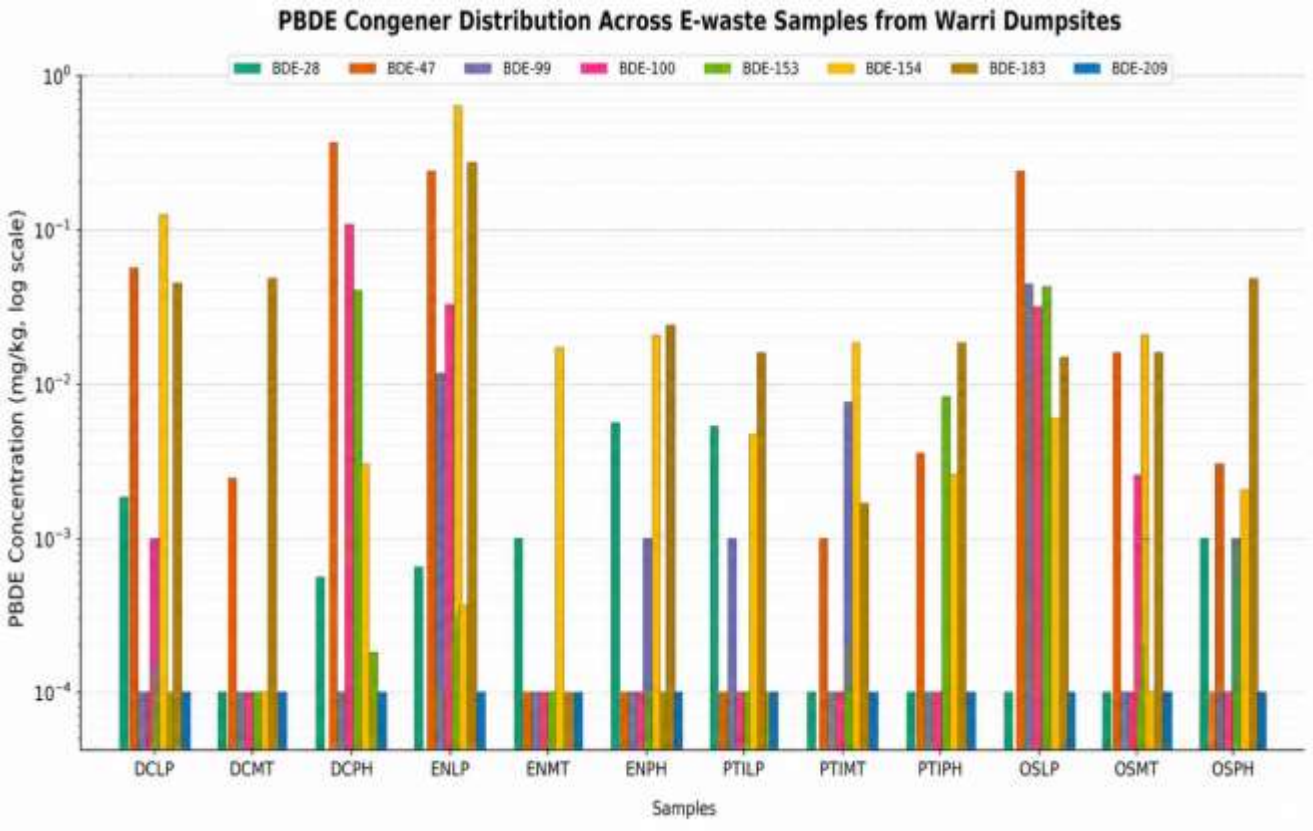


Figure 2: PGDE Congener Distribution Across E-waste Samples from Warri Dumpsites

Interpretation: The figure shows heterogeneous PBDE distribution across e-waste samples, dominated by BDE-47, BDE-154, and BDE-183. Laptop samples, particularly ENLP and OSLP, exhibited the highest contaminant burden relative to phones and monitors.

To elucidate spatial and material-specific variations in PBDE contamination, ΣPBDE concentrations were organized according to dumpsite location and device category, with site-level descriptive statistics presented in Table 5.

Table 5: Spatial–Device Distribution of ΣPBDE (mg/kg)

Location	Phone	Laptop	Monitor	Mean ± SD (mg/kg)
Enerhen	0.054	0.988	0.018	0.353 ± 0.550
PTI	0.033	0.035	0.032	0.033 ± 0.002
Osubi	0.054	0.397	0.068	0.173 ± 0.195
Deco	0.499	0.227	0.050	0.259 ± 0.226

Interpretation: Distinct spatial–device interactions are evident, with laptops consistently exhibiting higher ΣPBDE concentrations and Enerhen showing pronounced variability driven by elevated levels in ENLP.

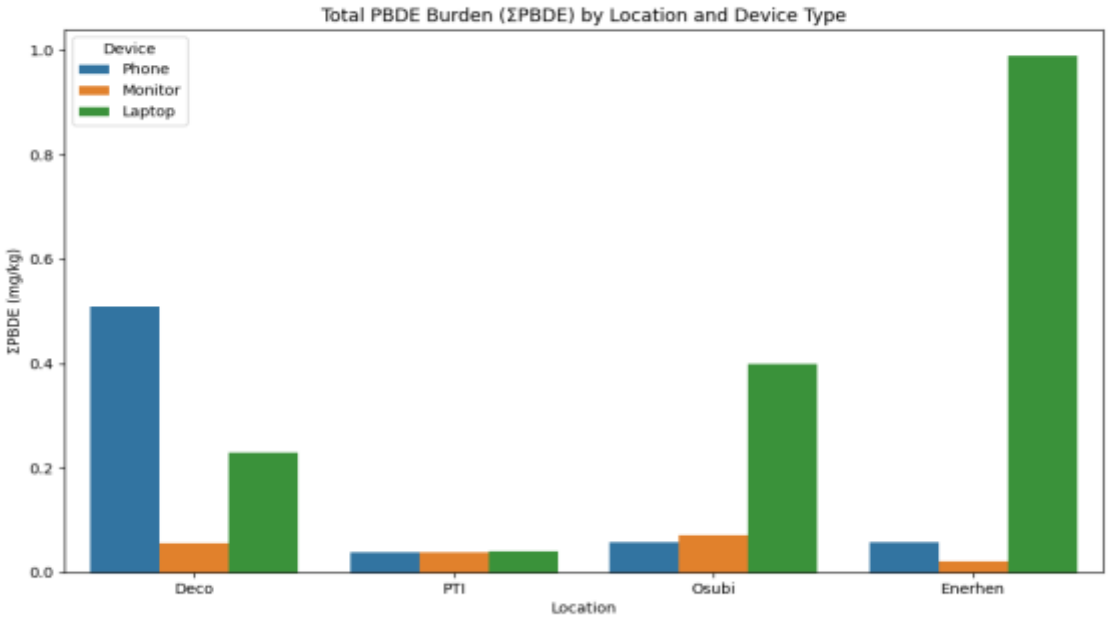


Figure 3: Total PBDE Burden (ΣPBDE) by location and device type

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Interpretation: The figure shows clear spatial and device-related variation in ΣPBDE, with laptops exhibiting the highest burden across most dumpsites. Enerhen recorded the greatest overall contamination.

A consolidated statistical summary of PBDE congeners across all samples, including mean concentrations and detection frequencies, is presented in Table 6 to highlight dominant compounds and overall distribution characteristics.

Table 6: Descriptive Statistics of PBDE Congeners Across Samples

Congener	Mean ± SD (mg/kg)	Detection Frequency (%)
BDE-28	0.002 ± 0.002	58
BDE-47	0.073 ± 0.112	75
BDE-99	0.006 ± 0.014	50
BDE-100	0.017 ± 0.034	42
BDE-153	0.009 ± 0.014	42
BDE-154	0.058 ± 0.132	92
BDE-183	0.040 ± 0.073	92
BDE-209	<0.001	0

Interpretation: BDE-47 exhibited the highest variability across samples, while BDE-154 and BDE-183 showed high detection frequencies, indicating persistence of higher brominated congeners within the e-waste matrices.

To assess the potential human health implications of PBDE exposure from e-waste handling, hazard quotient (HQ) values were calculated for each sample based on measured ΣPBDE concentrations and are presented in Table 7.

Table 7: Hazard Quotient (HQ) Based on ΣPBDE

Sample	Location	Device	ΣPBDE (mg/kg)	HQ	Risk Level
ENLP	Enerhen	Laptop	0.988	197.6	Very High
DCPH	Deco	Phone	0.499	99.8	High
OSLP	Osubi	Laptop	0.397	79.4	High
DCLP	Deco	Laptop	0.227	45.4	High

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OSMT	Osubi	Monitor	0.068	13.6	High
ENPH	Enerhen	Phone	0.054	10.8	High
OSPH	Osubi	Phone	0.054	10.8	High
DCMT	Deco	Monitor	0.050	10.0	Moderate
PTILP	PTI	Laptop	0.035	7.0	Moderate
PTIPH	PTI	Phone	0.033	6.6	Moderate
PTIMT	PTI	Monitor	0.032	6.4	Moderate
ENMT	Enerhen	Monitor	0.018	3.6	Moderate

Interpretation: Hazard quotient values exceeded unity for all samples, with several classified as high to very high risk, particularly ENLP, indicating substantial potential for adverse health effects under direct exposure scenarios.

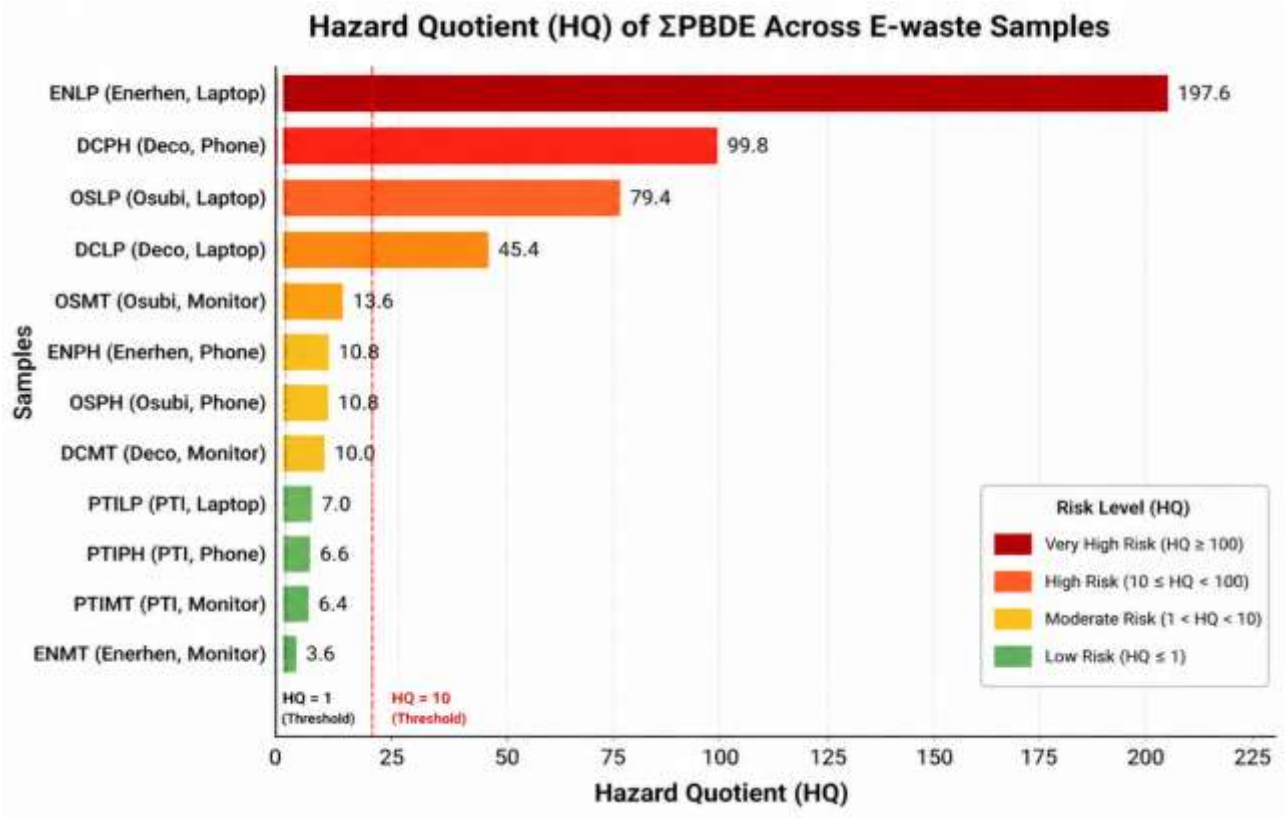


Figure 4: Hazard Quotient (HQ) of ΣPBDE Across E-waste Samples

Interpretation: The figure shows that HQ values exceeded the safety threshold in all samples, with ENLP, DCPH, and OSLP exhibiting the greatest non-carcinogenic risk potential. Overall, laptops constituted the highest-risk e-waste category across the studied dumpsites.

4. RESULTS AND DISCUSSION

4.1 Distribution of PBDEs Across Dumpsites and Electronic Waste Categories

PBDEs were detected in all samples, confirming that e-waste at Warri dumpsites functions as an active reservoir of legacy brominated flame retardants. However, concentrations were markedly heterogeneous, indicating that distribution is governed by device composition, product age, and site-specific waste handling rather than mere presence of electronic debris.

The highest ΣPBDE was observed in the Enerhen laptop, followed by the Deco phone, Osubi laptop, and Deco laptop, while the Enerhen monitor recorded the lowest value. This ranking demonstrates clear enrichment in specific device categories, particularly laptops, rather than uniform contamination across materials. The pattern reflects selective incorporation of PBDEs into polymer-rich and circuit-intensive components.

Device-level aggregation shows a clear hierarchy: ***laptops > phones > monitors.*** The elevated burden in laptops is consistent with their high polymer density and complex architecture, including flame-retarded casings, multilayer circuit boards, insulated wiring, and thermal components. Their longer usage cycles further increase the likelihood of containing legacy PBDE formulations. Comparable enrichment in computing devices has been widely reported (Gallen et al., 2021; Wang et al., 2022). Phones exhibited intermediate levels, though the high value in the Deco phone indicates that certain models can act as concentrated PBDE sources, likely due to polymer-dominant mass after removal of metallic fractions. Monitors consistently showed the lowest levels, attributable to dilution by non-combustible materials and progressive phase-out of PBDEs in newer designs.

Spatially, Enerhen exhibited the highest contamination, driven by the laptop fraction, suggesting accumulation of older, PBDE-rich electronics and intensified dismantling activities. Deco followed, reflecting mixed, high-turnover consumer waste streams with retention of plastic residues after metal recovery. Osubi showed moderate levels, while PTI displayed the lowest and most uniform concentrations, indicative of a more homogeneous and potentially newer waste stream.

From the above, PBDE distribution in Warri is jointly controlled by device type and dumpsite characteristics, with laptops representing the dominant contamination reservoir and site-specific practices modulating exposure intensity.

4.2 Congener Composition, Legacy Sources and Environmental Behaviour

The PBDE profile was dominated by BDE-47, BDE-154, and BDE-183, while BDE-209 was not detected in any sample. This distribution is characteristic of residues from historical penta- and octa-BDE commercial

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mixtures formerly used in electronic housings, engineering plastics, and office equipment. BDE-47 is strongly associated with penta-BDE products, whereas BDE-154 and BDE-183 are widely linked to octa-BDE-treated materials (EFSA, 2021; UNEP, 2022).

The prominence of these congeners indicates that many electronic items entering Warri dumpsites are likely older devices manufactured before global restrictions on PBDE use became widespread. This is plausible in Nigeria, where prolonged reuse of imported second-hand electronics can extend the environmental life span of legacy flame retardants. The higher burdens observed in laptops further support this explanation, since older computing equipment historically contained substantial quantities of brominated additives.

The non-detection of BDE-209 may reflect declining circulation of deca-BDE-treated products, selective disposal patterns, or transformation of highly brominated congeners during weathering. Thermal stress, ultraviolet radiation, and mechanical abrasion can debrominate BDE-209 into lower brominated congeners that are often more mobile and bioavailable (Wang et al., 2022). This may partly explain the dominance of tetra- to hepta-brominated compounds in the present study.

Mass reduction during grinding did not correspond with PBDE concentration, indicating that contaminant burden was not controlled by physical fragmentation alone. Samples with high mass loss sometimes contained low PBDE levels, whereas some moderately reduced samples contained the greatest burdens. This confirms that PBDE occurrence is primarily linked to the chemical nature of retained polymer fractions rather than bulk material loss during processing.

4.3 Exposure Significance, Public Health Risk and Management Implications

Hazard quotient values exceeded the benchmark threshold for all analyzed samples, indicating potential non-carcinogenic concern under the assumed exposure scenarios. The greatest risk estimates were associated with the Enerhen laptop, followed by the Deco phone, Osubi laptop, and Deco laptop, mirroring the concentration pattern and confirming that these materials are the priority exposure sources within the studied waste stream.

Although HQ values do not confirm clinical toxicity, they indicate that estimated exposures may exceed reference levels considered acceptable for chronic contact. This is particularly relevant for informal recyclers, scavengers, repair workers, and residents living close to dumpsites who may experience repeated contact with contaminated dust and debris. Children are especially vulnerable because of lower body mass, frequent hand-to-mouth activity, and the sensitivity of developing endocrine and neurological systems.

PBDE exposure has been associated with thyroid hormone disruption, impaired neurodevelopment, reproductive toxicity, immune dysregulation, and metabolic

disturbance (EFSA, 2021; Costa and Giordano, 2022). In practical terms, manual dismantling of high-burden devices such as laptops and phones may generate contaminated particulates that are inhaled, ingested, or transferred dermally.

The environmental context of Warri further amplifies concern. Seasonal rainfall, drainage movement, and flood-prone surfaces common in the Niger Delta may transport PBDE-bearing particles from dumpsites into nearby soils, drains, wetlands, and surface waters. Consequently, these wastes should be regarded not merely as discarded materials but as continuing sources of chemical emissions.

The findings support urgent implementation of formal e-waste collection systems, controlled dismantling facilities, occupational protection for handlers, and routine monitoring of both legacy PBDEs and replacement flame retardants. Priority intervention should focus on laptop and phone waste fractions, particularly at Enerhen and Deco, where the greatest contaminant burdens were observed.

CONCLUSION

This study confirmed that electronic debris from selected dumpsites in Warri contains measurable PBDE burdens, with contamination strongly influenced by device type and site characteristics. Laptops, particularly from Enerhen, showed the highest concentrations and hazard quotients, while monitors generally had the lowest burden. The dominance of BDE-47, BDE-154, and BDE-183 indicates continued circulation of legacy flame-retardant materials and potential non-carcinogenic exposure risks to informal waste handlers and nearby residents. Formal e-waste collection, controlled dismantling, worker protection, and routine monitoring of flame retardants should be prioritized, especially at high-burden locations such as Enerhen and Deco.

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