Polybrominated Diphenyl Ethers Accumulation in Dumpsites: A Threat to Environmental and Public Health

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Abstract

The environmental and human health impacts of polybrominated diphenyl ethers (PBDEs), widely used brominated flame retardants introduced in the 1970s to enhance fire resistance in consumer goods such as electronics, textiles, and plastics is being reviewed. Due to their additive nature, PBDEs are not chemically bonded to products, leading to their gradual release into air, water, soil, and biota. The structure, persistence, and bioaccumulative properties of PBDEs were examined, highlighting that lower-brominated congeners are more toxic and bioavailable. It explores how improper e-waste disposal, landfill leachate, atmospheric deposition, and industrial activities contribute to environmental contamination. Human exposure occurs primarily through ingestion, inhalation, and dermal contact, with vulnerable populations including children, waste workers, and residents near dumpsites. Health effects linked to PBDE exposure include endocrine disruption, neurotoxicity, liver damage, and possible carcinogenicity. Regulatory efforts such as the Stockholm Convention, EPA regulations, and the EU RoHS Directive have aimed to phase out PBDE production and use, but legacy pollution persists due to the chemical stability and widespread historical use of PBDEs. Municipal dumpsites are identified as major contamination sources, and the paper highlights contamination pathways such as leachate infiltration, airborne dispersion, and bioaccumulation in wildlife and ecosystems. Despite regulatory bans and phase-outs, PBDEs remain present in the environment, necessitating continued monitoring, improved waste management practices, development of safer alternatives, and targeted public health strategies. This study emphasizes the ongoing need for international cooperation, stricter enforcement, and remediation technologies to mitigate the enduring environmental and health challenges posed by PBDE pollution.

Keywords: PBDEs- Polybrominated diphenyl ethers, Stockholm Convention, Persistent Organic Pollutants, Municipal dumpsites, Environment

Introduction

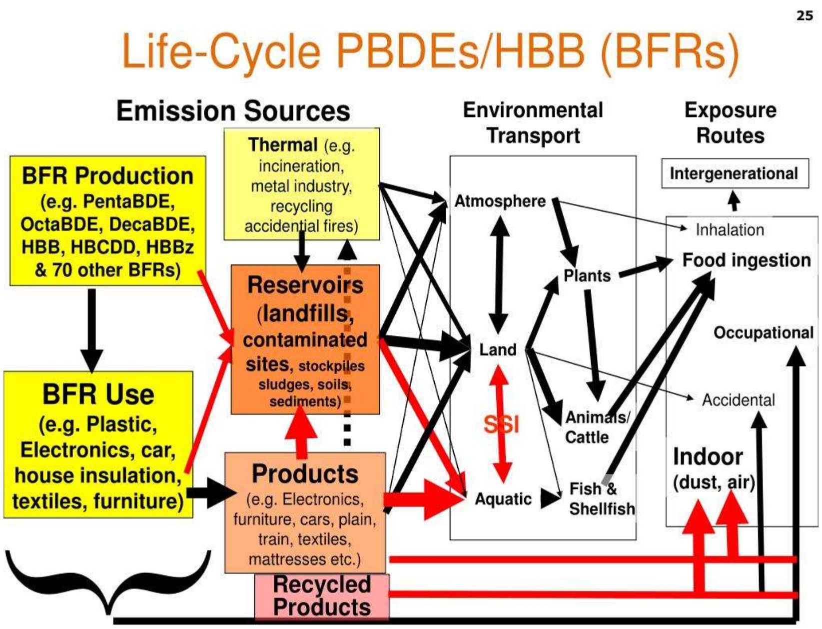
E-waste has emerged as a growing global environmental and health hazard, particularly in developing nations where poor disposal practices such as open burning, informal recycling, and landfill dumping are prevalent. The rising demand for electrical and electronic equipment (EEE), driven by rapid technological advancements and shorter product lifespans, has led to an exponential increase in e-waste generation. Globally, 57.4 million tonnes (Mt) of e-waste were produced in 2021, and this figure is expected to surpass 74 Mt by 2030 (WHO, 2021; UNEP, 2021).

Among the most hazardous substances released from e-waste are polybrominated diphenyl ethers (PBDEs), a class of persistent organic pollutants (POPs) used as flame retardants in electronics, textiles, and construction materials. PBDEs are not chemically bound to the products they are used in, making them prone to leaching into soil, water, air, and living organisms. These compounds persist in the environment, bioaccumulate, and are linked to serious health risks such as endocrine disruption, neurotoxicity, reproductive disorders, and carcinogenic effects (Pérez-Carrascosa et al., 2021; Morel et al., 2022). With PBDEs production annual outputs reaching 80,000 tonnes, although regulatory measures like the EU ban and the U.S. production phase-out began in the early 2000s, PBDE contamination remains due to their durability and continued presence in older products. The Stockholm Convention recognized PentaBDE and OctaBDE as POPs in 2009 and DecaBDE in 2017, mandating global efforts to restrict their use and production (UNEP, 2021)

The reviewed literatures clearly establish that dumpsites are critical hotspots for PBDE accumulation and environmental dissemination. The persistence, bioaccumulative nature, and toxicity of PBDEs, coupled with inadequate waste management practices, amplify public health risks, particularly in rapidly urbanizing settings. Despite growing evidence, gaps remain regarding long-term exposure assessment, seasonal variability, and combined risk from multi-media PBDE exposure. Addressing these gaps is essential for effective regulatory intervention, environmental monitoring, and public health protection.

Sources. Environmental Behaviour and Persistence of PBDEs

Improper disposal (e.g., dumping, burning of e-waste) introduces PBDEs into the environment. Landfills and dumpsites lacking proper containment systems serve as reservoirs for these compounds, resulting in long-term contamination of air, water, and soil. Recycling centers, especially in developing countries with weak regulatory enforcement, exacerbate the issue (UNEP, 2021). Despite restrictions and phase-outs beginning in the early 2000s, PBDEs persist due to their presence in older products and poor waste management. (Du et al., 2020; UNEP, 2021). PBDEs bind tightly to organic matter, showing low mobility but high persistence (Yuan et al., 2020)



Source: Weber, R. 2013

PBDEs Contamination in Municipal Dumpsites

Municipal dumpsites are key contributors to PBDE pollution due to the disposal of electronics, textiles, and treated furniture. PBDEs in leachate and soil have been found at dangerously high levels near poorly managed dumpsites. Case studies in New York, California, China, and the UK confirm widespread environmental damage (Environment Canada, 2021; Birnbaum & Staskal, 2020; & Gao et al., 2020). Contaminants escape via: leachate, air and biota (Vaverková et al., 2020; Wdowczyk, Szymańska-Pulikowska, 2020, Harner et al., 2021 & Chokwe et al., 2020). PBDEs are associated with a range of health effects. They interfere with thyroid hormone regulation, essential for metabolism and brain development thereby causing endocrine disruption (Meng et al., 2020; Zhang et al., 2021 & Gauthier et al., 2020). Prenatal and early-life exposure leading to neurodevelopmental toxicity causing cognitive and behavioral impairments in children (Meng et al., 2020; Kim et al., 2020). PBDEs also cause oxidative stress, liver damage, and metabolic disorders by interacting with PPARs (linked to obesity and diabetes) (Chen et al., 2021). Chronic exposure through food, water, or dust may also elevate cancer risks, though more human studies are needed. Biomonitoring indicates PBDEs' presence in nearly all human tissues (Kaifie et al., 2020; Echeverría et al., 2020).

Several studies have established that dumpsite leachates act as critical transport pathways for persistent organic pollutants, including PBDEs, into surrounding environmental media (Vaverková et al., 2020). demonstrated that open dumpsite leachates significantly degrade soil and groundwater quality, facilitating the downward migration of hydrophobic and toxic substances (Omeiza, 2023). Similarly, (Daniel et al., 2021) reported that leachates from municipal dumpsites contain complex mixtures of organic pollutants capable of contaminating surface water, groundwater, and agricultural soils, thereby posing both ecological and human health risks. Empirical evidence of PBDE accumulation around Nigerian dumpsites has been documented across multiple environmental matrices. Investigation of PBDEs concentrations in soils and plants around municipal dumpsites in Abuja was carried out by (Oloruntoba et al., 2021), the study revealed elevated PBDE levels particularly in surface soils and edible vegetation. Beyond soil and plants, groundwater contamination by PBDEs around dumpsites has also been confirmed by (Olujimi et al., 2024). They detected multiple PBDE congeners in groundwater samples collected in and around Lagos dumpsites, with compositional profiles reflecting mixed commercial PBDE formulations. Atmospheric pathways further compound PBDE exposure risks, (Ayodele et al., 2025) assessed persistent organic pollutants in ambient air around urban dumpsites and reported measurable levels associated with increased inhalation risks. Although the study focused on multiple POPs, its findings demonstrate that dumpsites function as emission points for airborne contaminants, thereby expanding PBDE exposure beyond localized soil and water pathways.

Table 1: Concentrations of PBDEs in Dumpsite-Related Soils and Environmental Media in Nigeria

Location	Site / Sample Type	ΣPBDEs	BDE-209	Total PBDEs	References
Nigeria	Abuja municipal dumpsites – soil (0–15 cm)	112–366	–	112–366	Oloruntoba et al., 2021
Nigeria	Abuja municipal dumpsites – edible plants	8.45–60.0	–	8.45–60.0	Oloruntoba et al., 2021
Nigeria	Lagos e-waste dumpsites – surface soil	141–302	Not separated	141–302	Oloruntoba et al., 2022
Nigeria	Lagos e-waste dumpsites – sub-soil (0–45 cm)	18–185	Not separated	18–185	Oloruntoba et al., 2022
Nigeria	Lagos e-waste dumpsites – sediments	29–96	–	29–96	Oloruntoba et al., 2022
Nigeria	Lagos e-waste dumpsite ponds – water (µg/L)	0.12–2.45	–	0.12–2.45	Oloruntoba et al., 2022
Nigeria	Benin City e-waste dumpsite soils	210–1,840	Dominant	–	Osemudiamen et al., 2020
Nigeria	Delta State municipal	–	42–310	–	Edjere et al., 2020

	dumpsite – leachate				
Nigeria	Delta State municipal dumpsite – sediments	–	38–256	–	Edjere et al., 2020
Nigeria	Lagos State dumpsite groundwater (µg/L)	–	0.3–2,700	–	Olujimi et al., 2024
Nigeria	Lagos/Ogun e-waste sites – dust & soil	180–4,600	Predominant	–	Bilikis et al., 2023

Notes: Values are reported primarily in ng g^{-1} dry weight unless otherwise stated. Water and groundwater concentrations are reported in µg L^{-1}. ΣPBDEs represent the sum of measured PBDE congeners as defined by individual authors.

As shown in **Table 1**, recent studies indicate that Nigerian dumpsites are significant reservoirs of polybrominated diphenyl ethers (PBDEs), with concentrations strongly influenced by waste type and environmental matrix. Municipal dumpsites in Abuja recorded ΣPBDE levels in surface soils of **112–366 ng g^{-1} dw**, while detectable concentrations in edible plants (8.45–60.0 ng g^{-1} dw) highlight active soil–plant transfer and potential dietary exposure **(Oloruntoba et al., 2021)**. Substantially higher contamination was observed at informal e-waste dumpsites in Lagos, Benin City, and Abraka, where ΣPBDEs in soils reached up to **1,840 ng g^{-1} dw**, reflecting uncontrolled electronic-waste dismantling and open burning (**Osemudiamen et al., 2020; Oloruntoba et al., 2022**). Across most e-waste-impacted matrices, **BDE-209 dominated the congener profiles**, consistent with extensive historical use of deca-BDE formulations in electronic plastics (**Edjere et al., 2020; Bilikis et al., 2023**). The occurrence of PBDEs in sub-soils, sediments, leachate, and groundwater including concentrations in the µg L^{-1} range in some wells further indicates vertical migration and off-site transport from dumpsites into surrounding environments (**Olujimi et al., 2024; Oloruntoba et al., 2022**). Overall, the distribution patterns summarized in Table 1 underscore Nigerian dumpsites, particularly informal e-waste sites, as important PBDE hotspots with clear implications for environmental persistence and multi-pathway human exposure.

Human Exposure Pathways to PBDEs

Human exposure occurs through inhalation, ingestion, and dermal contact, especially in urban settings, homes with PBDE-treated products, and regions near landfills or e-waste sites (Zuiderveen et al., 2020; Prasetyo & Sholikhah, 2023). Together, these pathways create a continuous cycle of exposure. Inhalation is a major pathway, particularly indoors where PBDEs settle in dust from aging electronics or furniture. Children are especially vulnerable due to hand-to-mouth behaviors. Studies show higher blood PBDE levels in individuals residing in homes with older furniture (Wu et al., 2020). Ingestion occurs via contaminated food particularly seafood and water. PBDEs accumulate in fish and livestock exposed to polluted environments. Groundwater near landfills can also be contaminated through leachate seepage (Wang et al., 2021). Additionally, crops irrigated with contaminated water or exposed to atmospheric deposition can serve as exposure sources (Oloruntoba et al., 2021). Dermal contact is less common but still significant, especially for children and e-waste workers. PBDEs can leach from materials like textiles or plastics and be absorbed through the skin. Workers in informal recycling sectors may absorb PBDEs via prolonged contact with contaminated materials (Liu et al., 2020).

Toxicological Effect of PBDEs

PBDEs exert several toxicological effects including neurotoxicity**,** endocrine disruption, and potential carcinogenicity. These outcomes are influenced by the PBDE congener type, exposure levels, and individual susceptibility (Prasetyo et al., 2023; Montalbano et al., 2020). PBDEs causes neurotoxicity by interfering with thyroid hormones, which are crucial for brain development. Studies associate prenatal exposure to PBDEs with reduced IQ, attention deficits, and behavioral issues in children (Wallenborn et al., 2024). Animal research supports these findings, showing impaired motor function and memory loss following exposure during developmental periods (Viberg et al., 2003). Another key effect is endocrine disruption by mimicking or blocking natural hormones, disruption during pregnancy may result in cognitive and developmental delays in offspring (Vuong et al., 2021). PBDE exposure has been linked to liver and thyroid tumors in rats. Some studies suggest possible links to breast cancer via estrogenic pathway disruptions. Lower-brominated congeners, such as PentaBDE, are especially potent due to their high bioavailability (Birnbaum & Staskal, 2004).

Table 2: Summary of Health Risk Metrics (HQ, HI, ILCR) for PBDEs at Nigeria Dumpsites

Location / Site	Exposure Pathway	HQ (Non-cancer)	HI	ILCR (Cancer risk)	References
Abuja municipal dumpsites	Dietary intake (vegetables, eggs, milk)	<1 (adults); ≈1 (children)	<1–1.2 (children)	10^{-7} – 10^{-6}	Oloruntoba et al., 2021
Lagos municipal dumpsites	Groundwater ingestion	<1 (adults); >1 (children at hotspots)	Up to 2.4 (children)	10^{-6} – 10^{-5}	Olujimi et al., 2024
Lagos e-waste dumpsites	Soil ingestion & dermal contact	<1	<1	10^{-7} – 10^{-6}	Oloruntoba et al., 2022
Delta State municipal dumpsites	Leachate and surface water (screening)	Potential >1	–	–	Edjere et al., 2020
Lagos & Ogun e-waste sites	Dust inhalation & soil ingestion	<1 (residents); ≈1 (workers)	≈1 (occupational)	≈10^{-6}	Bilikis et al., 2023

Notes: HQ = hazard quotient; HI = hazard index (sum of HQs across exposure pathways); ILCR = incremental lifetime cancer risk. HQ or HI <1 indicates negligible non-carcinogenic risk, while values >1 suggest potential concern. Acceptable ILCR benchmarks generally range from 10^{-6} to 10^{-4} depending on regulatory guidance.

Consistent with **USEPA human health risk assessment guidance**, the non-carcinogenic and carcinogenic risk metrics summarized in **Table 2** show that hazard quotients (HQ) and hazard indices (HI) generally remain below unity for adults, suggesting limited immediate non-cancer risk, whereas children and occupationally exposed groups approach or exceed threshold values at some sites, particularly for groundwater and dust-related exposure. Incremental lifetime cancer risks (ILCRs), evaluated against the **USEPA and WHO acceptable benchmark range (10^{-6} – 10^{-4})**, are largely within tolerable limits but trend toward upper bounds at identified hotspot These findings trigger concerns particularly Operational Safeguards related to pollution prevention, occupational health and safety, and community health.

Epidemiological Studies and Health Risk Assessments

Epidemiological studies reveal widespread human exposure to PBDEs globally. Surveys have detected PBDEs in blood, breast milk, and adipose tissues, particularly in industrialized nations with high consumption of treated products. Prenatal exposure studies show links between PBDE levels and neurodevelopmental issues in children. For example, research from California associated maternal PBDE levels with altered thyroid hormones and reduced IQ scores in offspring (Azar et al., 2024). Occupational studies in China show that informal e-waste workers bear the highest exposure burden, reinforcing the importance of occupational health protections (Pinto et al., 2020).

Health risk assessments (HRAs) evaluate PBDE hazards through dose-response analysis, exposure assessment, and risk characterization. Dietary intake particularly seafood is a major exposure route. PBDEs' lipophilicity causes accumulation in fatty animal tissues, leading to chronic exposure through diet (Sun, 2024). Non-dietary exposure, such as household dust inhalation and dermal contact, also contributes significantly, especially for children. Risk assessments suggest that BDE-47 and BDE-99 are among the most hazardous congeners. The EPA has considered developmental and reproductive risks when assessing safe exposure thresholds (USEPA, 2010).

Mitigation Strategies

Sustainable waste management practices, particularly targeting the improper disposal of PBDE-laden materials such as electronics, textiles, and furniture. Waste reduction and sustainable design focuses on minimizing hazardous materials in product manufacturing. Alternatives such as phosphorus-based flame retardants or nanomaterials are now used in electronics, replacing PBDEs (Zheng et al., 2025). Recycling helps divert PBDE-containing waste from landfills. However, informal recycling often results in the release of PBDEs into the environment. Safe recycling involves mechanical separation and advanced recovery technologies (Houessionon et al., 2021). Formalizing e-waste sectors, enforcing labor safety laws, and implementing Extended Producer Responsibility (EPR) policies are essential to controlling PBDE emissions (OECD, 2001; NESREA Regulation, 2011). Public education campaigns and environmental monitoring are vital. Banning open dumping, monitoring contamination, and enforcing compliance with the Stockholm Convention are critical (UNEP, 2019). Collective efforts among government, industry, and civil society can drastically reduce PBDE pollution. Replacing PBDEs with safer flame retardants is key to reducing environmental persistence and toxic exposure. Phosphorus Based Flame Retardants (PFRs) like TPP and RDP are common PBDE substitutes (Tang et al., 2020).

Remediation Strategies for Contaminated Sites

Remediation strategies include: Physical methods involves soil excavation; thermal desorption and activated carbon & biochar which adsorbs PBDEs in soil and water, reducing bioavailability (Wang et al., 2022). Chemical methods involve UV/Photodegradation; Advanced oxidation (Zhang et al., 2020). ZVI reduction (Zhong et al., 2021). Biological approaches; Fungal degradation and Phytoremediation (Zhang et al., 2021; Chen et al., 2022).

Policy and Regulatory Recommendations

Product Regulation by phasing out PBDEs following EPA, EU and NESREA regulations; Producers should be made accountable for end-of-life waste through the EPR program and Prevention of PBDEs laden goods from entering national markets (APHA, 2010). Waste management improvements; enabling safe treatment with high-temperature incineration; Ban open burning (Li et al., 2024). Environment monitoring involving PBDE surveillance; landfill upgrades and risk mapping (UNEP, 2019). Public health protection entailing health monitoring; training & awareness and promoting safe alternatives (APHA, 2010). International Collaboration, public awareness and advocacy.

Conclusion and Recommendations

The presence of PBDEs in soil, water, and air due to improper waste handling and open dumping necessitates urgent action across policy, waste management, public health, and advocacy fronts (UNEP, 2019; APHA, 2010; Miranda et al., 2022). Nationwide monitoring of PBDE levels in environmental media and human populations, especially near dumpsites, will allow timely risk assessments and remediation actions (Lei et al., 2022).

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