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Distribution of Polybrominated Diphenyl Ethers in Benthic Organisms from West Lake, Hanoi: Levels, Congener Profiles, and Seasonal Trends

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Abstract

This study evaluates the occurrence, spatial distribution, temporal changes and ecological risk of six phthalate esters (PAEs) - DMP, DEP, DBP, BBP, DEHP and DnOP - in surface sediments (0–5 cm) of West Lake, the largest urban lake in Hanoi, Vietnam. Sediment samples were collected at 10 stations during four campaigns: May 2022 and May 2023 (end of the dry sea-son) and November 2022 and November 2023 (end of the rainy season). DBP, BBP and DEHP were detected in all 40 samples and DnOP in 29 samples (all below the limit of quantification, LOQ, of 3 µg/kg dw), whereas DMP and DEP were not detected (< limit of detection, LOD, of 1 µg/kg dw). Procedural blanks were below the LOD, matrix-spike recoveries ranged from 83.0% to 97.0%, and the relative percent difference of duplicate analyses ranged from 0.7% to 6.9%. Σ_6PAEs ranged from 18.50 to 46.53 µg/kg dry weight (dw), with campaign means of 33.83–34.49 µg/kg dw (n = 10 stations per campaign). DEHP, DBP and BBP contributed approximately 55.2%, 20.8% and 19.9% of Σ_6PAEs, respectively, consistent with inputs from do-mestic wastewater and plastic materials in the densely urbanized areas surrounding the lake. Campaign means changed by −0.63 to +0.66 µg/kg dw (≤ 2.0%) between consecutive campaigns, a range comparable to the analytical precision, and showed neither a seasonal pattern nor an inter-annual trend. Single-compound risk quotients (RQ) indicated minimal risk for BBP and DnOP, low risk for DBP and medium risk for DEHP, with all RQ values below the high-risk threshold (RQ ≥ 1).

Keywords: Benthic organisms, PBDEs, seasonal, West Lake.

1. Introduction

Polybrominated diphenyl ethers (PBDEs) are a class of persistent organic pollutants (POPs) that have been used extensively as additive flame retardants since the 1970s in a wide variety of industrial and consumer products, such as electronic equipment, plastics, textiles, furniture, and polyurethane foam. Because of their high environmental persistence and strong hydrophobicity, together with their bioaccumulative potential and capacity for long-range transport, PBDEs have been detected across diverse regions worldwide, from polar areas to tropical urban centres in Southeast Asia [1]. Although the production and use of PBDEs have been restricted under the Stockholm Convention since 2009–2017, their concentrations in indoor dust, sediments, and biota across many regions remain at concerning levels, largely due to the continued use and disposal of legacy PBDE-containing products [1]. Furthermore, the rapid expansion of the polymer industry over recent decades has substantially increased the demand for brominated flame retardants (BFRs), among which PBDEs represent the most widely used group [2-4]

PBDEs can be released into the environment throughout the entire product lifecycle - from manufacturing and use to end-of-life disposal - as they are incorporated primarily as additives and are not chemically bonded to the host material. Numerous studies have documented the widespread occurrence of PBDEs in air, water, soil, sediment, and biota across diverse ecosystems globally [2, 3]. Studies conducted in Europe have reported the ubiquitous presence of PBDEs in aquatic environments, sediments, sewage sludge, and food chains, with evidence of increasing accumulation over recent decades [2]. This pervasive distribution highlights the capacity of PBDEs for long-range transport and prolonged environmental persistence, heightening the risk of exposure for both wildlife and humans.

Beyond their persistence, PBDEs are of particular concern due to their adverse effects on human health and ecosystems. Numerous toxicological studies have demonstrated that PBDEs can impair the nervous and endocrine systems, particularly thyroid hormone signalling, as well as the growth and development of organisms [5, 6]. A comprehensive review by Wu *et al.* (2020) [7] reported that PBDE exposure is associated with endocrine disruption, developmental neurotoxicity, carcinogenicity, and metabolic disorders. Notably, prevalent congeners such as BDE-47 and BDE-99 have been shown to interfere with thyroid hormone signalling

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pathways and cause developmental neurotoxicity in both experimental animals and human cell models [7]. The increasing concentrations of PBDEs detected in wildlife and human breast milk across multiple regions further underscore the chronic exposure risks posed by this contaminant group [5, 6].

Freshwater snails, particularly *Bellamya aeruginosa* and related species, have been recognised as effective bioindicators of POP contamination in urban lake ecosystems. Studies at Taihu Lake, China, demonstrated that lower-brominated PBDE congeners (tetra- to hexa-BDE) are efficiently bioaccumulated in snail tissue, whereas BDE-209 exhibits lower bioavailability despite its predominance in sediments [8]. In Vietnam, PBDEs have been detected in multiple environmental compartments, particularly at informal e-waste recycling sites in northern Vietnam, where BDE-209 was the dominant congener in indoor dust, sediments, and fish [9]. Subsequent studies reported PBDE concentrations in road dust from northern Vietnam ranging from 290 to 96,900 ng/g, substantially higher than those recorded in many developed countries [10]. In Hanoi, recent studies have identified BDE-209, BDE-99, and BDE-47 as the predominant PBDE congeners in urban sediments, while also noting the increasing occurrence of alternative brominated flame retardants such as PBDE [11]. Additionally, BDE-209 accounted for 62.6–86.5% of total PBDEs in indoor dust from inner-city districts of Hanoi, indicating that commercial deca-BDE mixtures remain a significant emission source in the urban environment [12]. BDE-154 showed the largest increase over the monitoring period among the analyzed congeners (~16.8%), which may be associated with debromination products of BDE-209 under anaerobic conditions in the shallow lake sediments [13, 14]. ΣPBDE concentrations in snails from this region ranged from 25 to 200 ng/g lipid weight, clearly reflecting the influence of surrounding industrial emission sources [8]. Snails have also been used as bioindicators of PBDEs in other settings in China. In the Fengjiang e-waste dismantling region, PBDE concentrations in apple snails (Ampullariidae) were significantly correlated with those in the surrounding soils and decreased with distance from the dismantling site, supporting the use of snails as reliable bioindicators [15]. In mudsnails (*Cipangopaludina cahayensis*) from an e-waste recycling region in South China, biota–sediment accumulation factors of most PBDE congeners increased as sediment concentrations decreased, and debromination of higher-brominated congeners was suggested as a source of some lower-brominated congeners (e.g., BDE-183) in snail tissue [16]. More recently, a food-web study in typical shallow lakes of the Yangtze River Delta, which included river snails, confirmed that PBDE congeners are bioaccumulated and biomagnified to varying degrees in lake organisms [17]. By contrast, data on PBDEs in molluscs from Vietnam remain scarce and are largely limited to coastal mussels from the Asian Mussel Watch programme, in which PBDEs were detected in all samples from Asian coastal waters, including Vietnam, at 0.66–440 ng/g lipid weight [18]. Earlier studies on freshwater molluscs in the Hanoi region focused on organochlorine pesticides and PCBs rather than brominated flame retardants [19].

This knowledge gap is particularly relevant for megacities such as Hanoi, where rapid urbanisation and population growth are increasing the generation of domestic waste, discarded electrical and electronic equipment, and demolition materials - all potential sources of PBDEs to inner-city lakes. The urban lakes of Hanoi are typically shallow, poorly flushed, and receive wastewater from the surrounding residential areas, making them effective sinks for hydrophobic contaminants in bottom sediments. Benthic snails living in these lakes both integrate sediment contamination and are harvested and consumed by local residents. However, existing PBDE studies in Hanoi have focused on dust and sediments [11, 12], and data on benthic organisms in urban lakes are still lacking; consequently, the transfer of PBDEs from the abiotic environment into the aquatic food chain, and the associated dietary exposure, remain unassessed.

West Lake (Ho Tay) is the largest natural freshwater lake within the inner city of Hanoi, covering approximately 526 ha and originating from an ancient oxbow of the Red River. The lake is characteristically shallow (mean depth approximately 1.5–2.5 m), has a low water exchange rate, and is surrounded by high-density residential, commercial, and hospitality developments. West Lake is in a state of severe eutrophication, with elevated concentrations of nutrients and organic matter, creating favourable conditions for the retention and accumulation of hydrophobic organic contaminants such as PBDEs in bottom sediments.

To the best of our knowledge, this is the first study in Vietnam to investigate PBDE accumulation in freshwater snails from an urban lake, and the first time-series dataset on PBDEs in benthic organisms from West Lake. Addressing the research gaps identified above, this study aimed to: (1) determine the concentrations of seven major PBDE congeners (BDE-28, BDE-47, BDE-99, BDE-100, BDE-153, BDE-154, and BDE-209) in snail samples as representative benthic organisms from West Lake, Hanoi, collected on a biannual basis during 2022–2023; (2) assess temporal and seasonal variations in PBDE concentrations; and (3) compare findings with regional studies to contextualise the relative contamination levels and provide a baseline dataset to support environmental management and food safety in the study area.

2. Materials and Methods

2.1. Study Area and Sampling

Snail samples were collected from West Lake (21°03'N, 105°49'E), Hanoi on a biannual basis in May

2022, November 2022, May 2023, and November 2023, corresponding to the wet and dry seasons respectively. giving a total of 40 snails over the two-year study (10 snails × 4 campaigns). Each snail and each sample was analysed in triplicate. Since sampling was restricted to the accessible littoral zone, where snails are most abundant, the dataset characterises exposure of the littoral benthic community rather than the entire lake bed; this limitation is acknowledged in Section 4. Following collection, samples were rinsed, soft tissue was dissected, homogenized, and stored at −20 °C until analysis.

Snail specimens were identified as *Sinotaia quadrata* (freshwater snail), a common benthic gastropod widely distributed in Vietnamese lakes and rivers. Only adult individuals of comparable size (shell length 2.5–4.0 cm) were selected to minimize variability attributable to age- and size-dependent bioaccumulation differences. At each sampling event, the collection site, water depth, and substrate type were recorded. Sampling locations were georeferenced using a handheld GPS device to ensure spatial consistency across campaigns. All samples were transported to the laboratory on ice within 6 hours of collection.

2.2. Chemicals and Instrumentation

Solvents including DCM, acetone, cyclohexane, and n-pentane were of HPLC grade (Merck, Germany). Anhydrous Na_2SO_4 was baked at 400 °C for 4 hours; silica gel (60–200 mesh) was activated at 130 °C for 12 hours. Native PBDE standard solutions at 50 µg/mL in isooctane were supplied by AccuStandard (USA).

Seven PBDE congeners, including BDE-28, BDE-47, BDE-99, BDE-100, BDE-153, BDE-154, and BDE-209, were selected for analysis based on their prevalence in commercial PBDE formulations and their reported occurrence in environmental and biological matrices in Southeast Asia [6, 9]. Working standard solutions were prepared by serial dilution of the native stock in isooctane at concentrations of 0.5, 1, 5, 10, and 50 ng/mL for external calibration. A surrogate standard (BDE-77, 10 ng/mL) was spiked into each sample prior to extraction to monitor procedural recovery. BDE-77 was chosen as the surrogate because it is not a significant constituent of the commercial penta-, octa- or deca-BDE mixtures [20] and is therefore unlikely to occur in environmental samples. All glassware was pre-cleaned by sequential rinsing with acetone and n-hexane and baked at 450 °C for 4 hours prior to use to minimize background contamination.

2.3. Sample Extraction and Cleanup

The extraction and cleanup procedure was adapted from US EPA Method 3540C (Soxhlet extraction) [21] and US EPA Method 3630C (silica gel cleanup) [22], with modifications based on published procedures for PBDEs in biota [8, 23]; the modified method was validated in-house as described in Section 2.4. Approximately 5–10 g of homogenized tissue was wrapped in Whatman No. 1 filter paper and Soxhlet-extracted with DCM:acetone at a reflux rate of 4–6 cycles/hour for 16–24 hours. The extract was cooled, filtered through anhydrous Na_2SO_4 to remove residual moisture, rinsed with 100–125 mL DCM, and concentrated by rotary evaporation at 40 °C to near dryness. The residue was solvent-exchanged into 5–6 mL cyclohexane and further reduced to 1–2 mL prior to cleanup. A DCM:acetone mixture was used because acetone, being water-miscible, improves solvent penetration into wet biological tissue, while DCM efficiently dissolves lipids and hydrophobic analytes; this solvent combination is among those recommended in US EPA Method 3540C for semivolatile organic compounds [21].

A glass cleanup column was packed sequentially with glass wool, activated silica gel (5–7 cm), and a thin layer of anhydrous Na_2SO_4, then conditioned with 50 mL n-pentane. After sample loading, interferences were eluted with 30 mL n-pentane (discarded), followed by target PBDE fractions eluted with 20 mL n-pentane:DCM (3:2, v/v) and 20 mL neat DCM (combined). The final extract was evaporated to 1 mL and transferred to a 2 mL amber vial with a Teflon-lined cap for instrumental analysis. Although PBDEs are non-polar, DCM was added to the eluent to ensure quantitative elution of all target congeners, including the highly brominated BDE-209, within a small solvent volume, in line with the hexane/DCM mixtures commonly used to elute PBDEs from silica columns [8, 23]. The initial n-pentane fraction mainly removes aliphatic interferences; its PBDE content was checked by eluting a standard mixture through the column.

2.4. GC-MS Analysis and Quality Assurance/Quality Control

PBDEs were quantified by GC-MS operated in negative chemical ionization (NCI) mode using a DB-5MS capillary column (30 m × 0.25 mm × 0.25 µm). The oven temperature program was as follows: 60 °C (1 min) → 200 °C (20 °C/min) → 280 °C (5 °C/min) → 310 °C (10 °C/min, held for 10 min). Quantification was performed using a five-point external calibration curve (0.5–50 ng/mL, $R^2 \geq 0.995$). Isotope dilution was not applied because, in the NCI mode, PBDEs are quantified from the bromide ions (m/z 79 and 81), which are common to native and ^{13}C-labelled congeners; co-eluting labelled analogues therefore cannot be distinguished from their native counterparts for most congeners, and isotope dilution quantification requires electron-ionisation high-resolution MS as specified in US EPA Method 1614A [24, 25].

Procedural blanks were processed concurrently with each sample batch to monitor potential contamination. Recoveries of individual congeners and of the surrogate BDE-77 were all within the acceptance range of 70–120%. Repeatability was expressed as the relative

standard deviation (RSD) of triplicate analyses. All samples were analyzed in triplicate, and results are reported as mean ± SD (µg/kg wet weight). Congeners with concentrations below the method detection limit (MDL) were assigned a value of zero for ΣPBDE calculation. Potential sources of analytical error were also considered: (i) thermal degradation of BDE-209 in the GC injector and column, which was monitored through the response of BDE-209 in the calibration standards [24]; (ii) background contamination from laboratory dust and materials, controlled by procedural blanks and by baking all glassware [23]; (iii) matrix effects from co-extracted lipids, assessed through matrix-spike recoveries; and (iv) evaporative losses of the more volatile lower-brominated congeners, minimised by avoiding evaporation to complete dryness and monitored through the surrogate recovery.

3. Results and Discussion

3.1. Total PBDE Concentrations in Snail Samples

PBDEs were detected in all snail samples collected from West Lake across the four monitoring campaigns, with ΣPBDE concentrations ranging from 2.50 to 3.27 µg/kg wet weight (Fig. 1, Table 1). The ubiquitous presence of PBDEs throughout all samples confirms that this contaminant group is pervasive in the benthic fauna of this urban lake, consistent with the characteristics of West Lake being situated within a high-density residential and commercial district where emission pressures from e-waste and PBDE-containing consumer products are continuous [1, 12].

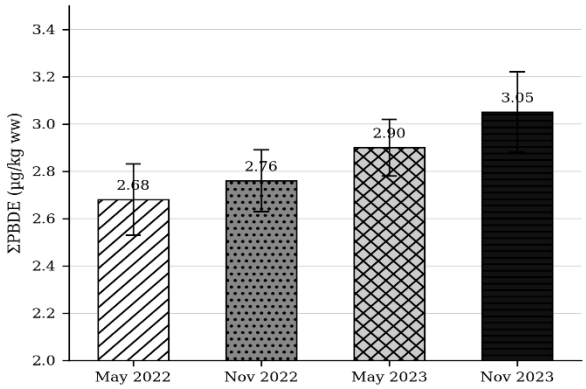


Fig. 1. Mean ΣPBDE concentrations (mean ± SD, µg/kg ww) in snail samples from West Lake, Hanoi across four sampling periods

Among individual congeners, BDE-209 consistently dominated across all sampling periods, accounting for approximately 57% of ΣPBDE, followed by BDE-99 and BDE-47 (~11% each). The remaining congeners, including BDE-153, BDE-100, BDE-154, and BDE-28, contributed 8%, 6%, 5%, and 2%, respectively. This stable congener profile throughout the entire monitoring period suggests a consistent and uniform emission source, most likely associated with commercial deca-BDE mixtures widely used in electronic equipment and construction materials in the surrounding urban area [11, 12]. Notably, the combined proportion of BDE-47 and BDE-99 (~22%) reflects the concurrent contribution of legacy penta-BDE mixtures from products still in circulation, and is particularly significant from a toxicological perspective given that these two congeners are among the most potent endocrine disruptors and developmental neurotoxicants within the PBDE family [4, 7].

Mean ΣPBDE values increased continuously across successive monitoring campaigns, rising from 2.68 ± 0.14 µg/kg ww (May 2022) to 3.05 ± 0.15 µg/kg ww (November 2023), corresponding to a cumulative increase of 13.7% over 18 months (Fig. 3). The average annual rate of increase reached 8–11% for most congeners (Table 1). This apparent upward trend may reflect ongoing bioaccumulation against a backdrop of insufficiently controlled PBDE emission sources, including e-waste, legacy construction materials, and general urban activities - in Hanoi [9, 10, 12]. However, this trend is based on only four campaigns over 18 months, and the increase between consecutive campaigns is of similar magnitude to the within-campaign variability (SD is approximately 5% of the mean); it should therefore be regarded as preliminary. If sustained, such an increase would be of concern for West Lake, and continued monitoring over a longer period is required to confirm whether it represents a persistent trend.

Table 1. Concentration ranges of PBDE congeners (µg/kg ww) in snails from West Lake, Hanoi (n = 10 per campaign)

Congener	May 2022	Nov 2022	May 2023	Nov 2023
BDE-28	0.03–0.06	0.03–0.06	0.03–0.06	0.03–0.07
BDE-47	0.27–0.34	0.27–0.34	0.29–0.36	0.30–0.38
BDE-99	0.27–0.34	0.28–0.34	0.30–0.36	0.31–0.38
BDE-100	0.15–0.18	0.16–0.18	0.17–0.19	0.18–0.20
BDE-153	0.20–0.23	0.21–0.24	0.22–0.25	0.23–0.27
BDE-154	0.10–0.13	0.11–0.14	0.12–0.15	0.12–0.16
BDE-209	1.36–1.79	1.38–1.79	1.45–1.89	1.52–1.98
ΣPBDE	2.50–2.96	2.55–2.96	2.68–3.12	2.82–3.27

Cumulative change in the mean concentration between May 2022 and November 2023

3.2. PBDE Congener Profile Characteristics

BDE-209 was the overwhelmingly dominant congener across all samples, accounting for a stable proportion of approximately 57% of total ΣPBDE (Fig. 2, Table 1). This congener profile remained virtually unchanged across all sampling campaigns, suggesting that PBDE inputs into West Lake are stable and primarily derived from commercial deca-BDE mixtures [11].

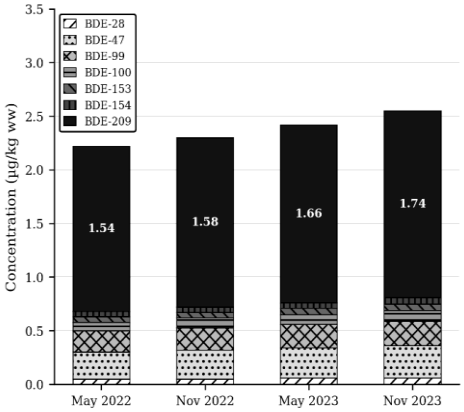


Fig. 2. Stacked bar chart of mean PBDE congener concentrations (µg/kg ww) across four sampling periods from West Lake, Hanoi

The dominance of BDE-209 in snail tissue, despite its relatively low bioavailability compared to lower-brominated congeners, reflects the overwhelming prevalence of deca-BDE formulations in the surrounding urban environment. This is consistent with findings from indoor dust and road dust studies conducted in Hanoi, where BDE-209 accounted for 62.6–86.5% of total PBDEs [11, 12], confirming that the congener signature observed in benthic organisms at West Lake is a direct biological reflection of the ambient contamination profile. The fact that this profile remained stable across all four campaigns - spanning two full annual cycles - further supports the interpretation that no major new point sources were introduced into the lake catchment during the study period, and that the observed accumulation is driven by chronic, diffuse urban inputs rather than episodic discharge events.

From a toxicological standpoint, while BDE-209 numerically dominates the congener profile, the ecological and health significance of BDE-47 and BDE-99 should not be underestimated. These lower-brominated congeners are known to be more readily absorbed and metabolized by aquatic organisms, resulting in substantially higher internal tissue concentrations relative to sediment levels [8]. Their combined contribution of approximately 22% to ΣPBDE, maintained consistently across all monitoring periods, indicates a persistent co-exposure scenario involving both deca- and penta-BDE derived contamination. Given that BDE-47 and BDE-99 are among the most extensively studied PBDE congeners in terms of endocrine disruption and developmental neurotoxicity [3, 7], their stable and non-negligible presence in benthic fauna from West Lake merits continued monitoring; however, because dietary exposure was not assessed in this study, no conclusion on human health risk can be drawn.

3.3. Seasonal Variation

Dry-season (November) ΣPBDE concentrations were consistently higher than wet-season (May) values in both monitoring years: by approximately 2.9% in 2022 and approximately 5.0% in 2023 (Table 1, Fig. 3). This seasonal trend was consistent across all congeners. The widening seasonal amplitude from 2022 to 2023 may reflect the gradual accumulation of PBDEs in sediments over time, resulting in increased dry-season exposure of snails to an increasingly PBDE-enriched sediment matrix.

Three mechanisms are tentatively proposed to explain the consistently elevated PBDE concentrations observed during the dry season. First, reduced precipitation and surface runoff during the dry season diminish the dilution effect on contaminant concentrations in the water column and limit the deposition of relatively clean sediment layers onto the lake bed, thereby increasing the bioavailability of PBDEs accumulated in existing surface sediments. Second, lower water levels and reduced water exchange rates characteristic of the dry season at West Lake extend the contact time between snails and PBDE-enriched bottom sediments, promoting greater uptake via both ingestion and direct contact pathways. Third, seasonal changes in the physiological condition of the snails, such as lipid content and reproductive status, may alter the tissue burden of lipophilic compounds; seasonal differences of almost two-fold in total lipid content have been reported for tropical–subtropical molluscs such as *Perna viridis* [30]. The linear trend line shown in Fig. 3 indicates an upward trajectory over the monitoring period; however, given the limited number of campaigns, this trend should be regarded as preliminary (Section 3.1).

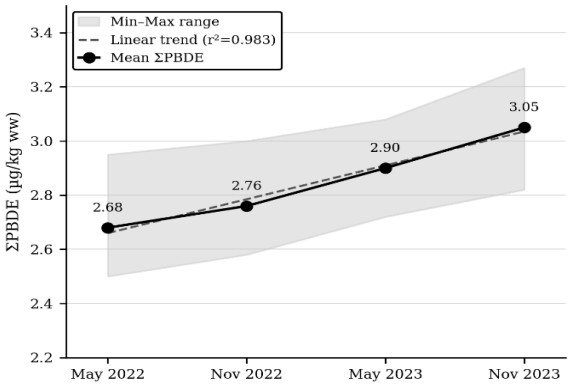


Fig. 3. Temporal trend of ΣPBDE concentrations in snail samples from West Lake, Hanoi (May 2022 – Nov 2023). Shaded band: observed min–max range; dashed line: linear trend (n = 10 per period)

These interpretations are consistent with observations in other urban water bodies in Asia. In reservoirs of Shenzhen, a megacity in South China, ΣPBDE concentrations in water were significantly higher in the dry season than in the wet season [28], and in the East Lake, the largest urban lake in Wuhan, China, dissolved PBDE concentrations in winter (2.92–5.54 ng/L) were several times higher than in summer (0.67–1.51 ng/L) [29], consistent with a stronger dilution effect during the rainy season. West Lake is subject to a comparable seasonal regime: Hanoi has a tropical monsoon climate with a rainy season from May to October and a dry season from November to April, and the lake receives stormwater and wastewater inputs from its densely populated catchment, so that water level, dilution, and sediment resuspension differ between seasons. It should also be noted that the May samples were collected at the transition from the dry to the rainy season, and the November samples at the transition from the rainy to the dry season. Since snail tissue integrates exposure over the preceding weeks to months, the observed differences may partly reflect conditions in the preceding season. Paired sediment–water–biota monitoring at a higher temporal resolution is needed to verify the proposed mechanisms.

The comparatively large increase of BDE-154 (Table 1 suggests that sediment diagenetic processes may be contributing to the transformation and redistribution of PBDE congeners within the lake system, a dynamic that warrants further investigation through paired sediment-biota monitoring. In contrast, BDE-28, the least brominated congener analyzed, showed the smallest absolute concentration range despite a comparable relative trend (+13.0%), consistent with its lower abundance in commercial PBDE formulations and its higher susceptibility to photodegradation in the water column [3]. The remarkably stable congener profiles across all four campaigns - with coefficients of variation remaining low for each individual congener - further support the interpretation that PBDE inputs to West Lake originate from diffuse, spatially consistent urban sources rather than from episodic or point-source discharge events.

3.4. Comparison with Regional and Global Studies

ΣPBDE concentrations in snail samples from West Lake (2.50 – 3.27 µg/kg ww) are compared with published data for snails and other benthic invertebrates from Asia in Table 2. Most previous studies on snails report lipid-normalised concentrations: Σ24PBDEs in *Bellamya aeruginosa* from Taihu Lake ranged from 25 to 200 ng/g lw [8], Σ8PBDEs in apple snails from an e-waste recycling area in South China ranged from 41 to 270 ng/g lw [26], and estuarine snails (*Cerithidea rhizophorarum*) from the Ariake Sea, Japan, contained 31 ng/g lw [27]. In this study, these values cannot be compared quantitatively with our wet-weight data. A clearer difference was found in congener composition: BDE-47 and BDE-99 were the main congeners in snails from Taihu Lake, where BDE-209 showed low bioavailability despite dominating the sediments [8], whereas BDE-209 accounted for ~57% of ΣPBDE in West Lake snails. At informal e-waste recycling sites in Vietnam, Anh *et al.* (2017) [9] reported markedly higher PBDE concentrations in fish tissue, suggesting that West Lake is not affected by high-intensity sources comparable to e-waste recycling activities.

Table 2. Comparison of PBDE levels in benthic organisms and related environmental matrices from selected studies in Asia

Location	**Matrix**	**ΣPBDE (µg/kg)**	**Dominant congener**	**Reference**
West Lake, Hanoi, Vietnam (This study)	Snail, Sinotaia quadrata (ww)	2.50 – 3.27	BDE-209 (~57%)	This study
Taihu Lake, China	Snail, Bellamya aeruginosa (lw)	25 – 200 (Σ24PBDEs)	BDE-47, BDE-99	Yin *et al.,* 2017 [8]
South China (e-waste area)	Apple snail, Ampullariidae (lw)	41 – 270 (Σ8PBDEs)	BDE-209	She *et al*., 2013 [26]
Fengjiang, SE China (e-waste area)	Apple snail, Ampullariidae (dw)	0.09 – 27.7 (excl. BDE-209)	n.r.	Fu *et al*., 2011 [15]
Ariake Sea, Japan	Snail, Cerithidea rhizophorarum (lw)	31 (Σ8PBDEs)	BDE-209	Kobayashi *et al*., 2015 [27]
Asian coastal waters, incl. Vietnam	Mussels (lw)	0.66 – 440	n.r.	Ramu *et al.*, 2007 [18]
E-waste sites, N. Vietnam	Fish (ww)	ND – 45.6	BDE-209	Anh *et al*., 2017 [9]

However, direct numerical comparison across studies must be interpreted with caution, as PBDE concentrations in biota are highly matrix-dependent and unit-dependent. The values reported for Taihu Lake snails are expressed on a lipid-weight basis (ng/g lw), which are not directly comparable to the wet-weight values reported in this study; when lipid content is taken into account, the concentration gap between the two sites narrows considerably. Similarly, fish tissue tends to exhibit higher PBDE burdens than gastropods due to differences in lipid content, trophic position, and metabolic capacity, making cross-species comparisons inherently limited [8, 12]

Within the Vietnamese context, the contamination levels at West Lake are more meaningfully compared with data from urban sediments and biota in Hanoi. Hoang *et al.* (2021) [11] reported median ΣPBDE concentrations of 6.6 ng/g dw in surface sediments of five urban lakes in Hanoi, which documented a range of 0.03–17.5 ng/g dw in river and lake sediments across the Hanoi metropolitan area. The PBDE burden observed in West Lake snails in the present study is consistent with bioaccumulation from this sediment contamination background, suggesting that snails are effectively integrating the ambient sediment pollution signal over time. This interpretation is further supported by the stability of the BDE-209-dominated congener profile across all campaigns, which mirrors the deca-BDE signature consistently reported in Hanoi urban sediments [11].

The absence of an e-waste-type signature in West Lake snails may reflect the absence of major industrial or e-waste processing facilities in the immediate catchment of West Lake, as well as the buffering effect of the lake's high organic matter content, which may sequester a portion of the incoming PBDEs within the sediment matrix and reduce their bioavailability to benthic organisms.

Overall, the available evidence suggests that West Lake currently represents a diffuse urban contamination scenario, rather than a hotspot situation, which has important implications for risk communication and regulatory prioritisation.

A notable observation emerging from the cross-study comparison is the dominance of BDE-209 at most of the Asian sites included in Table 2, particularly those affected by e-waste recycling. This pattern reflects the historical predominance of deca-BDE commercial mixtures in Asian markets - particularly in rapidly industrialising economies such as China and Vietnam - and the environmental persistence of BDE-209 and its transformation products.

The consistency of this signature across geographically diverse sites reinforces the utility of BDE-209 proportion as a diagnostic indicator of deca-BDE contamination in urban aquatic environments, and suggests that monitoring programmes focused on this congener alone could serve as a cost-effective screening tool for initial contamination assessment in data-scarce settings.

Nevertheless, the upward concentration trend documented at West Lake - occurring despite the relatively low absolute levels - distinguishes this site from stable or declining contamination scenarios reported in some East Asian urban lakes following regulatory interventions [4]. This divergence likely reflects the contrasting regulatory trajectories between Vietnam and more developed economies in the region: while countries such as Japan and South Korea implemented strict controls on PBDE-containing products from the mid-2000s onwards, Vietnam's regulatory framework for legacy flame retardants remains less stringent, and large quantities of PBDE-containing imported second-hand electronics and construction materials continue to enter the domestic waste stream [1, 9, 12]. Addressing this regulatory gap represents a prerequisite for reversing the current accumulation trend in urban aquatic ecosystems such as West Lake.

3.5. Environmental Significance and Management Implications

Although absolute concentrations remain relatively low, several points merit attention from an environmental management and public health perspective. BDE-47 and BDE-99 - two congeners with confirmed developmental neurotoxicity and endocrine-disrupting activity [7] - account for approximately 22% of ΣPBDE across all samples. As a screening-level comparison, the concentrations of BDE-99 (0.27–0.38 µg/kg ww) and BDE-100 (0.15–0.20 µg/kg ww) in West Lake snails were below the Canadian Federal Environmental Quality Guidelines for fish tissue (1 µg/kg ww for each congener), and BDE-47 (0.27–0.38 µg/kg ww) was far below the corresponding tetraBDE guideline of 88 µg/kg ww [31]. However, the penta-BDE congeners were within a factor of about three of their guideline values, and these fish-tissue guidelines are used here only as a benchmark because no guidelines exist for gastropods; a formal ecological risk assessment was beyond the scope of this study.

The data generated by this study provide the necessary foundation for such risk evaluations. From a management perspective, controlling emission sources from the dismantling of end-of-life electrical equipment and construction materials within the lake catchment represents a priority measure; this is also a consistent recommendation of Hoang *et al.* (2021) [1, 12] in the context of the ongoing transition from legacy PBDEs to novel brominated flame retardants (NBFRs) in Vietnam.

From a broader urban lake governance perspective, the findings of this study highlight the need to integrate chemical contaminant monitoring into the existing water quality management framework for West Lake. Current monitoring programmes at West Lake primarily focus on conventional water quality parameters such as dissolved oxygen, nutrients, and biological oxygen

demand, with limited attention to micropollutants including POPs. Incorporating biomonitoring of benthic organisms into routine lake management assessments would provide a more holistic and ecologically meaningful picture of lake health, consistent with the ecosystem-based management approaches increasingly advocated in international environmental policy frameworks [11].

Beyond emission control, sediment management represents another critical intervention point. Given that West Lake sediments function as both a sink and a secondary source of PBDEs - releasing contaminants back into the water column under conditions of sediment disturbance, bioturbation, or seasonal anoxia - any large-scale dredging or lake management activities should be preceded by thorough assessment of sediment PBDE burdens and their potential for remobilisation. Paired sediment–biota monitoring in future campaigns would also allow calculation of biota-sediment accumulation factors (BSAFs) on a seasonal basis, providing deeper mechanistic insight into the transfer dynamics of individual congeners from sediment to benthic fauna under varying hydrological conditions.

4. Conclusions

This study analyzed the concentrations of seven PBDE congeners in snail samples collected from West Lake, Hanoi across four monitoring campaigns during 2022–2023. PBDEs were detected in all samples, with ΣPBDE concentrations ranging from 2.50 to 3.27 µg/kg wet weight. Since most previous studies on snails report lipid-normalised concentrations, a direct quantitative comparison is limited; however, the BDE-209-dominated profile of West Lake snails differed clearly from the BDE-47/BDE-99-dominated profile reported for snails from Taihu Lake, China, suggesting exposure mainly to diffuse urban deca-BDE sources rather than to intensive point sources such as e-waste recycling. Nevertheless, a cumulative increase of 13.7% over 18 months, with an average annual growth rate of 8–11% for most congeners - most notably BDE-154, which showed the fastest increase (approximately 16.8% over the monitoring period) - is a noteworthy but preliminary signal that may indicate continuous inputs from urban emission sources within the lake catchment; because it is based on only four campaigns, it needs to be confirmed by longer-term monitoring. Regarding congener composition, BDE-209 was the overwhelmingly dominant congener (approximately 57% of ΣPBDE) and remained stable throughout the monitoring period, suggesting commercial deca-BDE mixtures as the primary emission source; while the combined proportion of BDE-47 and BDE-99 (approximately 22% in total) reflects the concurrent contribution of penta-BDE mixtures from legacy products still in circulation. In terms of seasonal variation, dry-season (November) PBDE concentrations were consistently 3–5% higher than wet-season (May) values across all congeners; these differences were small relative to within-campaign variability and may be related to reduced dilution, extended sediment contact time and seasonal changes in the physiological condition of the snails. This is the first study to provide a time-series dataset on PBDEs in benthic organisms from West Lake, laying the groundwork for more comprehensive ecological and human health risk assessments, including quantification of dietary exposure for local residents who consume aquatic products from the lake. The main limitations of this study are the restriction of sampling to the littoral zone, the short monitoring period (four campaigns), and the absence of paired sediment data and of a dietary exposure assessment; these should be addressed in future work.

Acknowledgements

References

[1] A. Q. Hoang, T. M. Tran, M. B. Tu, and S. Takahashi, Polybrominated diphenyl ethers in indoor and outdoor dust from Southeast Asia: An updated review on contamination status, human exposure, and future perspectives, Environmental Pollution, vol. 272, Mar. 2021, Art. no. 116012. https://doi.org/10.1016/j.envpol.2020.116012

[2] C. A. de Wit, An overview of brominated flame retardants in the environment, Chemosphere, vol. 46, iss. 5, pp. 583–624, Feb. 2002. https://doi.org/10.1016/S0045-6535(01)00225-9.

[3] M. Alaee, P. Arias, A. Sjödin, and Å. Bergman, An overview of commercially used brominated flame retardants, their applications, their use patterns in different countries/regions and possible modes of release, Environment International, vol. 29, no. 6, pp. 683–689, Sep. 2003. https://doi.org/10.1016/S0160-4120(03)00121-1

[4] R. J. Law, C. R. Allchin, J. de Boer, A. Covaci, D. Herzke, P. Lepom, S. Morris, J. Tronczynski, and C. A. de Wit, Levels and trends of brominated flame retardants in the European environment, Chemosphere, vol. 64, no. 2, pp. 187–208, Jun. 2006. https://doi.org/10.1016/j.chemosphere.2005.12.007

[5] P. O. Darnerud, Toxic effects of brominated flame retardants in man and in wildlife, Environment International, vol. 29, no. 6, pp. 841–853, Sep. 2003. https://doi.org/10.1016/S0160-4120(03)00107-7

[6] L. S. Birnbaum and D. F. Staskal, Brominated flame retardants: cause for concern?, Environmental Health Perspectives, vol. 112, no. 1, pp. 9–17, Jan. 2004. https://doi.org/10.1289/ehp.6559

[7] Z. Wu, C. He, W. Han, J. Song, H. Li, Y. Zhang, X. Jing, and W. Wu, Exposure pathways, levels and toxicity of polybrominated diphenyl ethers in humans: A review, Environmental Research, vol. 187, Aug. 2020, Art. no. 109531. https://doi.org/10.1016/j.envres.2020.109531

[8] G. Yin, Y. Zhou, A. Strid, Z. Zheng, A. Bignert, T. Ma, I. Athanassiadis, and Y. Qiu, Spatial distribution and bioaccumulation of polychlorinated biphenyls (PCBs)

and polybrominated diphenyl ethers (PBDEs) in snails (Bellamya aeruginosa) and sediments from Taihu Lake area, China, Environmental Science and Pollution Research, vol. 24, no. 8, pp. 7740–7751, Mar. 2017. https://doi.org/10.1007/s11356-017-8467-x

[9] H. Q. Anh, V. D. Nam, T. M. Tri, N. M. Ha, N. T. Ngoc, P. T. N. Mai, D. H. Anh, N. H. Minh, N. A. Tuan, and M. B. Tu, Polybrominated diphenyl ethers in plastic products, indoor dust, sediment and fish from informal e-waste recycling sites in Vietnam: A comprehensive assessment of contamination, accumulation pattern, emissions, and human exposure, Environmental Geochemistry and Health, vol. 39, no. 4, pp. 935–954, Aug. 2017. https://doi.org/10.1007/s10653-016-9865-6

[10] H. Q. Anh, K. Tomioka, N. M. Tue, T. M. Tri, T. B. Minh, and S. Takahashi, PBDEs and novel brominated flame retardants in road dust from northern Vietnam: Levels, congener profiles, emission sources and implications for human exposure, Chemosphere, vol. 197, pp. 389–398, Apr. 2018. https://doi.org/10.1016/j.chemosphere.2018.01.066

[11] A. Q. Hoang, S. Takahashi, N. D. Le, T. T. Duong, T. M. H. Pham, T. N. M. Pham, T. A. H. Nguyen, T. M. Tran, M. B. Tu, and T. P. Q. Le, Comprehensive determination of polychlorinated biphenyls and brominated flame retardants in surface sediment samples from Hanoi urban area, Vietnam: Contamination status, accumulation profiles, and potential ecological risks, Environmental Research, vol. 197, Jun. 2021, Art. no. 111158. https://doi.org/10.1016/j.envres.2021.111158

[12] M. T. T. Hoang, H. Q. Anh, K. Kadokami, H. T. Duong, H. M. Hoang, T. Van Nguyen, S. Takahashi, G. T. Le, and H. T. Trinh, Contamination status, emission sources, and human health risk of brominated flame retardants in urban indoor dust from Hanoi, Vietnam: The replacement of legacy polybrominated diphenyl ether mixtures by alternative formulations, Environmental Science and Pollution Research, vol. 28, no. 32, pp. 43885–43896, Aug. 2021. https://doi.org/10.1007/s11356-021-13822-9

[13] B. Zhu, J. C. W. Lam, S. Yang, and P. K. S. Lam, Conventional and emerging halogenated flame retardants (HFRs) in sediment of Yangtze River Delta (YRD) region, East China, Chemosphere, vol. 93, no. 3, pp. 555–560, Sep. 2013. https://doi.org/10.1016/j.chemosphere.2013.06.052.

[14] V. van der Schyff, M. du Preez, K. Blom, N. S. C. K. Yive, J. Klánová, P. Přibylová, O. Audy, J. Martiník, and H. Bouwman, Chlorinated and brominated persistent compounds in hard coral, soft coral, and parrotfish from remote Mascarene islands, Chemosphere, vol. 267, Mar. 2021, Art. no. 129316. https://doi.org/10.1016/j.chemosphere.2020.129316

[15] J. Fu, Y. Wang, A. Zhang, Q. Zhang, Z. Zhao, T. Wang, and G. Jiang, Spatial distribution of polychlorinated biphenyls (PCBs) and polybrominated biphenyl ethers (PBDEs) in an e-waste dismantling region in Southeast China: Use of apple snail (Ampullariidae) as a bioindicator, Chemosphere, vol. 82, no. 5, pp. 648–655, Jan. 2011. https://doi.org/10.1016/j.chemosphere.2010.11.014

[16] Z. Z. Yang, X. R. Zhao, Z. F. Qin, S. Fu, X. H. Li, X. F. Qin, X. B. Xu, and Z. X. Jin, Polybrominated diphenyl ethers in mudsnails (Cipangopaludina cahayensis) and sediments from an electronic waste recycling region in South China, Bulletin of Environmental Contamination and Toxicology, vol. 82, no. 2, pp. 206–210, Feb. 2009. https://doi.org/10.1007/s00128-008-9600-9

[17] B. Li, J. Wang, G. Hu, X. Liu, Y. Yu, D. Cai, P. Ding, X. Li, L. Zhang, and C. Xiang, Bioaccumulation behavior and human health risk of polybrominated diphenyl ethers in a freshwater food web of typical shallow lake, Yangtze River Delta, International Journal of Environmental Research and Public Health, vol. 20, no. 3, Feb. 2023, Art. no. 2671. https://doi.org/10.3390/ijerph20032671

[18] K. Ramu, N. Kajiwara, A. Sudaryanto, T. Isobe, S. Takahashi, A. Subramanian, D. Ueno, G. J. Zheng, P. K. S. Lam, H. Takada, M. P. Zakaria, P. H. Viet, M. Prudente, T. S. Tana, and S. Tanabe, Asian mussel watch program: Contamination status of polybrominated diphenyl ethers and organochlorines in coastal waters of Asian countries, Environmental Science and Technology, vol. 41, no. 13, pp. 4580–4586, 2007. https://doi.org/10.1021/es070380p

[19] D. D. Nhan, F. P. Carvalho, N. M. Am, N. Q. Tuan, N. T. Y. Yen, J. P. Villeneuve, and C. Cattini, Chlorinated pesticides and PCBs in sediments and molluscs from freshwater canals in the Hanoi region, Environmental Pollution, vol. 112, pp. 311–320, May 2001. https://doi.org/10.1016/S0269-7491(00)00149-4

[20] M. J. La Guardia, R. C. Hale, and E. Harvey, Detailed polybrominated diphenyl ether (PBDE) congener composition of the widely used penta-, octa-, and deca-PBDE technical flame-retardant mixtures, Environmental Science and Technology, vol. 40, pp. 6247–6254, 2006. https://doi.org/10.1021/es060630m

[21] U.S. EPA, Method 3540C: Soxhlet Extraction, Revision 3, Dec. 1996, [Online]. Available: https://www.epa.gov/sites/default/files/2015-12/documents/3540c.pdf, Accessed on: Sep. 30, 2026.

[22] U.S. EPA, Method 3630C: Silica Gel Cleanup, Revision 3, Dec. 1996, [Online]. Available https://www.epa.gov/sites/default/files/2015-12/documents/3630c.pdf, Accessed on: Sep. 30, 2026.

[23] A. Covaci, S. Voorspoels, and J. de Boer, Determination of brominated flame retardants, with emphasis on polybrominated diphenyl ethers (PBDEs) in environmental and human samples - a review, Environment International, vol. 29, no. 6, pp. 735–756, Sep. 2003. https://doi.org/10.1016/S0160-4120(03)00114-4

[24] H. M. Stapleton, Instrumental methods and challenges in quantifying polybrominated diphenyl ethers in environmental extracts: A review, Analytical and Bioanalytical Chemistry, vol. 386, no. 4, pp. 807–817, Oct. 2006. https://doi.org/10.1007/s00216-006-0400-y

[25] U.S. EPA, Method 1614A: Brominated Diphenyl Ethers in Water, Soil, Sediment, and Tissue by HRGC/HRMS, EPA-821-R-10-005, May 2010. [Online]. Available: https://www.epa.gov/sites/default/files/2015-08/documents/method_1614a_2010.pdf, Accessed on: Sep. 30, 2026.

[26] Y. Z. She, J. P. Wu, Y. Zhang, Y. Peng, L. Mo, X. J. Luo, and B. X. Mai, Bioaccumulation of polybrominated diphenyl ethers and several alternative halogenated flame retardants in a small herbivorous food chain, Environmental Pollution, vol. 174, pp. 164–170, Mar. 2013. https://doi.org/10.1016/j.envpol.2012.11.024

[27] J. Kobayashi, T. Isobe, H. Takada, K. Ramu, N. Kajiwara, A. Sudaryanto, and S. Tanabe, Trophic magnification of polychlorinated biphenyls and polybrominated diphenyl ethers in an estuarine food web of the Ariake Sea, Japan, Chemosphere, vol. 118, pp. 201–206, Jan. 2015. https://doi.org/10.1016/j.chemosphere.2014.08.066

[28] T. Zhu, Y. Zhu, Y. Liu, C. Deng, X. Qi, J. Wang, Z. Shen, D. Yin, Y. Liu, R. Sun, W. Sun, and N. Xu, Polybrominated diphenyl ethers in water, suspended particulate matter, and sediment of reservoirs and their tributaries in Shenzhen, a mega city in South China, Environmental Science and Pollution Research, vol. 30, no. 18, pp. 53524–53537, Mar. 2023. https://doi.org/10.1007/s11356-023-26066-6

[29] J. Ge, M. Liu, X. Yun, Y. Yang, M. Zhang, Q. X. Li, and J. Wang, Occurrence, distribution and seasonal variations of polychlorinated biphenyls and polybrominated diphenyl ethers in surface waters of the East Lake, China, Chemosphere, vol. 103, pp. 256–262, Apr. 2014. https://doi.org/10.1016/j.chemosphere.2013.12.014

[30] D. Li, Y. Zhang, and A. J. Sinclair, Seasonal variations of lipid content and composition in Perna viridis, Lipids, vol. 42, no. 8, pp. 739–747, Aug. 2007. https://doi.org/10.1007/s11745-007-3078-9

[31] Environment Canada, Canadian Environmental Protection Act, 1999 - Federal Environmental Quality Guidelines: Polybrominated Diphenyl Ethers (PBDEs), 2013. [Online]. Available: https://www.canada.ca/content/dam/eccc/migration/ese-ees/05df7a37-60ff-403f-bb37-0cc697dbd9a3/feqg_pbde_en.pdf, Accessed on: Sep 30, 2026.