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Research Article
Levels of Polybrominated Diphenyl Ethers (PBDEs) in Some Ghanaian Water Body Environments

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Abstract

Background and Objective: Polybrominated diphenyl ethers (PBDEs) are known to be possible carcinogens, teratogenic and endocrine disruptors producing neurobehavioral effects, reproductive abnormalities and thyroid disruption in infants. Despite the worldwide growing concern of these toxins, there were very little studies on the presence and health effects of PBDEs on the Ghanaian environment. The objective of study was to look at the levels, fate, assessment of their sources and possible health effects associated with PBDEs in water and sediments along the Western coast of Ghana. **Materials and Methods:** Water and sediment samples collected from six water bodies along the Central and Western coast of Ghana were extracted using SPE cartridges and Soxhlet for water and sediment samples respectively. Instrumental analysis for PDBEs in extracted samples (n = 46, include solvent blanks) were done using GC-ECD. Data were analyzed by two-way analysis of variance (ANOVA) at 95% confidence level (CL) for triplicates of the water and sediment samples. **Results:** The mean total PBDE levels in water and sediment samples ranged from 37.2-170.5 and 19.8-70.6 ng kg^{-1}, respectively. These levels indicated that the studied water bodies were polluted with PBDEs and may pose significant health risk to users. Two-way ANOVA conducted at 95% CL showed no significant difference ($p>0.05$) between the water bodies with respect the PBDE levels and the sediment samples collected. Source assessment conducted using PCA showed two significant sources of BDEs with major source being deposits from deca-BDE formulations for the water and deca- and octa-mix BDE for the sediment samples. **Conclusion:** Most of these water bodies are being used in one way or the other, hence, the need to clean them.

Key words: PBDEs levels, sediment, principal component analysis (PCA), source assessment

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Competing Interest: The authors have declared that no competing interest exists.

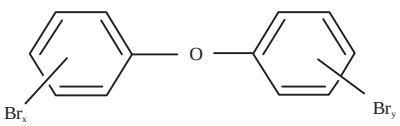
Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Polybrominated diphenyl ethers (PBDEs) belong to a class of flame retardant chemicals added to many consumer products found in homes, offices, automobiles and airplanes such as textile, printed circuits, polyurethane foams, building materials, electronic appliances and plastics, to reduce the risk of ignition or burn[1,2]. The entire family of PBDE comprises 209 possible congeners with 1-10 bromine atoms (Fig. 1)[1]. The industrial production of brominated diphenyl ethers primarily yields a mixture of tetra, penta, hexa, hepta, octa, nona and deca homologues in various percentages as stated by Siddiqi *et al.*[3]. The three important generic commercial formulations or mixtures: Penta, octa and deca-BDE are produced[1] under a variety of product names such as DE-71, Bromkal 70-5DE, DE-79, Bromkal 790-8DE, Saytex 102E and Bromkal 82- 0DE.

The production of this eco-toxicant voluntarily ended in the United States of the formulations of penta and octa in 2004 after studies showed elevated levels of PBDES in breast milk.[4] However, some amount of the PBDEs, 97.5% for penta and 35.9% for octa was reported to be still available in large reservoir in North America[4] and in a 2009 assessment, the highest known concentrations of PBDEs in human populations in the Arctic were reported in Yupik women from the Yukon Kuskokwim Delta of Alaska[5]. The deca formulation were produced and used primarily in plastic electronic castings such as televisions and computer casings as well as upholstery for covers of items such as furniture and car seats[6,7]. For these and many reasons, the "Alaska's flame retardants and toxic chemicals bills-SB 295 and HB 385", was aimed at phasing out the manufacture and sale of products containing penta and octa-BDEs by January 1, 2011 and also at, phasing out the manufacture and sale of electronic products, furniture, textiles and mattresses containing deca-BDE by 2011 (SB 295/HB 385). PBDEs are part of a larger chemical class called polyhalogenated aromatic hydrocarbons (PHAHs) which are intrinsically hazardous because of their chemical make-up[2]. They are stable and persist in the environment for quite a long time[8]. They are lipophilic and as such build up in fatty tissues of living organisms that are exposed to them which allows them to both biomagnify and bioaccumulate [9,10]. They also act as endocrine disruptors[11-13]. Even though not all the PBDEs congeners are endocrine disruptors, a significant portion has been found to exhibit these characteristics.

Animal studies of PBDE exposure during the prenatal and perinatal period identified neurobehavioral effects such as deficits in learning and memory, changes in motor activity and reactivity to the environment[14,15], thyroid disruption such as



Where, x+y = 1-10

Fig. 1: General structure of PBDE

decreased thyroid weight and T3, T4 levels in prenatally exposed lambs[14,16,17]. Reproductive effects, such as, marked decreases in sex steroid hormones and decreased anogenital distance (a marker of estrogenization) in male animal studies have also been reported. Human studies of PBDE exposure in early life (assessed as breast milk or cord blood concentrations) report of some association of PBDEs with: Decreased birth weight and length, chest circumference and BMI in a study of 20 Taiwanese infants[18], worsened fine manipulative abilities and worsened attention in an exploratory study of 62 Dutch school children[19], worsened performance on neurodevelopmental test scores at ages 1-4 and 6 years in a longitudinal cohort of approximately 100 children in New York City[11]. Increased risk of cryptorchidism in a nested case-control (62 cases) study of Danish-Finnish infants[20] has also been reported.

A study conducted by Herbstman *et al.*[11] reported that children with higher concentrations of PBDE congeners 47, 99 and 100 in their umbilical cord blood at birth scored lower on tests of mental and physical development between the ages of 1 and 6. Developmental effects were particularly evident at 4 years of age, when verbal and full IQ scores were reduced 5.5-8.0 points for those with the highest prenatal exposures[11].

Although, the main component in deca-BDE, BDE-209, has a relatively short half life in people. One animal studies showed that the liver breaks down BDE-209 into the more persistent and bioaccumulative forms of hepta-BDE, octa-BDE and nona-BDE[9,10].

Many occupational exposure studies have linked deca-BDE and decabromobiphenyl manufacturing plant to hypothyroidism in exposed workers[21-23]. Exposure to PBDEs (BDE-153), has been associated with a decrease in testicle size and the sperm concentration in humans and animals, low birth weight, birth defects, reduced weight gain during pregnancy, changes in ovary cells[21,24-26]. A study suggested that *in utero* exposure to PBDE concentrations was associated with an increased risk of testicular cancer in men, although inconclusive[27]. The International Agency for Research on Cancer (IARC) has classified PBDE as a Group 3 carcinogen meaning, not classifiable as to its carcinogenicity to humans, based on inadequate evidence of carcinogenicity in humans

and inadequate or limited evidence in experimental animals. The EPA has assigned the cancer category Group D-meaning, "not classifiable as to human carcinogenicity", to mono-, di-, tri-, tetra-, penta-, hexa-, octa- and nona-BDEs, based on the fact that there is "inadequate information" to classify the specific congeners 2,2',4,4'-tetra-BDE, 2,2',4,4',5-penta BDE and 2,2',4,4',5,5'-hexa BDE. However, EPA assigned a classification of "suggestive evidence of carcinogenic potential" for decaBDE[1].

When PBDEs were suspended in air, they can be present as particular matter and eventually return to land or water as the dust settles which get washed by snow and rainwater. However, the very small amount of PBDEs that do occur in water stick to particles and eventually settle to the bottom sediments. Sediments at the bottom of water bodies, such as lakes and rivers, generally act as reservoirs for PBDEs (especially deca-BDEs), which can remain there for years[23]. Some lower brominated PBDEs (e.g., tetra- and penta-congeners of PBDE) in water may build up in fish from low concentrations of about 10 billionths of a gram to 1 millionth of a gram of PDBE per gram of fresh fish or (10×10^{-9}-1×10^{-6} g of PBDE per gram of fresh fish)[23]. However, higher brominated PBDEs, such as deca BDE, are not found in fish at measurable concentrations. In general, the breakdown of PBDEs in soil is very slow and that allows them to remain in soil for several years by binding strongly to soil particles. Rainwater is not expected to spread them much below the soil surface; thus, it is unlikely that PBDEs will enter groundwater[23].

Most countries, states and federal governments have responded to the rising environmental and human health concerns over PBDEs via encouraging voluntary phase-outs and institutions of bans on production and use of PBDEs and their products[28,29]. Unfortunately, Ghana has not passed any legislature on the shipment, use, handling and disposal of PBDEs and products containing PBDEs formulations.

With this, there was need for some studies in Ghana on the levels and distribution in the Ghanaian environment and the possible health hazards associated with exposure to the PBDEs. The study determined the levels of polybrominated diphenyl ethers in water and sediment from some coastal water bodies (Pra and Okye river, Benya and Fosu Lagoon, Sweet and Kakum river Estuary) and compared the levels with standards. Source assessments were conducted to ascertain the sources of these pollutants in water bodies.

MATERIALS AND METHODS

Sample collection: Water and sediments samples were collected from six water bodies namely Fosu Lagoon, Okye river at Mankessim, the Sweet, Nkontro and Kakum river estuary along the Cape Coast-Takoradi road, Benya lagoon at Elmina and Pra river at Beposo along the western coast of Ghana (Fig. 2). The water samples were collected into 2.5 L amber bottles. Bottles were dipped into the water, filled up to brim and cocked under the water surface to prevent air from entering the bottle. It was then taken to the laboratory in an ice chest. Water samples were kept below 4.0°C until extractions were done.

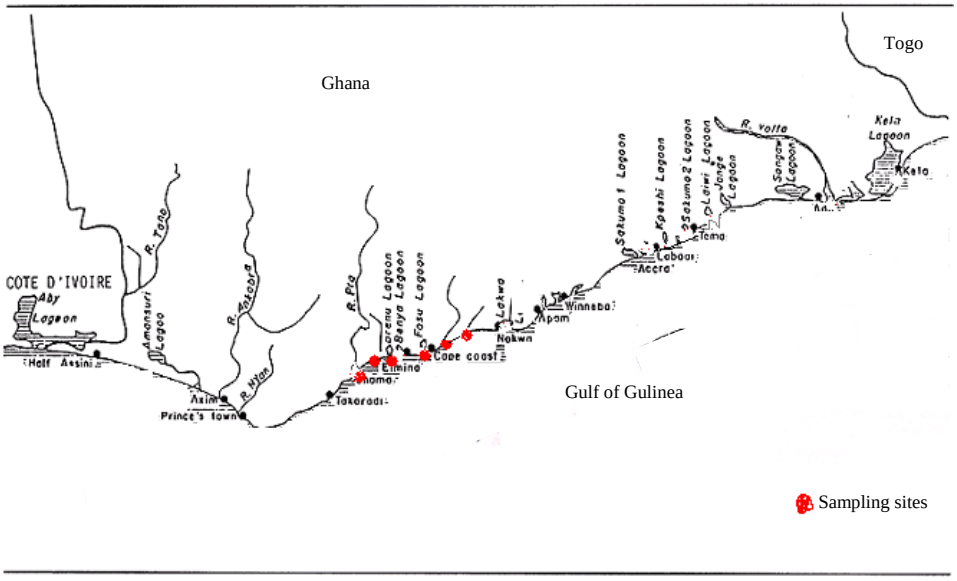


Fig. 2: A map of Southern Ghana showing the sampling sites

The sediments samples were also taken from almost the same place where the water samples were taken with an auger, wrapped with an aluminum foil and sent to the laboratory. The sediments were allowed to air dry (protected from sunlight) and homogenized. The dried sample was then sieved with 1 micron sieve to remove large particles of sand and others. Sea algae sample was also taken from the Sweet, Nkontro and Kakum river estuary and analysed for PBDE's.

Extraction procedure

Liquid-liquid extraction of PBDEs in the water samples: One liter of water samples each (filtered with 0.45 µm filter) was extracted 3 times with a total of 300 mL hexane: acetone mixture (3:1v/v) using separatory funnel with a glass stopcock (liquid-liquid extraction). The matrices trapped on filter were also extracted using same procedure as used for the filtered water. The extracts were combined and dried with 20 g of powdered anhydrous Na_2SO_4 and left in a desiccators for 24 h in the dark to remove any water present. The extract was then concentrated to 2 mL using rotary evaporator (EPA method 1614A)[30].

Soxhlet extraction of PBDEs in the water sediments samples: Ten grams each of the dry sediment samples was weighed and homogenized with 10 g anhydrous Na_2SO_4. The homogenate was carefully transferred into an extraction thimble made from cellulose. The cellulose thimble containing the homogenate was then placed in the extraction chamber (200 mL) of the Soxhlet extractor. The apparatus was then fitted to a 500 mL round bottomed flask containing 300 mL n-hexane/acetone (3:1v/v) solvent with boiling chips added and connected to a reflux condenser (the double layer type). The extraction was done for 18 h with an average solvent circulation of 4 cycles h^{-1} (EPA method 1614A)[30]. The extracts were allowed to cool to room temperature and concentrated using Rotavapor R-114 (BÜCHI-Sibata, Switzerland) at a temperature of 55°C to about 2 mL.

Post-extraction clean-up: The column (0.75 m, 16 mm ID) was plugged with glass wool, filled with 5 g anhydrous Na_2SO_4, followed by 15 g silica gel (preheated overnight at 105°C) and 5 g of anhydrous Na_2SO_4 (warm) placed on top. The column was preconditioned (wet) with 30 mL hexane. Two hundred and fifty millimeter flask was placed under the column and the solvent was drained to reach just below the packed anhydrous sodium sulphate top layer. The concentrated 2 mL extract was transferred to the top of the packed column and allowed to drain to just below the top packed Na_2SO_4 by opening the controlled stopcock (Teflon made). The column was first eluted with 30 mL of hexane followed by 30 mL of hexane: acetone (3:1 v/v) solvent system. The eluate was concentrated to about 2.0 mL as previously done and finally transferred into 2 mL amber sample bottle. The samples were reconstituted into ethyl acetate to 2 mL in the amber sample bottle and kept in refrigerator at 4°C prior to GC-ECD analysis[30]. The NIST marine standard reference material was also extracted and cleanup using the same Soxhlet extraction and clean procedure respectively.

Solvent blanks were also processed for GC-ECD using the same procedure as applied to the samples.

GC-ECD analysis: A Varian GC-ECD (CP-3800 GC) system with 3800 auto-sampler (mass data type: centroid) was used for the analysis. The system was also equipped with 30 m×0.25 mm×0.25 µm VF-5ms fused capillary column. Helium gas was used as the carrier gas. The column head pressure was maintained at 2 psi for 1.5 min with a constant flow rate of 150 mL min^{-1} at 4 min. The front injector line was maintained at 250°C. Injection volumes were 2.0 µL in the splitless mode. The column temperature was initially held at 50°C for 3 min and ramped to 320°C at a rate of 20°C min^{-1} and then held at 320°C for 20 min (total run time of ~37 min). The amount of PBDE in the sample was detected by the Electron capture detector and acquisition was done by comparison of base peaks with Peak areas of standard used for calibration[30].

Analytical quality control: The analytical precision and recovery of the PBDEs were checked with NIST standard reference material (1941b) which is marine sediment collected at the mouth of the Baltimore Harbour intended for use in evaluating analytical methods for the determination of selected PAHs, PCBs congeners and chlorinated pesticides in marine sediments and similar matrices since it was the only available SRM at the time of studies. Further two-way analysis of variance (ANOVA) at 95% confidence level for triplicates of the water and sediment samples analyzed was conducted.

RESULTS AND DISCUSSION

Quality control result: The result from the NIST-1941B reference material used for checking the efficiency of the extraction system and the GC/ECD instrument used had a recovery range of 62-101%. Analysis of variance of replicate results of each sample at the 95% confidence level showed no statistical significant difference.

Table 1: Mean concentrations of PBDE (n = 3) in water from six sites along the Western coast of Ghana

Sites	BDE 47	BDE 99	BDE 100	BDE 153	BDE 183	Total (ng kg^{-1})
Pra river	23.5	45.2	56.4	ND	45.4	170.5
Fosu lagoon	17.8	32.6	75.7	0.3	33.4	159.8
Benya lagoon	ND	35.3	58.0	8.4	ND	101.7
Estuary	ND	24.1	31.0	ND	ND	55.1
Okye river	ND	33.8	ND	3.4	ND	37.2
Kakum river estuary	ND	31.3	12.7	ND	ND	44.0

PBDEs in water samples: From the result, only five PBDE congeners were detected in the water samples (Table 1). The mean total PBDEs levels recorded for the water samples from the various sites ranged from 37.2 ng kg^{-1} (Sweet river and Nkontro river estuary) to 170.5 ng kg^{-1} (Pra river). The levels of PBDEs in these water bodies were general indicative of the extent of pollution of the water bodies by anthropogenic sources. That is the highest mean total PBDEs level was recorded by Pra river which showed that the river was comparatively highly polluted than the other water bodies. Fosu Lagoon recorded the second highest mean total followed by Benya Lagoon, then by Okye river and Kakum Estuary respectively. Sweet and Nkontro Estuary recorded the least. This trend may be attributed to the levels of human activities around the water bodies since they are mostly sited in residential areas where human activities are high. Thus, these water bodies may pose health hazards to humans that utilize them and also have an implication on the life of aquatic organisms living there in. These results showed that the use of consumer products containing PBDEs formulations in Ghana is relatively higher despite the effort made by the international communities and various federal governments to halt the production and use of these chemicals by 2013[28]. This implied that the Ghanaian government has not done enough to eliminate this PBDEs and their formulation from the system despite the growing concern on the health effect posed by these toxins. Thus, the situation now may be indeed very alarming and needs urgent attention.

Among the congeners detected BDE 100 (penta BDE) was the largest contributor to the levels detected, followed by BDE 99 (penta BDE). The high levels of BDE 100 may be attributed to leachate or deposits from the improper disposal of penta BDE formulations like the polyurethane foams used in furniture cushions, automobile seats and head rests and mattresses, refrigerators packaging, some electronic gadget packaging, carpet, shoes etc.[28], which found their way into such water bodies. The significant level of BDE-183 in Pra river indicated deposition of such contaminants from acrylonitrile-butadiene-styrene (ABS) which were present in computers and housing appliances[28]. This may be attributed to the high human residents' activities such as improper disposal and burning of electronic gadget, foams in upholsteries etc which eventually exposed these toxins, hence, ending up in the water bodies via storm water runoff or by atmospheric transport.[31] These results were comparable to that obtained by Klosterhaus *et al.*[32], Gilbreath *et al.*[33] and McKee *et al.*[34], where a maximum levels of 4300, 369 and 370.3 ng kg^{-1} were, respectively recorded in waterbodies.

The federal water quality guidelines for PBDE congeners adopted by environment Canada are BDE-47 (24 ng L^{-1}) BDE-99 (3.9 ng L^{-1}), BDE-100 (0.23 ng L^{-1})[35] and BDE-153 (120 ng L^{-1})[36]. With the exception of the value recorded for BDE-153, the mean levels recorded for the various congeners far exceeded the guideline levels adopted by Environment Canada, indicating the alarming nature of Ghana's water pollution situation.

Relative to the higher brominated PBDE congeners (e.g., BDE-209), many of the lower-brominated congeners (e.g., BDE-47) are considered more toxic and certainly more bioaccumulative, leading to the potential for increased risk to the environment[37]. Lower molecular weight PBDE's are known to accumulate more in human tissues (adipose tissues, serum and breast milk) than higher PBDE[38]. Hence, their presence especially the high level of BDE-99 and -100 may have had a significant contribution to the upsurge in breast cancer incident cases and other forms of ailment in Ghana reported by Ghana Health Service[39], since these BDE are carcinogenic[27].

Polybrominated diphenyl ethers BDEs-47, -99 and -100 have been linked with low IQ in children[40]. In the present study, PBDE 99 and 100 were found in abundance in most of the water samples from the various sites. This may pose significant health risk to unborn babies and other resident children when exposed to such teratogenic contaminates in the water bodies.

Analysis of Varian conducted at the 95% confidence level showed that statistically there is no significant difference ($p = 0.0573$) between the various water bodies with respect to the mean total PBDE levels recorded. This may imply that similar trend of significant pollution may be found in all water bodies across the length and breadth of Ghana.

Table 2: Mean concentrations of PBDE (n = 3) in sediments from seven sites along the Central-Western coast of Ghana and in algae from the Sea

Sites	BDE 47	BDE 99	BDE 100	BDE 153	BDE 183	Total (ng kg^{-1})
Elmina lagoon	1.0	35.3	4.3	ND	ND	70.6
River Pra (Bed)	ND	37.5	23.6	ND	ND	61.1
Kakum river	ND	33.7	10.7	ND	4.2	48.6
River Pra (shore)	ND	28.1	13.3	5.0	ND	46.4
Fosu lagoon	ND	19.8	ND	ND	ND	19.8
Okye river	ND	30.3	ND	8.9	ND	39.2
Sweet river	ND	44.2	ND	1.5	ND	45.7
Sea algae	ND	19.4	18.6	12.6	ND	50.6

ND: Values below detection limit

PBDEs in sediments samples: From the result only five PBDEs congeners were detected in the sediment (Table 2). The mean total PBDEs recorded in sediments from the various sites are shown in Table 2. The elevated level of PBDEs in sediment from these water bodies is an indication of the extent of pollution in such site. The highest mean total PBDEs was recorded by sediments from Sweet river which indicated that sweet river was comparatively polluted than the other water bodies. River Pra (bed) recorded the second highest mean total followed by Benya lagoon, Kakum river then by Okye river and Fosu lagoon recorded the least (Table 2). This trend may be attributed to the human activities around the water bodies as stated earlier, since they are mostly close to residential areas where human activities are high. The results imply that the water bodies from these sites are indeed polluted with appreciable levels of BDE's and may pose health hazards to humans that utilized these waters. These also have an implication on the life of aquatic organisms in waterbodies. These results were comparable to that obtained in similar studies by Napravnikova *et al.*[41] and Mai *et al.*[42]. Most of the levels reported in literature for individual congeners in sediment samples are below 50 ng kg^{-1} and were in consistence with the results of this study.

A number of European and Japanese studies have reported extremely higher levels of PBDEs in sediment samples. For example, Allchin *et al.*[43] reported up to 368 and 898 ng g^{-1} for BDE-47 and BDE-99, respectively, for sediments samples from the Tees Estuary, the downstream area of a manufacturing plant, in the United Kingdom and up to 352 ng g^{-1} for PBDEs was found in sediment from Osaka Bay, Japan[44]. Luo *et al.*[45] reported an extreme total PBDE concentrations ranging from 4434-16088 ng g^{-1} (dry weight) in Nanyang river bank sediment, from 55-445 ng g^{-1} in Nanyang river bottom sediment and 51.3-365 ng g^{-1} in Lianjiang river bottom sediment in Guiyu. These levels showed that, though the situation in sediment samples studied herein was alarming, it was relatively not to the extreme and could be remedied if immediate attention is given. Two way ANOVA conducted at 95% CL for the PBDEs levels in sediments from the various sites, showed that statistically there was no significant difference between the various sites ($p = 0.512$). This also confirmed that similar trend of pollution may be found in almost all the water bodies in Ghana.

According to Strandberg *et al.*[46], PBDEs can be dissolved in materials and then leached into the environment and enter biota where they may bioaccumulate in organisms. The value recorded by algae sample used as biota representative (Table 2), suggested an increase in pollution of the Ghanaian sea with PBDE from anthropogenic sources which indicated an increased threat on marine life and hence on human beings. The algae sample recorded significant values for three congeners, which is BDE-99 (highest), 100 and 153 with a mean total concentration of 50.6 ng kg^{-1} (Table 2). Congeners of PBDEs known to be generally dominant in biota worldwide were BDEs-47, -99, -100, -153 and -154. These congeners appear to have a higher potential for bioaccumulation[47]. This statement is consistent with the results obtained in the study (Table 2).

Amongst the congeners detected in the sediments, BDE-99 was the abundant PBDE congener followed by BDE-100 and the least detected was BDE-47 (Table 2). The high levels of BDE-99 may be attributed to deposits/leachate from the use and improper disposal of penta-BDE formulation like the polyurethane foams, such as those used for refrigerator packaging, some electronic gadget packaging shoes etc, which found their way into such water bodies. The significant level of BDE-183 (a marker compound for the octa-mix PBDE formulation), coupled with elevated level of BDE-99 in Kukum river suggested the use and improper disposal of commercial octa-mix PBDE formulation (acrylonitrile-butadiene-styrene, ABS raisins) used in plastics for some household electric devices such as computers and housing appliances in the local area. These toxins (PBDEs) once exposed through burning of the gadgets get deposited into the water body by storm water runoffs and get bound to the sediments.

Table 3: Principal Component Analysis of PBDEs in water

	Initial eigenvalues			Extraction sums of squared loadings		
Components	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)
Total variance explained						
1	3.129	62.576	62.576	3.129	62.576	62.576
2	1.174	23.487	86.063	1.174	23.487	86.063
3	0.669	13.384	99.447			
4	0.028	0.552	99.999			
5	5.535E-005	0.001	100.000			

	Component	
	1	2
Component matrix[a]		
BDE 47	0.991	-0.110
BDE 100	0.724	0.328
BDE 99	0.728	0.396
BDE 153	-0.328	0.941
BDE 183	0.992	-0.109

Extraction method: Principal component analysis, a: 2 Components extracted

The Federal environmental quality guidelines from Canada Environmental for PBDE, have set the maximum level of BDE-99 and 100 at 0.4 ng kg^{-1} d.wt. When compared with the result obtained in this study, it may be said that samples are highly polluted and this may have significant influence on the quality of water, fish and oysters from the water body.

Lower molecular weight PBDE's are known to bioaccumulate when ingested and they accumulate more in human fatty tissues (adipose tissues, serum and breast milk) than higher PBDE[48]. Hence, it may be said that their presence, especially the elevated level of BDE-99 may have contributed significantly to the increase in breast cancer and other forms of cancer related ailment in Ghana as reported by Ghana Health service[39], since these BDEs are known carcinogen[10,20,24,27].

Source assessment/apportionment: Principal component analysis (PCA) was used for the source apportionment of the PBDEs analyzed. This usually correlates the analytes and predicts the possibilities of emanating from the same source or different sources.

Source of PBDEs in water: The results from the PCA (Table 3), showed two significant components with a total contribution of 86.06% of which "component 1" contributed about 62.58% (Kaiser-Meyer-Olkin measure Of sampling adequacy, KMO = 0.422, Bartlett's test of sphericity, BTS = 0.001). The result showed that BDEs-47, 99, 100, 183 were from the same source whereas BDE 153 was significantly of different source. The moderate inverse correlations (-0.424, -0.423) found between BDE-153 and BDE-47, 183, respectively showed, the presence of BDE-153 in "component 1" was as a result of photo-degradation of HMW BDE-183 to LMW BDE-47 and not directly from "source 1". The relation also suggested that, where the degradation resulted in the production of more BDE-153 only a few BDE-47 will be present and vice versa. The possible source of "component 1" BDEs was deposits (or leachates) from high temperature and photo degradation of commercial products of deca-BDEs such as in textiles in upholstery, electronic circuit boards, mattresses and TVs used etc. "Component 2" could possibly come from the deposits from products containing penta-BDE formulation as additives such as textiles and polyurethane foams. This suggested that the major source of PBDEs (about 63%) in the Ghanaian waters is from deca-BDE formulations in the above mentioned products.

Source of PBDEs in sediments: The results from the PCA (Table 4), showed two significant components extracted with a total contribution of 61.06% of which component 1 contributed about 36.16% whereas, component 2 contributed a significant level of 24.91% (KMO = 0.551, BTS = 0.99). The PCA results for the sediment showed an interesting pattern where BDEs 47, 99 and 153 are suggested to have come from the similar source (component 1), but BDE-153 showed a good inverse correlation (-0.51) with BDE 99 and a moderate inverse correlation (-0.29) to BDE-47, strongly indicating the interconversion or coupling of LMW BDEs-47, 99 to form HMW BDE-153 and vice versa in sediment samples possibly at high temperatures. Whereas, BDE-100, 183 and to some extent BDE-47 were also found to have emanated from a common source (component 2). The weak negative correlations (<-0.20) of BDE-47 to the others in component 2 suggested that the presence of BDE-47 in the sediment was slightly influenced by

Table 4: Principal component analysis of PBDEs in sediment (source apportionment)

	Initial eigenvalues			Extraction sums of squared loadings		
Components	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)
Total variance explained						
1	1.808	36.159	36.159	1.808	36.159	36.159
2	1.245	24.905	61.064	1.245	24.905	61.064
3	0.841	16.818	77.882			
4	0.685	13.691	91.573			
5	0.421	8.427	100.000			

	Component	
	1	2
Component matrix[a]		
BDE 47	0.534	-0.548
BDE 99	0.758	0.132
BDE 100	-0.378	0.521
BDE 153	-0.850	-0.190
BDE 183	0.289	0.787

a: 2 components extracted

the presence of HMW BDEs and could be attributed to the degradation of HMW BDE to LMW BDE, which may also be explained by the moderately weak negative correlations of (-0.29) found between BDE-153 and 47, 183. The possible source for "component 1" BDEs was pyrolytic/thermally degraded residual deposits from deca-BDEs formulations such as in textiles, electronic circuit boards, mattresses and TVs used etc. On the other hand, the possible source for "component 2" PBDEs was leachate/residual deposits from penta/octa-mix BDE formulations such as in polyurethane foams, acrylonitrile-butadiene-styrene, (ABS raisins) used in plastics for some household electric devices such as computers and housing appliances. The two components (sources) were proportionally significant, thus suggesting PBDEs in sediment samples have their major source from residual deposits/ leachates from both commercial deca- and octa-mix BDEs formulations.

CONCLUSION

The elevated levels of PBDEs recorded for water and sediment samples are studied and may present significant health risk to users and organisms in such water bodies. Again levels recorded in sea algae used as bio-indicator also suggests some PBDE pollution in the Eture estuary. Source assessment conducted using PCA showed two significant sources of BDEs with major source being residual deposits from deca-BDE formulation in the case of water and deca- and penta/octa-mix BDE in the case of sediment samples. The elevated levels of PBDE recorded in the study strongly indicated that the international policy on PBDEs' ban has not been effectively enforced in certain countries like Ghana and that needs to be implemented to curb the menace.

SIGNIFICANCE STATEMENTS

Polybrominated diphenyl ethers (PBDEs) are known to be possible carcinogens. The study for the first time assessed the levels, fate, sources and possible health effects associated with PBDEs in water and sediments along the Western coast of Ghana. The result would provide data that will be used to assess the various risk factors and to help policy makers to make inform decisions to safeguard the Ghanaian environment.

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