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Soil adsorption coefficient and bioaccumulation of PBDEs in the liver, intestine and parasites of *Heterotis niloticus* of Lekki Lagoon, Lagos State, Nigeria

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ABSTRACT

The study aimed at investigating the adsorption capacities of polychlorinated diphenyl ethers (PBDEs) on bottom sediment of Lekki lagoon and the subsequent uptake of the chemical from the soil into the tissues of *H. niloticus* in the lagoon. The study further aimed at investigating the comparative or synergistic roles of two endoparasites of host *Heterotis niloticus*, namely *Tenuisentis niloticus* and *Sandonella sandoni* in modulating the accumulated PBDEs in Lekki lagoon, Lagos State, Nigeria. The concentrations of PBDE congeners were tested in the water, soil, and the liver, intestine and enteric parasites of *H. niloticus* using gas chromatography mass spectrometer (GC-MS). Most importantly, the two PBDE congeners of greatest biota-sediment accumulation concerns were BDE-47 and BDE-99. Unfortunately, both parasites showed poor bioaccumulation potentials for BDE-47 which had great adsorption coefficient. This indicates that the aquatic habitat requires stringent monitoring of this congener in order to forestall the prognostic health and environmental hazards this cause. This study however demonstrated that *T. niloticus* exhibited better sequestration potentials for BDE-183, BDE-99 and BDE-100 than *S. sandoni.* Although the latter also showed appreciable sequestration potential for BDE-183. Of the two PBDE congeners that exhibited the greatest threats *T. niloticus* showed promising potentials to bioaccumulate one. The study showed that the synergy of both parasites may depurate some of the toxicant burdens in the host fish *H. niloticus*. We recommend further study into the possibilities of harnessing the synergy of other harmless bioremediation techniques in order to combat the prognosis of health and environmental hazards BDE-47 may pose. We hereby recommend *T. niloticus* as a better bioaccumulator and bioindicator of selected PBDEs in the lagoon than *S. sandoni.*

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Introduction

The fish *Heterotis niloticus* (The African Arowana) is considered predominantly planktivorous (Akinsanya *et al.,* 2018). However, the fish was considered as omnivorous by Adite *et al.* (2005); in respect of the relative gut length an omnivore. Lake Chad recorded the diet of *H. niloticus* as: fish 2.2%, aquatic insects 19.3%, ostracods 23%, seeds 14%, and zooplankton 11.3% [1]. Other Researchers who studied the gut content of the fish in various environments have determined planktivory and herbivory (Sitja-Bobadilla, 2008). It is thus most appropriate to consider the *Heterotis* an opportunistic feeder due to the different food habits of the fish in different habitats which suggest a degree of trophic plasticity. In the Lake Hlan – River Sô system of Benin, smaller *H. niloticus* tended to consume insect larvae and microcrustacea and larger fish tended to consume hard seeds and adults. The thick-walled gizzard of *H. niloticus*, which generally contains sand, aids digestion of seed coats. Diet breadth tended to increase with size, indicating that bony tongues consume a broader range of food resources as they grow (Adité *et al*., 2005). The wide spectrum of diet of the fish, which further broadens with age marks the susceptibility of the fish to diverse xenobiotics released through anthropogenic activities in the environment. Furthermore, *H. niloticus* being a pelagic fish is also constantly exposed to the precipitated contaminants in the bottom of the aquatic environment causing contamination incidences is of great concern in the Lekki Lagoon, Lagos State, Nigeria. This is due to the tremendous anthropogenic activities around the catchment area of the lagoon.

Recently, several Authors have reported detection of organochlorine chemicals in some sampled environmental media from the lagoon (Akinsanya *et al.,* 2019; [2,3], Akinsanya *et al.,* 2021). Adewuyi and Adeleye [4] earlier reported relatively high concentrations of selected PBDE congeners in the mid-sediment of Lekki lagoon in comparison to selected water bodies around the world. They linked the elevated levels of the contaminants to dumpsites around the catchment area of the lagoon. Recently, Osuala *et al.* [5] reported unacceptable levels of PBDEs in the bottom sediment of Epe lagoon, a section of the larger Lekki Lagoon. The Derivation of Biota-Sediment Accumulation Factor (BSAF) for BDE 7 and 28 congeners was greater than 1 at some stations. They conclude the lagoon was in an unhealthy state thus recommending a stringent biomonitoring. Going by the earlier discussed life style and feeding habits, *H. niloticus* of the lagoon may be susceptible to this recently discovered contaminant in the lagoon. The perturbed state of the lagoon may also be favorable to opportunisitic parasites which may take advantage of possible immunosuppression in the impacted aquatic biota. The detection of polybrominated diphenyl ethers (PBDEs) has been linked to the predominant application of agrochemicals in agricultural farms around the catchment area of the Lagoon. PBDEs are also applied as flame retardants in many consumer products whose discarded cans are found floating on the lagoon. This is of concern since PBDEs are persistent, bioaccumulative, toxic and are classified as endocrine disruptive chemicals. Many studies have analyzed environmental samples and modeled the fate of these chemicals in the environment. Concerns about PBDEs and other brominated flame retardants have been rising in the recent past since measured concentrations have increased exponentially during the last 30 years [2]. The lipophilic nature of the chemical coupled with its high octanol-water partition coefficient is of paramount ecotoxicological concern. This is due to the fact that the chemical has great precipitation potential and adsorption to the bottom sediment. Upon release into the open water, large amount leaves the overlying water column and contaminates the bottom sediment. Unfortunately, the repository bottom sediment exposes *H. niloticus* to bioaccumulation of PBDEs from the environment into its tissues. The fish being an exotic animal protein of high commercial value may be a threat to the health of the consumers.

All parasites have evolved ways to evade the host's immune response and host immune systems have evolved numerous ways to counter these evasive strategies (Sitja-Bobadilla, 2008). A trade-off is established that is essential to the survival of the parasite and provokes a state of illness in the host, which is not necessarily lethal (Sitja-Bobadilla, 2008). However, when a parasite efficiently evades the host immune system, it may damage the host, but actually reduce damage to the parasite (Sitja-Bobadilla, 2008). Some parasites have evolved strategies that use the host immune system to aid their attachment to the fish host. For example, *Pseudocatylogyrus bini* improves its attachment to the gill structures due to the embedding host reaction, while the mechanisms responsible for this are unknown (Buchmann, 2002, Sitja-Bobadilla, 2008). *Cyathocephalus trucatus* attaches firmly to the trout pyloric caeca because of the inflammatory reaction that encapsulates its scolex in a spherical structure (Sitja-Bobadilla, 2008). Inflammation by the host around the proboscis and bulb of the acanthocephalan *Pomporhynchus laevis* secures a firm attachment, and finally one of the host reactions to the ciliate *Ichthyophthirius multifiliis* is the increased production of mucus which reduces the immune damage to the parasite (Matthews, 2005). Other research on immunomodulation has focused on the deleterious effects of secondary infections that occur in fish hosts already infected with parasitic species. Densmore *et al*. [6] studied rainbow trout (*Oncorhynchus mykiss*) co-infected with the bacterial pathogen *Yersinia ruckeri* and the protozoan, *Myxobolus cerebralis*. Densmore *et al*. [6] determined that *M. cerebralis* infected fish had lower proliferative lymphocyte responses to four mitogens, displayed greater bactericidal activity of anterior kidney macrophages, and had slightly lower survival and a more rapid onset of mortality. These results can often lead to complicated conclusions that cannot always be inferred to different parasites or pathogens. This is because immunomodulatory changes in parasite infected fish involve both functional enhancement and suppression of different leukocyte populations, disease resistance, secondary pathogens, and the nature of the immune response that the pathogen evokes [6]. Consequently, more recent studies have explored the net role of parasites in several other fish species exposed to organochlorine pesticides in the lagoon (Akinsanya *et al.,* 2018; Akinsanya *et al.,* 2019; [2,3]. Some studies observed net depurative impact of the parasite which was beneficial to the fish host [3], some observed net parasitic impacts, while others observed a synergy between the endoparasites and the ambient toxicant to exert multi-stress conditions on the fish host [2]. It is therefore

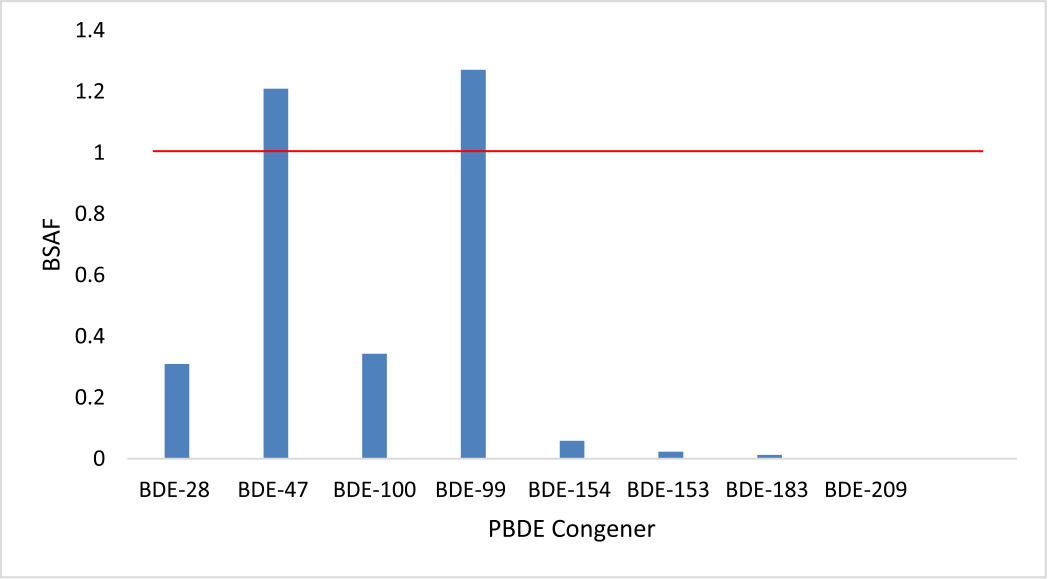

Fig. 1. Map of Lekki Lagoon.

important to understand the complex interactions that exist between the fish *H. niloticus,* its enteric parasites and PBDEs in the lagoon.

The study aimed at investigating the adsorption capacities of PBDEs on bottom sediment of Lekki lagoon and the subsequent uptake of the chemical from the soil into the tissues of *H. niloticus* in the lagoon. The study further aimed at investigating the comparative or synergistic roles of two endoparasites of host *H.* niloticus, namely *Tenuisentis niloticus* and *Sandonella sandoni* in modulating the accumulated PBDEs. The outcome of the study will provide information on the fitness of the fish for consumption and the rate of bioaccumulation of PBDEs within the lagoon. The study may also provide useful information as to the safety of the aquatic environment and the health of the dependent populace.

Materials and methods

The study area

The study was conducted at the Oluwo Market area of Lekki lagoon. Lekki lagoon (Fig. 1) This aquatic habitat supports a major fishery in Nigeria. The lagoon is located in Lagos State, Nigeria and it is part of an intricate system of waterways made up of lagoons and creeks that are found along the coast of south-western Nigeria from the Dahomey border to the Niger Delta stretching over a distance of about 200 km. It is fed by the River Osun and Saga discharging into north-western parts of the lagoon. Vegetation around the lagoon is characterized by stilt rooted trees with dense undergrowth of shrubs and herbs such as *Raphia sudanica, Elaeis guineensis* and the *Cocos nucifera* (Coconut palms) which is found wide spread in the surrounding villages (Edokpayi *et al.*, 2008; Lawal *et al.*, 2010). The collection fishes in the lagoon include *Heterotis niloticus, Gymnarchus niloticus, Clarias gariepinus, Malapterurus electricus, Synodontis clarias, Chrysichthys nigrodigitatus, Parachanna obscura, Mormyrus rume, Calabaricus calamoichthys, Tilapia zilli, Tilapia galilae, Hemichromis fasciatus* and *Sarotherodon melanotheron* (Kusemiju, 1981).

Lekki lagoon is located in Lagos State, South-Western Nigeria. It lies between longitudes 4°00′ and 4°15′ E and between latitudes 6°25′ and 6°37′N, has a surface area of about 247 square kilometers with a maximum depth of 6.4m, though a greater portion of the lagoon is shallow with a depth less than 3.0m.

Sample collection

A total of 38 *H. niloticus* fish samples were procured fresh but lifeless from local fishmongers at Epe jetty, nearby Oluwo Market, Lagos, Nigeria (Fig. 2) and recruited into the study. The sex, weights, standard and total lengths of the fish were determined and recorded. The weights were taken with the aid of standard weighing balance while the lengths of the fish were taken with a tape rule. The fish were immediately subjected to parasitological examinations. The liver and intestine of the fish were excised and the parasites obtained from the intestine were persevered in a saline solution for further analysis. The two predominant parasites among the fish samples dissected were identified as *Tenuisentis niloticus* and *Sandonella sandoni* using identification keys adopted from Akinsanya *et al.* (2021) and Bruno *et al.* [7] a as identification manual.s.

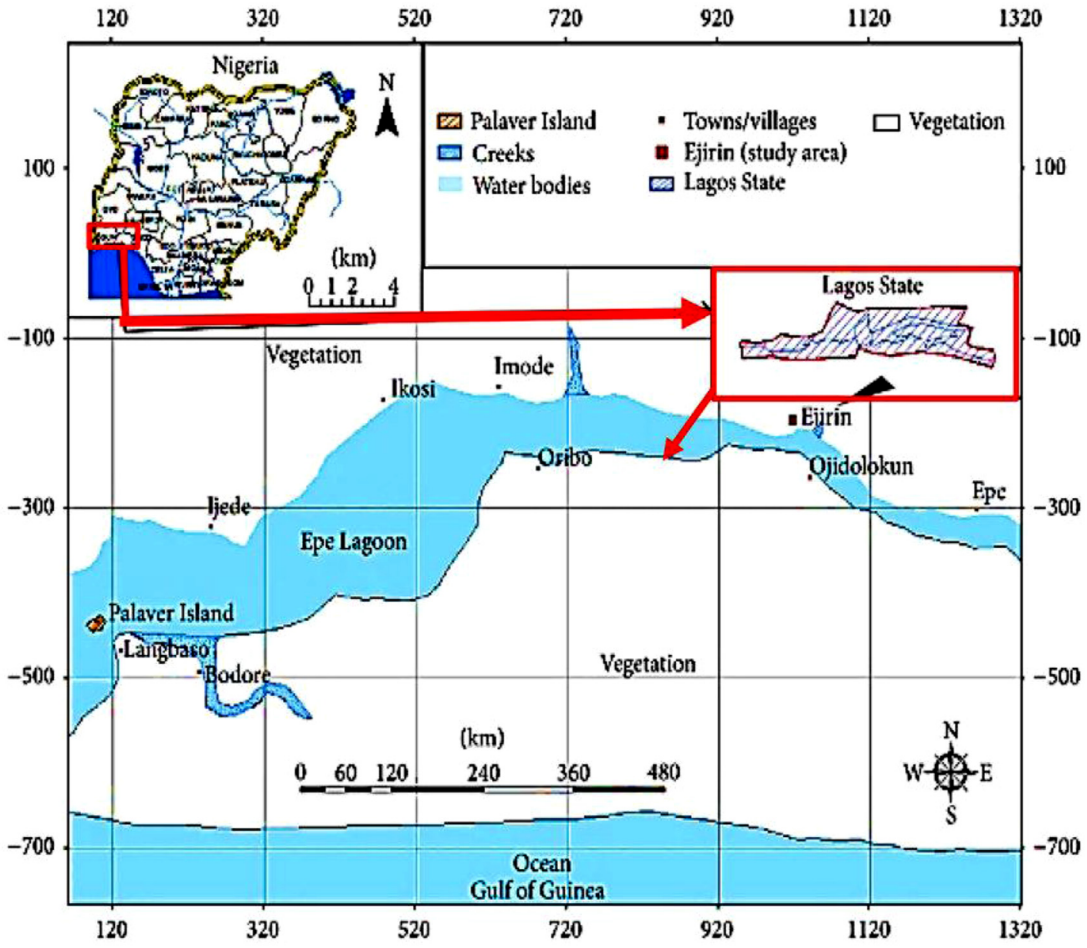

Fig. 2. Biota-sediment accumulation factors of PBDE congeners in the intestine from the bottom soil of the lagoon.

Water samples were collected in 150 mL sampling bottles and sediment samples were collected in labelled aluminium foil papers with the aid of a Van Veen grab sampler (12 × 12 × 12 cm dimension) from the bed of the water body. The samples were preserved in chest coolers ladened with ice blocks and transported immediately to the laboratory for analysis. The sampling periodicity was monthly for four months, between January and May 2021.

Determination of PBDEs

Determination of PBDEs in water sample

The EPA Method 3510C [8] was employed in the extraction of organic fraction from the water samples.

We measured 100 mL of water sample into 250 mL separatory funnel, then extracted three times with 20 mL of methylene chloride, giving ~60mL of final extracting solvent. Cover and shake the separatory funnel vigorously for 1 – 2mins, periodically venting the funnel to release excess pressure. The organic layer was allowed to separate from the water phase for a minimum of 10 min, then decanted the organic layer into a clean beaker/round-bottom flask. Sample extracts were concentrated (organic layer) to about 1 – 2 mL using a rotary evaporator prior to fractionation for PBDEs. about 1 – 3 spatula full of activated Sodium sulphate to the concentrated extract in order to eliminate water/aqueous portions [9].

Determination of PBDEs in sediment samples

The extraction of organic fraction from the sediment samples was done using Microwave assisted method [9]. About 10g ± 0.05g of the homogenized sample was weighed into 250 mL Teflon bottle. About 1 – 3 spatula full of activated Sodium sulphate was added to the samples in the Teflon bottles in order to eliminate water/aqueous portions, if any. 20mL of 1:1 acetone: hexane was used for extraction procedure thrice, giving ~60mL of final extracting solvent. The covered Teflon bottles were then sonicated in an ultrasonic bath at 70°C for 30 min. Organic layer was decanted into a clean beaker/round-bottom flask, further dried with sodium sulfate and clean-up procedure using silica gel column carried out. The sample

extract was then concentrated to ~2 mL using a rotary evaporator prior analysis using gas chromatography mass spectrometer (GC-MS).

Determination of PBDEs in tissues

KOH Refluxing/Vortex Extraction [10] – EPA Method 3611C cleanup method was employed in the analysis. We weighed 15 g wet weight of excised liver, intestine, and pooled parasite samples of the fish specimens into a crucible then macerate and homogenized it. From the homogenized tissue, 10 g was placed in a 50 mL centrifuge tube, 15 mL of 6N KOH was added, the tubes were sealed and incubated for 18 h in a 35 °C water bath, shaking vigorously for 30 second for every ½ hour for the first 4 h and allowed to cool afterwards.

We then added 15 mL of methylene chloride or ethyl ether to centrifuge tube, vortex for 1 min and centrifuge at 2000 rpm for 5 min to facilitate phase separation. The upper/aliquot layer was then removed using a Pasteur pipettes into a 250 mL round-bottom flask. Repeat solvent centrifugation twice and combine all aliquots fractions in the round-bottom flask.

Sample extracts concentration to about 5 – 10 mL was carried out by rotary evaporator prior to fractionation cleanup using alumina gel column and GC-MS analysis.

Quality control/ quality assurance

Six (6) sample replicates were analyzed for each tested medium and the mean of the values were reported for accuracy. Before the samples were analyzed the instrument was calibrated for the analysis. This was done by injecting a series of Calibration standards. The volume injected is 1 µL. A five-point calibration curve was prepared using the calibration standard that was commercially obtained. The calibration curve was checked to ensure that, the R2 value is $\geq$0.995. The response factor (RF) was calculated for each analyte/components in the calibration standard using the area response and the amount of standard material. The relative standard deviation percentage (%RSD) of the Rf was also calculated for each analyte across the calibration curve. The value ascertained not to have exceeded 15% for the curve to be adjudged valid. The average response factor for the weight ranges were calculated and used for sample quantification. In the event where any component alkane exceeded 15%, then the weight range response factors was evaluated and used having met the criteria. Sample analysis and quality control were ascertained using initial calibration standards, continuous calibration standard (5µg/ml or 10 µg/ml), standard reference material (SRM), and instrument blank.

Statistical analysis

The descriptive statistics of the concentrations of the PBDE concentrations in the liver, intestine and parasites in the sampled fish were presented as mean ± standard deviation, which were subjected to analysis of variance (ANOVA) to determine the significant differences using Microsoft Excel (2010) and SPSS (version 20). The actual locations of the significant differences were further determined by Tukey post-hoc test. All statistical analyses were conducted at probability level of 0.05.

Results

The soil adsorption coefficient (Kd) of 2,4,4′-Tribromodiphenyl ether (BDE-28), 2,2′,4,4′-Tetrabromodiphenyl ether (BDE-47), 2,2′,4,4′,5,-Penabromodiphenyl ether (BDE-99), 2,2′,4,4′,6-Pentabromodiphenyl ether (BDE-100), 2,2′,4,4′,5,5′-Hexabromodiphenyl ether (BDE-153), 2,2′,4,4′,5,6′-Hexabromodiphenyl ether (BDE-154), 2,2′,3,4,4′,5′,6-Heptabromodiphenyl ether (BDE-183), 2,2′,3,3′,4,4′,5,5′,6,6′-Decabromodiphenyl ether (BDE-209) was investigated to undertstand the the rate at which each congener precipitated onto the bottom sediment of the aquatic habitat (Table 1). The order of adorption coefficient was BDE-153 (60.17) > BDE-183 (4.76) > BDE- 100 (4.68) > BDE-47 (2.64) > BDE- 28 (1.30). The Kd values of BDE-99, BDE-154, and BDE-209 were zero as they were not detected in the water samples which may be as a result of complete precipitation from the PBDE congeners from the overlying water, hence couldn't be ascertained.

The rate at which PBDEs were accumulated in the intestine from the soil was expressed as the biota-sediment accumulation factor (BSAF) and presented in Fig. 2. Only BDE-99> BDE- 47 exhibited significant BSAF in the intestine of the fish. The other PBDE congeners were not significantly bioaccumulated in the intestine. BSAF estimation was not presented in the liver as the parasites were detected only in the intestine.

Analysis of variance (ANOVA) was conducted on the differential concentrations of the PBDE congeners in the liver, intestine, *T. niloticus* and *S. sandoni* of *Heterotis niloticus* fish (Table 2).

The concentration of BDE-47 in the liver, intestine, and *T. niloticus* parasites were significantly higher than the concentrations detected in the *S. sandoni* parasites ($p<0.01$). The concentrations of BDE-100 and BDE-99 in the liver of the fish was significantly higher than the concentrations detected in the intestine, *T. niloticus* and *S. sandoni* of the fish ($p<0.01$). The concentrations of BDE-183 in the liver, *T. niloticus,* and *S. sandoni* were significantly higher than the concentration in the intestine of the fish ($p<0.01$). On the overall comparative analysis, the total PBDEs in the liver of the fish was significantly higher than the concentrations in the parasite *T. niloticus* and *S. sandoni* ($p<0.01$), which were in turn significantly higher than the concentration in the intestine.

Table 1
Soil adsorption coefficient (Kd) of PBDEs from water.

Components	Sediment	Water	Kd
BDE-28	0.08	0.06	1.30
BDE-47	0.02	0.01	2.64
BDE-100	0.04	0.01	4.68
BDE-99	0.01	0.00	*
BDE-154	0.02	0.00	*
BDE-153	0.05	0.00	60.17
BDE-183	0.21	0.04	4.76
BDE-209	0.28	0.00	*

BDE-28= 2,4,4′-Tribromodiphenyl ether, BDE-47= 2,2′,4,4′-Tetrabromodiphenyl ether, BDE-100= 2,2′,4,4′,6-Pentabromodiphenyl ether, BDE-99= 2,2′,4,4′,5,-Penabromodiphenyl ether, BDE-154= 2,2′,4,4′,5,6′-Hexabromodiphenyl ether, BDE-153= 2,2′,4,4′,5,5′-Hexabromodiphenyl ether, BDE-183= 2,2′,3,4,4′,5′,6-Heptabromodiphenyl ether, BDE-209= 2,2′,3,3′,4,4′,5,5′,6,6′-Decabromodiphenyl ether. Emboldened figures indicate significant adsorption coefficients.

Table 2
ANOVA of PBDE concentrations in the liver, intestine, and parasites of *H. niloticus*.

PBDEs	Liver MEAN	SD	Intestine MEAN	SD	*T. niloticus* MEAN	SD	*S. sandoni* MEAN	SD
BDE-28	0.041	0.019	0.025	0.034	0.029	0.013	0.028	0.014
BDE-47	0.055^{a}	0.035	0.030^{a}	0.019	0.023^{a}	0.008	0.013^{b}	0.011
BDE-100	0.064^{a}	0.038	0.015^{b}	0.006	0.015^{b}	0.007	0.014^{b}	0.016
BDE-99	0.065^{a}	0.053	0.013^{b}	0.006	0.044^{b}	0.012	0.011^{b}	0.015
BDE-154	0.010	0.007	0.001	0.001	0.000	0.000	0.005	0.005
BDE-153	0.015	0.011	0.001	0.001	0.001	0.002	0.019	0.025
BDE-183	0.051^{a}	0.046	0.002^{b}	0.003	0.045^{a}	0.076	0.034^{a}	0.012
BDE-209	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.015
Total PBDEs	0.301^{a}	0.108	0.088^{c}	0.047	0.157^{b}	0.060	0.131^{b}	0.067

BDE-28= 2,4,4′-Tribromodiphenyl ether, BDE-47= 2,2′,4,4′-Tetrabromodiphenyl ether, BDE-100= 2,2′,4,4′,6-Pentabromodiphenyl ether, BDE-99= 2,2′,4,4′,5,-Penabromodiphenyl ether, BDE-154= 2,2′,4,4′,5,6′-Hexabromodiphenyl ether, BDE-153= 2,2′,4,4′,5,5′-Hexabromodiphenyl ether, BDE-183= 2,2′,3,4,4′,5′,6-Heptabromodiphenyl ether, BDE-209= 2,2′,3,3′,4,4′,5,5′,6,6′-Decabromodiphenyl ether. Emboldened figures indicate occurrence of significant differences. Alphabets a>b>c indicate the order of occurrences of the significant differences. Sample size (N)= 38.

Table 3
Bioaccumulation factors (BAFs) of PBDE in parasites from host tissues.

	T. niloticus		*S. sandoni*	
PBDE Components	Intestine	Liver	Intestine	Liver
BDE-28	1.14	0.72	1.09	0.68
BDE-47	0.75	0.41	0.44	0.24
BDE-100	1.04	0.24	0.98	0.22
BDE-99	3.41	0.68	0.85	0.17
BDE-154	0.25	0.02	4.97	0.46
BDE-153	0.91	0.07	16.92	1.29
BDE-183	18.02	0.87	13.59	0.66
BDE-209	*	*	*	*
Total PBDEs	1.79	0.52	1.50	0.44

BDE-28= 2,4,4′-Tribromodiphenyl ether, BDE-47= 2,2′,4,4′-Tetrabromodiphenyl ether, BDE-100= 2,2′,4,4′,6-Pentabromodiphenyl ether, BDE-99= 2,2′,4,4′,5,-Penabromodiphenyl ether, BDE-154= 2,2′,4,4′,5,6′-Hexabromodiphenyl ether, BDE-153= 2,2′,4,4′,5,5′-Hexabromodiphenyl ether, BDE-183= 2,2′,3,4,4′,5′,6-Heptabromodiphenyl ether, BDE-209= 2,2′,3,3′,4,4′,5,5′,6,6′-Decabromodiphenyl ether. Emboldened figures indicate significant bioaccumulation factors. Sample size (N)= 38.

The level of bioaccumulation of PBDE congeners in the enteric parasites of *Heterotis niloticus* fish was presented at the bioaccumulation factor (BAF) in Table 3. A comparative analysis of the BAFs of the two enteric parasites detected in the fish showed that much of the toxicant was absorbed differently by the parasites from the intestine of the fish than the liver. Both *T. niloticus* (at 1.14 folds) > *S. sandoni* (at 1.09 folds) significantly bioaccumulated BDE-28 from the intestine, while no significant bioaccumulation occurred in the liver. The parasites also bioaccumulated BDE-183 at 18.02 and 13.59 folds respectively from the intestine, while the BAFs in the liver were also insignificant. *T. niloticus* alone bioaccmulated BDE-100 (1.04 folds) and BDE-99 (at 3.41 folds) from the intestine only, while only *S. sandoni* bioaccumulated BDE-154 (4.97 folds from the intestine) and BDE-153 (16.92 and 1.29 folds from the intestine and liver respectively). The total accumulated PBDEs were significant only in the intestine but no significant accumulation occurred in the liver. The overall PBDE showed the parasite *T. niloticus* bioaccumulated higher concentration than *S. sandoni.* No significant BAF was recorded for BDE-47, and BDE-209 in either of the compared parasites.

A correlation analysis conducted among the concentrations of the PBDE congeners in the biological media was presented in Table 4. The analysis was conducted to have a clearer understanding of the dynamics of the toxicants in the tissues. The concentrations of BDE-99 in *T. niloticus* and the liver of the fish exhibited a strong negative correlation (-0.87). The concentrations of BDE-28 in the parasite *S. sandoni* and the intestine of the fish exhibited a positive correlation (0.67). BDE-47 in the parasite and intestine has a strong positive correlation (0.97), while BDE-100 had a positive correlation of 0.63 between the same media. Conversely, BDE-99 in the same media had a negative correlation of -0.58. BDE-154 exhibiteda strong positive correlation (0.97) between *T. niloticus* and the intestine of the fish. BDE-183 exhibited a negative correlation (-0.56) between the parasite *T. niloticus* and the intestine of the fish, while it had a strong negative correlation (-0.73) between *S. sandoni* and the intestine of the fish. Interestingly, BDE-28 exhibited a strong negative correlation (-0.83) between the two parasites investigated.

Discussion

The results of the study shows that Lekki lagoon and the humans that depend on its services may be exposed to elevated concentrations of PBDEs through the predominant activities. The order of the adsorption coefficient of the investigated PBDE congeners was BDE-153 (60.17) > BDE-183 (4.76) > BDE- 100 (4.68) > BDE-47 (2.64) > BDE- 28 (1.30). Polybrominated diphenyl ethers are naturally hydrophobic and lipophilic due to their high octanol-water partition coefficients characterized by the high biota-sediment accumulation factors (BSAF) observed in most of the congeners investigated. BDE- 153 (2,2′,4,4′,5,5′-Hexabromodiphenyl) ranking highest in the order of adsorption is indicative of an ecological concern.

However, among these adsorptive chemicals, *Heterotis niloticus* in the lagoon only bioaccumulated BDE-47 (2,2′,4,4′-Tetrabromodiphenyl ether), and BDE- 99 (2,2′,4,4′,5-Penabromodiphenyl ether) from the bottom sediment. These two congeners may pose threat to the consumers of the fish if the exposure of the fish is not mitigated. The BDE-47 was poorly accumulated by *T. niloticus* and *S. sandoni* from the intestine and liver of *H. niloticus* fish. Yang *et al.* (2017) earlier reported that the most abundant congeners among PBDEs in Hong Kong are 2,2′,4,4′-tetrabromodiphenyl ether (BDE-47) and 2,2′,4,4′,5-pentabromodiphenyl ether (BDE-99). Although *T. niloticus* appreciably accumulated BDE-99 from the intestine, the PBDE congener was however not cleared from the liver. *S. sandoni* showed inability to clear the chemical from either the intestine or the liver of the fish. The results of this study have validated that the abundance of these chemicals is consistent even in Lekki lagoon in Nigeria (Liu *et al.,* 2005). *T. niloticus* may thus be harnessed a tool to modulate the bioaccumulation of selected PBDEs in Lekki lagoon and other aquatic habitats with similar trends of pollution. This study showed that most of the PBDE congeners were not sequestered by the enteric parasites because they were obtained from the intestine and absent in the liver. Furthermore, the liver's physiological role of detoxification is partly responsible for the higher concentrations detected in the organ as most of the toxicants a passed to the liver from the intestine through the hepatic portal vein for breakdown.

According to Cheung *et al.* [11], in Hong Kong, the dietary intake of PBDEs to Hong Kong residents was estimated between 510 ng day^{-1} for marine fish and 924 ng day^{-1} for freshwater fish, which was higher than that calculated in other countries and raised a concern about PBDE contamination of fishery products. The burdens of PBDEs in both marine and freshwater fish were reported to range from 3.0 ng/g to 5366.07 ng/g in lipid weight [12–16]. Bioaccumulation of PBDEs in aquatic species and the transfer to humans warrants a more careful risk assessment than those previously performed.

BDE-28 and BDE-183 were concertedly sequestered significantly from the intestine of the fish by both parasites. *S. sandoni* showed better adaptation to sequestration of BDE-153 (from the intestine and the liver) and BDE-154 from the intestine alone, while *T. niloticus* alone exhibited sequestration capacities on BDE-100 and BDE-99.

In humans, endocrine disruptors are liable to cause obesity and diseases via various signaling pathways [17]. Human exposure to PBDEs is related to endocrine system disorder, neurodevelopment interference, and energy balance interruption [18]. A study of 207 pregnant women suggested that exposure to PBDEs (26.5 ng/g lipids) is associated with lower levels of thyroid-stimulating hormone (1.2 mU/L) during pregnancy, in which a 10-fold increase in PBDEs was associated with a 16.8% decrease in thyroid-stimulating hormone; these results have implications for maternal health and fetal development (Jevier *et al.,* 2010). Both prenatal and childhood PBDE exposures were reported to be associated with poorer attention, fine motor coordination, and cognition in school-age children whose mother lived in California's agricultural Salinas [19]. PBDEs exposure in breast milk at 3 months postpartum were shown to be associated with increased anxiety in early childhood of

Table 4
Correlation analysis of PBDE concentrations in the liver, intestine, and parasites of *H. niloticus*.

	BDE-28 L	*BDE-47 L*	*BDE-100 L*	*BDE-99 L*	*BDE-154 L*	*BDE-153 L*	*BDE-183 L*	*BDE-28 I*	*BDE-47 I*	*BDE-100 I*	*BDE-99 I*	*BDE-154 I*	*BDE-153 I*	*BDE-183 I*	*BDE-28 A*	*BDE-47 A*	*BDE-100 A*	*BDE-99 A*	*BDE-154 A*	*BDE-153 A*	*BDE-183 A*	*BDE-28 C*	*BDE-47 C*	*BDE-100 C*	*BDE-99 C*	*BDE-154 C*	*BDE-153 C*	*BDE-183 C*	*BDE-209 C*
BDE-28 L	1.00																												
BDE-47 L	-0.04	1.00																											
BDE-100 L	0.88	0.28	1.00																										
BDE-99 L	0.14	0.94	0.32	1.00																									
BDE-154 L	0.11	0.97	0.33	0.99	1.00																								
BDE-153 L	0.69	-0.64	0.55	-0.59	-0.60	1.00																							
BDE-183 L	-0.32	-0.25	-0.70	-0.04	-0.13	-0.42	1.00																						
BDE-28 I	0.75	-0.11	0.87	-0.16	-0.12	0.82	-0.82	1.00																					
BDE-47 I	0.31	0.03	0.63	-0.19	-0.10	0.56	-0.97	0.86	1.00																				
BDE-100 I	0.55	0.50	0.88	0.38	0.45	0.31	-0.91	0.80	0.81	1.00																			
BDE-99 I	0.36	0.12	0.02	0.45	0.34	-0.20	0.69	-0.35	-0.76	-0.34	1.00																		
BDE-154 I	-0.29	0.96	0.08	0.82	0.87	-0.74	-0.26	-0.22	0.06	0.41	-0.09	1.00																	
BDE-153 I	0.60	0.48	0.91	0.38	0.44	0.35	-0.89	0.82	0.80	1.00	-0.29	0.37	1.00																
BDE-183 I	-0.55	-0.73	-0.58	-0.89	-0.86	0.23	0.04	-0.10	0.15	-0.45	-0.64	-0.50	-0.47	1.00															
BDE-28 A	-0.45	-0.27	-0.79	-0.09	-0.17	-0.46	0.99	-0.87	-0.96	-0.95	0.59	-0.24	-0.94	0.14	1.00														
BDE-47 A	-0.33	-0.89	-0.67	-0.83	-0.87	0.23	0.58	-0.35	-0.39	-0.83	0.00	-0.79	-0.82	0.76	0.63	1.00													
BDE-100 A	0.27	-0.95	-0.14	-0.79	-0.85	0.67	0.36	0.13	-0.16	-0.49	0.17	-0.99	-0.44	0.47	0.33	0.82	1.00												
BDE-99 A	0.25	-0.98	-0.09	-0.87	-0.92	0.76	0.20	0.25	0.02	-0.38	-0.02	-0.99	-0.35	0.58	0.19	0.80	0.98	1.00											
BDE-154 A	-0.34	0.94	-0.05	0.87	0.90	-0.85	-0.03	-0.41	-0.19	0.22	0.12	0.97	0.19	-0.55	-0.01	-0.70	-0.94	-0.98	1.00										
BDE-153 A	-0.34	0.94	-0.05	0.87	0.90	-0.85	-0.03	-0.41	-0.19	0.22	0.12	0.97	0.19	-0.55	-0.01	-0.70	-0.94	-0.98	1.00	1.00									
BDE-183 A	-0.35	0.93	-0.09	0.87	0.89	-0.88	0.03	-0.46	-0.25	0.17	0.17	0.95	0.14	-0.56	0.05	-0.67	-0.92	-0.97	1.00	1.00	1.00								
BDE-28 C	0.59	0.66	0.89	0.60	0.65	0.16	-0.77	0.67	0.62	0.96	-0.10	0.52	0.97	-0.67	-0.83	-0.93	-0.58	-0.52	0.38	0.38	0.34	1.00							
BDE-47 C	0.48	-0.14	0.70	-0.30	-0.23	0.75	-0.91	0.94	0.97	0.77	-0.65	-0.16	0.77	0.15	-0.91	-0.27	0.06	0.22	-0.39	-0.39	-0.44	0.58	1.00						
BDE-100 C	0.87	-0.28	0.84	-0.24	-0.23	0.92	-0.61	0.95	0.67	0.63	-0.12	-0.44	0.67	-0.13	-0.68	-0.17	0.37	0.45	-0.58	-0.58	-0.61	0.53	0.82	1.00					
BDE-99 C	0.55	-0.19	0.73	-0.32	-0.26	0.80	-0.87	0.96	0.94	0.75	-0.58	-0.23	0.75	0.13	-0.89	-0.24	0.13	0.29	-0.45	-0.45	-0.50	0.56	0.99	0.87	1.00				
BDE-154 C	0.15	0.30	0.57	0.04	0.14	0.29	-0.98	0.71	0.95	0.86	-0.77	0.35	0.83	0.04	-0.95	-0.57	-0.45	-0.28	0.12	0.12	0.06	0.71	0.85	0.46	0.80	1.00			
BDE-153 C	0.91	-0.20	0.61	0.09	0.01	0.58	0.09	0.45	-0.08	0.17	0.65	-0.47	0.24	-0.52	-0.04	-0.06	0.48	0.39	-0.42	-0.42	-0.40	0.26	0.13	0.67	0.23	-0.26	1.00		
BDE-183 C	0.63	0.11	0.31	0.44	0.34	0.04	0.46	-0.05	-0.53	-0.09	0.95	-0.14	-0.03	-0.73	0.33	-0.13	0.20	0.04	0.01	0.01	0.05	0.13	-0.38	0.17	-0.30	-0.58	0.84	1.00	
BDE-209 C	-0.34	0.94	-0.05	0.87	0.90	-0.85	-0.03	-0.41	-0.19	0.22	0.12	0.97	0.19	-0.55	-0.01	-0.70	-0.94	-0.98	1.00	1.00	1.00	0.38	-0.39	-0.58	-0.45	0.12	-0.42	0.01	1

BDE-28= 2,4,4′-Tribromodiphenyl ether, BDE-47= 2,2′,4,4′-Tetrabromodiphenyl ether, BDE-100= 2,2′,4,4′,6-Pentabromodiphenyl ether, BDE-99= 2,2′,4,4′,5,-Penabromodiphenyl ether, BDE-154= 2,2′,4,4′,5,6′-Hexabromodiphenyl ether, BDE-153= 2,2′,4,4′,5,5′-Hexabromodiphenyl ether, BDE-183= 2,2′,3,4,4′,5′,6-Heptabromodiphenyl ether, BDE-209= 2,2′,3,3′,4,4′,5,5′,6,6′-Decabromodiphenyl ether. L= liver, I= intestine, A= acanthocephalan *T. niloticus* and, C= cestode *S. sandoni*. Emboldened figures indicate occurrence of significant correlation (>/ = 0.5).

36 months age [20,21]. A survey on a U.S. population group showed involvement of PBDEs in the pathogenesis of diabetes and metabolic syndrome [22].

However, knowledge about the environmental fate is still limited and there remain many uncertainties in the modeling studies performed so far. This is partly due to limited research on chemical properties and thus uncertain property data for many PBDE congeners. For some congeners data are even missing and must be extrapolated from other congeners.

In the current study, where significant differences occurred among the PBDE congeners. For example, the liver had a significantly higher concentration of BDE-99, BDE-100 and total PBDEs than other tested biological media ($p<0.01$). The liver has the primary role of detoxifying the chemicals, hence the relatively higher concentrations of the chemicals is expected. In the case of BDE-47 there was no significant difference among the concentrations in the liver, intestine and *T. niloticus,* which were higher than the concentration in *S. sandoni* ($p<0.01$) [25]. In the overall concentrations of PBDEs the order of congener concentrations was liver> *T. niloticus* and *S. sandoni* > intestine. This implies that the parasites may have played appreciable sequestration roles in relieving the host fish of the chemical burden. The liver exhibited the highest concentration being the organ with primary role of detoxification of the chemicals. The study is consistent with the observations of Isibor *et al.* [3] who discovered significant sequestration potential in *Raphidascaroides brasiliensis* (Nematoda: Anisakidae) on polycyclic aromatic hydrocarbons in *Gymnarchus niloticus* of Lekki lagoon.

The current study has demonstrated the essentiality of organ functions in the toxicokinetics of PBDEs. The study has compared the sequestration potentials of *T. niloticus* to be a better bioindicator and bioaccumulator of BDE-28, BDE-183, BDE-99, and BDE-100, while *S. sandoni* showed better affinity for BDE-153 and BDE-154 only [26,27]. However, the sequestration potential of the former is more relevant to the situation at Lekki lagoon as the latter showed sequestration potentials for PBDE congeners that were not of concern [28,29]. The high adsorption of BDE-28 on the bottom soil of the lagoon was matched by the strong positive correlation in the concentrations of BDE-28 in *T. niloticus* and *S. sandoni* was consistent with significant sequestration of the chemical in both parasites from the intestine of the fish host. Also, BDE-183 which exhibited significant negative correlations between both parasites and the intestine was buttressed by the sequence of concentration in the biological media; which showed that the concentrations of the chemical in the two parasites were competitive with that in the liver, and outcompeted the concentration in the intestine. This implies that the resultant low rate of bioaccumulation of BDE-28 and BDE-183 in the intestine of the fish might be as result of the sequestration interferences of both parasites.

Recommendation and conclusion

As expected, all the PBDE congeners tested showed high adsorption coefficients in the soil, BDE-153 however showed a marked and attendant adsorption coefficient [23]. Even though the present concentration of the PBDE congener was relatively low, the adsorption coefficient might initiate extreme concentrations in the tissues of the fish in the nearest future, thus posing threat to the consumers [24,30]. This is of great concern as the parasites showed exhibited inability to bioaccumulate the toxicant from the host. Most importantly, the two PBDE congeners of greatest biota-sediment accumulation concerns were BDE-47 and BDE-99 [31]. Unfortunately, both parasites showed poor bioaccumulation potentials for BDE-47 which had great adsorption coefficient. This indicates that the aquatic habitat requires stringent monitoring of this congener in order to forestall the prognostic health and environmental hazards this cause. This study however demonstrated that *T. niloticus* exhibited better sequestration potentials for BDE-183, BDE-99 and BDE-100 than *S. sandoni.* Although the latter also showed appreciable sequestration potential for BDE-183. Of the two PBDE congeners that exhibited the greatest threats *T. niloticus* showed promising potentials to bioaccumulate one. The study showed that the synergy of both parasites may depurate some of the toxicant burdens in the host fish *H. niloticus*. We recommend further study into the possibilities of harnessing the synergy of other harmless bioremediation techniques in order to combat the prognosis of health and environmental hazards BDE-47 may pose.

We hereby recommend *T. niloticus* as a better bioaccumulator and bioindicator of selected PBDEs in the lagoon than *S. sandoni.*

Declaration of Competing Interest

No conflict of interest during the course of this research.

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