Archives of Environmental Contamination and Toxicology
https://doi.org/10.1007/s00244-021-00904-5

Organochlorine Pesticides and Polychlorinated Biphenyls in Sediment Impacted by Cage Aquaculture in the Volta Basin of Ghana

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Received: 3 June 2021 / Accepted: 9 November 2021

Abstract

Seventeen organochlorine pesticides (OCPs) and seven indicator polychlorinated biphenyls (PCBs) residues in 80 sediment samples from four cage aquaculture farms on the Volta Basin were determined to find out the extent of their contamination as well as their risk to biota in the aquatic ecosystem. The extracted residues of the OCPs and PCBs were analysed on a gas chromatograph equipped with an electron capture detector and mass spectrometer, respectively. Eleven (11) OCPs: methoxychlor, δ-HCH, *o*,*p*′-DDD, α-endosulphan, β-HCH, *o*,*p*-DDE, *p*,*p*-DDE, *p*,*p*′-DDT, β-endosulphan, endrin, and heptachlor and seven (7) PCBs: PCB 18, PCB 28, PCB 52, PCB 101, PCB 138, PCB 153, and PCB 180 were detected in the sediments from the farms. The OCPs level ranged < LOD − 33.0 µg/kg. δ-HCH (8.154 ± 0.414 µg/kg), α-endosulphan (6.000 ± 1.414 µg/kg), *o*,*p*′-DDD (2.010 ± 1.46 µg/kg), endrin (13.867 ± 8.716 µg/kg), and α-endosulphan (0.503 ± 0.398 µg/kg) were predominant with frequencies of detection 100%, 45%, 68%, 92%, and 25% in fish farms A, B, C, D and controls, respectively. PCBs concentrations ranged 0.042–5.320 ng/g wet weight. PCB 153 recorded the highest concentration of 3.328 ± 1.700 ng/g in farm D. PCB 18 and PCB 180 dominated the profiles in the sediment from all the farms. The ecotoxicological risk of the OCPs and PCBs in the surface sediment using the SQGs indicated that ∑HCH in the sediment from all the farms except that the controls may pose a health risk to the benthic organisms. Therefore, a comprehensive remedial intervention is required to arrest the situation.

Some large groups of semi-volatile persistent organic pollutants (POPs) that are commonly found in the environment are organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs). They are increasingly gaining concern globally because of their toxicity, persistence, long-range transmission, and bioaccumulation (Wong et al. 2005). Because POPs are generally hydrophobic, they easily attach to the particle portion in surface waters. They last a long time in the sediment processes because of their long half-lives and high stability (Darko et al. 2008; Sakan et al. 2017).

OCPs and PCBs input sources in riverine environments include public health, agriculture, forestry, household and industrial wastewater discharge, direct disposal of wastes into the river, as well as nonpoint source run-off after rainfall (Montuori et al. 2014). Despite their prohibition or regulated usage, the PCBs and pesticides studied have been among the most common environmental contaminants, comprising abiotic (soil, sediment, air, water) and biotic (plankton to man) components. Surface sediments have been identified as one of the critical sources of PCB build-up in many studies (Kanzari et al. 2014; Albanese et al. 2010; Barhoumi et al. 2014; Zhao et al. 2010b). Because the sediment is the main base for chemical pollutants discharged into aquatic environments, it frequently receives large concentrations of these pollutants, posing a severe threat to benthic species and the whole aquatic food web (Botwe et al. 2012).

The Volta Basin in Ghana is known for producing many cage aquaculture fish, especially Nile tilapia (*Oreochromis niloticus*). There are many large farms including, irrigation facilities, dotted along the banks of the Basin, which produce large quantities of food and vegetables. Farmers have used pesticides extensively and unregulated throughout the Basin watershed to increase agricultural productivity and maximise profit. During run-off, after rainfall, residual pesticides in the soil are discharged into aquatic ecosystems, resulting

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Published online: 19 November 2021

in the contamination of all compartments of the ecosystem (water, sediment, flora, and fauna).

Additionally, about 80% of the small, medium, and large commercial cage aquaculture farms are located in the Volta Basin. Fish feed for the farms is sourced from the Rannan and Beacon Hills and others imported from other countries (Karikari 2017). These feeds are manufactured with grains, fishmeal, and fish oil from different sources and may contain persistent organic pollutants such as dioxin, PCBs, and organochlorine pesticides (Easton et al. 2002; Antunes and Gil 2004; Hites et al. 2004; Navas et al. 2005; Bordajandi et al. 2006; Maule et al. 2007; Kelly et al. 2007; McKee et al. 2008; Shaw et al. 2008; Botaro et al. 2011; Perugini et al. 2013). The recent expansion in the aquaculture industry by the Ghanaian Government initiative programme on planting for food and jobs will further exacerbate the residuals levels of these pollutants in the Basin. According to Yu et al. (2011), fish farms, boats, cages, and structures are prone to biofouling, and to reduce the effects of biofouling; antifoulants paints are applied to them. The antifoulants have DDT and some heavy metals as their active ingredients, which leaches gradually into the water column polluting the biota and threatening the entire aquatic ecosystem.

Whereas few studies on POPs (OCPs and PCBs) have been documented in freshwater and marine fishes in Ghana (Kuranchie-Mensah et al. 2012; Ntow 2005; Gbeddy et al. 2015; Adu-Kumi et al. 2010; Asante et al. 2013; Elegbede et al. 2015; Gbeddy et al. 2012; Karikari 2017), little or no studies have been carried out on these contaminants in sediment from the cage aquaculture farms on the Volta Basin. Therefore, it is imperative to examine the levels of these undesirable contaminants and their potential risk to aquatic organisms.

Materials and Methods

Study Area

The study area comprises the Asuogyaman District in the Eastern region and the Shai Osudoku of the Greater Accra region of Ghana. Figure 1 is a map showing the location of the fish farms, where samples were collected. The districts are situated roughly between latitudes 6° 34° N and 6° 10° N and longitudes 0° 1° W and 0° 14° E. The Basin has one of the largest hydroelectric dams that generate power to the country and other neighbour countries such as Togo. The Basin also has an inland port that facilitates goods from the southern part of Ghana to the northern territories and beyond. Rain-fed agriculture and irrigation are the major economic activities in terms of employment and rural income generation. To boost their crop yield, the farmers use agrochemicals extensively on their farms. As a result, the potential usage of restricted or banned pesticides cannot be ruled out. The area is characterised by a double maximum rainfall pattern, with the major season being from September to November and the minor season occurring from May to July.

Chemicals and Reagents

Pesticide grade ethyl acetate, distilled water (HPLC grade), acetone, and hexane (both analytical grade) were supplied by Fisher Scientific (Loughborough, UK); silica gel and sodium sulphate were purchased from E. Merck (Germany). Sigma-Aldrich Chemicals USA provided disposable solid-phase florisil cartridges (500 mg/6 mL). Dr. Erhenstorfer GmbH (Germany) provided the certified, high purity (> 99.0%), reference standards of α–HCH, γ–HCH, β–HCH, delta-HCH, endrin, heptachlor, aldrin, dieldrin, *o*,*p*´-DDT, *p*,*p*´-DDT, *p*,*p*´-DDD, *o*,*p*´-DDD, *p*,*p*´-DDE, *o*,*p*´-DDE, α-endosulphan, β-endosulphan, and methoxychlor, and they were kept frozen to prevent them from degrading.

Sample Collection and Preparation

A sampling of bottom sediment samples for POPs was obtained with an Ekman grab sampler. A total of 60 (Farm A = 15, farm B = 15, farm C = 15, and farm D = 15) sediment samples for the pesticide extraction were collected and stored in a cleaned zip lock bag, labelled with an indelible pen, and sealed to avoid cross-contamination. Two grabbed sediment samples were obtained at two separate locations in the cages in each of the fifteen randomly selected cages from each farm and combined to form composite samples. Samples were collected in March, May, and July 2019. All samples were obtained early in the morning between 6:00 am and 9:45 am to avoid the breakdown of specific contaminants.

Additionally, twenty (20) samples of sediment were collected as controls from the upstream in the Volta Basin above from where aquaculture is practised. For further investigation, all samples were transported to the Ghana Atomic Energy Research laboratory in an air-tight ice-chest at 4 °C for further investigation. The sediment samples were air-dried before being crushed with a pestle in a laboratory mortar (Fritsch mortar grinder P-2). The content was filtered with a 250 µm mesh size sieve to remove stony particles and debris. The sieved fine samples were immediately used for the extraction.

Extraction of Sediment for Organochlorine Pesticides and Polychlorinated Biphenyls

The US EPA 3550C method, as described by Solomon (2016) and Adeshina et al. (2019) with a slight modification,

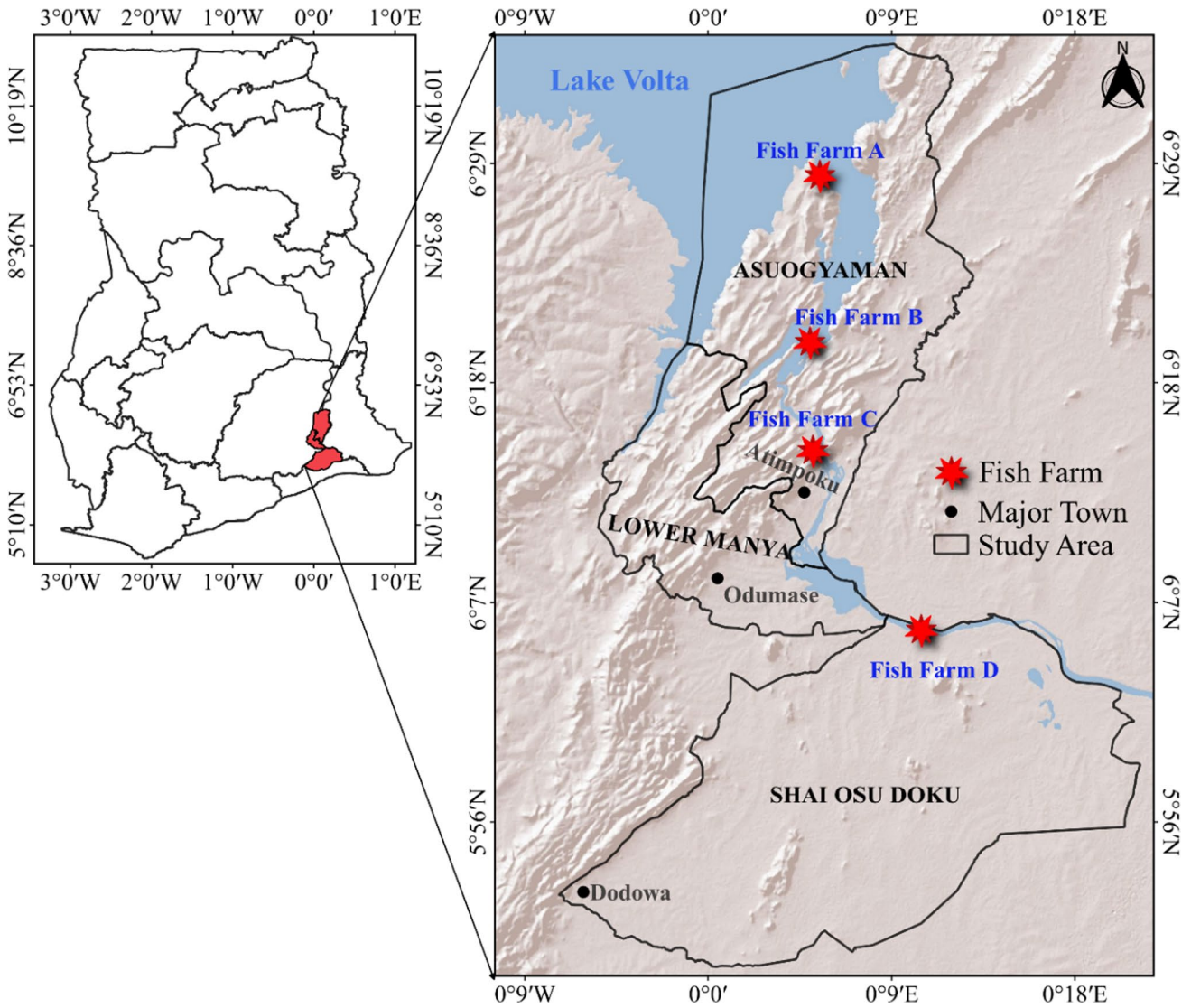

Fig. 1 Map of the study area of the Volta Basin, Ghana

was used to extract organochlorine pesticide residues from the sediment samples. A quantity of 10 g of sediment and 5 g of anhydrous sodium sulphate (Na_2SO_4) was weighed into an extraction jar. A volume of 50 ml acetone/n-hexane (2:1 v/v) was thoroughly incorporated into the mixture. The organic extract was filtered through a Whatman filter paper into a volumetric flask after 30 min of sonication in a Bransonic 220 high-frequency ultrasonic bath at 60 °C. The extraction process was repeated twice. The combined extracts were concentrated to a volume of 25 ml at a temperature of 45 °C.

Sample Clean-Up

In order to avoid interferences, the clean-up system is important for the pesticide residues analysis in a sample. Before the clean-up, silica gel was activated by heating it moderately to about 150 ℃ in an air-tight oven. This process removes water content in the gel and increases its adsorptive capacity significantly. The glass separating column (20 cm) was packed with three layers. The agents were arranged with the activated charcoal (Kaipper et al. 2001) at the top, followed by 2 g of anhydrous granulated Na_2SO_4 and the bottom packed with 4 g of activated silica gel (90% < 45 µm). The activated charcoal was purified using procedures reported by Kaipper et al. (2001). The activated charcoal removes colouration; the anhydrous Na_2SO_4 serves as a demoisturiser; and the silica gel removes co-extractants. Prior to cleaning, the column was moistened and rinsed with 10 ml n-hexane. The extract was then loaded into the column, and a 20 ml portion of acetone/hexane mixture was used to elute it. The eluates were collected into a round bottomed-flask and then concentrated to dryness using a rotary evaporator at a temperature

of 45 °C and picked in 2 ml ethyl acetate vial for gas chromatography analysis.

Determination of the OCPs and PCBs Residues

A Varian CP-3800 gas chromatograph (Varian Association Inc. USA) with combiPAL auto-sampler and 63Ni electron capture detector was used to analyse the final extracts. VF-5 coated capillary column (30 m + 10 m EZ protection column, 0.25 mm inner diameter, 0.25 m film thickness) was employed for the analysis. The temperature of the injector and detector was set at 270 ℃ and 300 °C, respectively. The furnace temperature was programmed as follows: 70 °C held for 2 min, ramp at 25 °C/min to 180 °C, held for 1 min, and finally ramp at 5 °C/min to 300 °C. In order to compensate for the relative retention times and the response behaviour, the GC conditions and the detector response were determined. N was used as carrier gas with a flow rate of 1.0–29 mL/min as detector additive gas. The injection volume of the GC was 1.0 µl. The total running time for one sample was 31.4 min.

GC–MS analysis was carried out with Agilent Technologies 6890 N (for GC) and 5975 (for MS) in EI mode. The ion source and interface temperatures were 300 °C and 280 °C, respectively. Chromatographic separation was conducted on a Phenomenex ZB-5MS capillary column (30 m × 0.25 mm × 0.25 µm). The gas flow of the carrier was 1.1 mL/min. The temperature of the injection was 265 °C. The amount of the samples infused was 1µL. The temperatures were optimised as follows: The initial oven temperature was maintained for 1 min at 60 °C, increased to 170 °C with a 20° C/min ramp, kept for 0.30 min, and then increased by 10° C/min to 310 °C with a maintaining time of 1.20 min. A mixture of PCB 18, PCB 28, PCB 52, PCB 101, PCB 153, PCB 138, and PCB 180, at a concentration of 10 µg/mL in isooctane from Sigma-Aldrich, was injected into the GC 2µL to determine each PCB holding time.

The residue of pesticide was identified based on comparison of the measured relative retention times to those of known standards. The levels were determined using an external standard approach that matched the peak heights of the samples with the corresponding peak heights of the reference standards for specified concentrations. The calculation was done within the detector's linear range. The peak heights which retention periods corresponded with the standards were then extrapolated to their individual calibration curves to determine the concentration.

Quality Assurance and Quality Control

The analytical system integrated quality control and assurance. Measures were taken to guarantee the reliability of the results. All glass apparatus used for research (extraction and cleaning) has been thoroughly rinsed with detergent and tap water. The glassware was cleaned with distilled water before being meticulously cleaned with analytical grade acetone and dried overnight in an oven set at 70 °C. They were taken out of the furnace and placed in dust-free cabinets after cooling. Routine analyses of procedural blanks, solvent blanks, spiking with internal standard (isodrin), sample replicates as well as samples of a Standard Reference Material for sediments (SRM) from the National Institute of Standards and Technology (NIST) were conducted to ensure the quality of the results of the organochlorine compounds (see Table 1). The target organic contaminants were not detected in both procedural and solvent blanks. Calibration curves were created by plotting mixed standards for seventeen organochlorine pesticides and seven PCBs with concentrations of 0.005, 0.01, 0.02, and 0.05 against the peak area. $R^2 = 0.995$ was found in the curve's region. Each set of samples was subjected to recalibration guidelines to ensure that the correlation coefficient remained over 0.99. The analytical procedure was optimised by spiking samples with 0.05 mg/kg internal standard (isodrin). Spiked samples were taken through the same technique as the field samples, and the OCPs and PCBs were quantified with good recoveries of 78–95% for OCPs and 80–94% for PCBs, indicating that the approach used was reproducible.

Table 1 Certified Reference materials results of sediment and LOD (µg/kg)

Compound	Sediment homogenate			
	SRM value	This study	SD	LOD
α-endosulphan	14.00	13.20	0.42	0.042
β-endosulphan	5.10	4.80	0.14	0.015
β-HCH	2.80	2.66	0.16	0.018
Endrin	7.10	5.54	0.15	0.041
Methoxychlor	NA	–	–	0.016
δ-HCH	NA	–	–	0.025
o,*p*-DDE	3.70	3.41	0.18	0.014
p,*p*-DDE	14.00	13.44	0.45	0.007
o,*p*-DDD	38.00	35.35	0.76	0.003
p,*p*-DDT	19.00	18.10	0.55	0.003
Heptachlor	2.00	1.88	0.13	0.028
PCB 18	51.00	47.94	2.10	0.024
PCB 28	80.80	74.34	1.70	0.016
PCB 52	79.40	78.10	4.30	0.023
PCB 101	73.40	66.10	2.50	0.034
PCB 138	62.10	49.68	4.70	0.048
PCB 153	74.00	69.56	2.90	0.072
PCB 180	44.30	40.75	1.20	0.087

SRM Standard reference material, *LOD* Limit of detection

Statistical Analysis

The Kolmogorov–Smirnov (K–S) analysis was performed to assess the normality of the data, and at the p value less than 0.05, findings were considered to be statistically significant. Descriptive statistics such as the mean and standard deviation (SD) were used for the levels of OCPs, and PCBs. Ranges were computed for the contaminants. One-way ANOVA was used to test the differences in the contaminants from the fish farms and controls where samples were obtained, with a Tukey's post hoc test.

Ecological Risk Assessments of the Pesticides in Sediment to Aquatic Species

Sediment quality values that provide a benchmark for evaluating the adverse effects in the aquatic ecosystem were used to calculate the sediment toxicity. Hong Kong Interim Sediment Quality Value (HK-ISQV), Canadian Sediment Quality Guidelines (CSQG), USEPA, and some published sediment quality guidelines (Eqani 2012) include Threshold Effect Concentrations (TECs) for freshwater, Probable Effect Concentrations (PECs), and Interim Sediment Quality Guidelines (ISQG). The Canadian Sediment Quality Guidelines (CSQG) uses the Threshold Effect Level (TEL) and Probable Effect Level (PEL), USEPA (1997) uses Effect Range Low (ERL) and Effect Range Median (ERM), while the Hong Kong Interim Sediment Quality Value (HK-ISQV) uses Lowest Effect Level (LEL) and the Severe Effect Level (SEL).

These benchmarks have been used as EPA Ghana does not have its own benchmarks. TEC (TEL, LEL, ERL, and CB-TEC) indicates concentrations at which pollution will start to be detected in sensitive aquatic life or concentrations at which adverse effects will not occur, while PECs (PEL, SEL, ERM, and CB-PEC) indicate concentrations above which adverse effects will occur in aquatic species. The range of OCPs and PCBs found in sediment samples from all four fish farms was compared to sediment quality parameters to determine the overall quality of sediments and the risk to aquatic species in the Volta Basin.

Results and Discussion

Levels of Organochlorine Pesticides in the Sediment

Table 2 presents the detected organochlorine pesticides in the sediments from the fish farms in the Volta Basin. In all, a total of eleven OCPs were found in the sediments, i.e. A (9 OCPs), B (10 OCPs), C (10 OCPs), D (11 OCPs), and control (6 OCPs).

Generally, the OCP residues in the sediment ranged between < LOD and 33.00 µg/kg in all the studied fish farms, including the control. Endrin in fish farm D had the highest mean concentration of 13.867 ± 8.716 µg/kg with 83% detection frequency. However, the same compound recorded the least level in fish farm B with a 20% detection frequency in the samples analysed. The OCPs, δ-HCH (7.72–8.80 µg/kg), *o*,*p*′-DDD (0.52–2.12 µg/kg), *α*-endosulphan (< LOD-2.00 µg/kg), *o*,*p*′-DDD (1.00–28.00 µg/kg), and heptachlor (0.234–0.472 µg/kg) were the predominant with frequency of detection 100%, 45%, 68%, 92%, and 25% in fish farms A, B, C, D, and control, respectively. All the eleven OCPs levels in the sediment from the farms were below the USEPA maximum residue levels.

In the present study, ∑DDTs (equivalent sum of *o*,*p*′-DDE, *p*,*p*′-DDE, *o*,*p*′-DDD, *p*,*p*′-DDT) in (µg/kg) in the fish farms were: 7.185 µg/kg, 3.483 µg/kg, 5.938 µg/kg, 12.263 µg/kg, and 0.163 µg/kg for fish farms A, B, C, D, and controls, respectively. The concentration of total DDT reached a maximum value at fish farm D (12.263 µg/kg wet mass) followed by farm A (7.185 µg/kg wet mass) and least in the controls (0.163 µg/kg wet mass). *o*,*p*-DDD (Fish farm A), *o*,*p*-DDD (fish farm B), *o*,*p*-DDE (fish farm C), *o*,*p*-DDD (fish farm D), and *o*,*p*-DDE(controls) were the predominant isomers detected, accounting for on average 45%, 45%, 67%, 93%, and 15% of detection frequency, respectively. *p*,*p*′-DDTs were detected in samples from fish farms C and D, but less frequently (8% of samples) in farm D. The higher amount of DDT in farm D in comparison with other farms is attributed to the fact that it is retained in most parts of the sediment and remains unchanged for a long period due to high stability, persistence, and resistance to degradation (Veljanoska-Sarafiloska et al. 2013). Additionally, the high ∑DDTs in fish farm D indicate predominant inputs of antifouling paints (with a high concentration of *p*,*p*-DDT as an active ingredient) from farm structures as well as maintenance of fishing boats (Li and Macdonald 2005; Guo et al. 2008; Yu et al. 2011), which leaches gradually into the water column. When the range of ∑DDTs (0.163–12.263 µg/kg) in the measured sediment was used to compare with studies within the world, it was found to be in the range of measured sediment in water bodies from Nigeria (Williams 2013), China (Sun et al. 2010; Zhao et al. 2010b), Pakistan (Eqani 2012), and Thailand (Sudaryanto et al. 2011).

The relative proportions of the parent DDT compound and its biological derivatives, DDD and DDE, can be utilised as benchmarks to evaluate potential contamination sources (Doong et al. 2002; Muhayimana et al. 2009). DDT can be metabolised into DDE and DDD in aerobic and anaerobic conditions, respectively. To measure the decomposition of the parent chemical and recent DDT input, different

Table 2 Concentration (µg/kg) of organochlorine pesticides in sediment from cage fish farms

OCPs	β-HCH	δ-HCH	*o,p′*-DDE	*p,p′*-DDE	*o,p′*-DDD	*p,p′*-DDT	Hept	Meth	Endrin	*α*-endos	*β*-endos
Fish farm A											
Mean	2.336	8.154	2.120	–	5.065	ND	3.985	8.253	< LOD	2.753	1.037
SD	0.231	0.414	1.659	–	1.796	–	1.479	5.252	–	1.262	0.701
Frequency	71	100	29	–	45	–	57	57	–	43	43
	∑HCH = 10.490		∑DDE = 3.779		∑DDD = 5.065	∑DDT = 7.185	∑Chlors = 12.238			∑END = 3.790	
Fish farm B											
Mean	2.152	0.710	0.710	1.480	1.293	ND	2.585	1.860	0.275	6.000	0.970
SD	0.052	0.410	0.410	0.646	0.793	–	1.639	1.612	0.092	1.414	0.415
Frequency	20	20	20	30	45	–	40	20	20	20	20
	∑HCH = 2.862		∑DDE = 2.190		∑DDD = 1.293	∑DDT = 3.483	∑Chlors = 4.445			∑END = 6.970	
Fish farm C											
Mean	2.362	1.793	1.012	1.113	2.010	1.803	ND	ND	5.000	1.555	1.103
SD	0.091	1.053	0.125	0.196	1.406	0.981	–	–	3.606	0.492	0.179
Frequency	33	33	67	33	56	44	–	–	33	68	33
	∑HCH = 4.155		∑DDE = 2.125		∑DDD = 2.010	∑DDT = 5.938	∑Chlors = ND			∑END = 2.658	
Fish farm D											
Mean	1.613	1.325	1.163	1.510	4.590	5.000	1.080	0.908	13.867	1.103	1.615
SD	0.321	0.148	0.142	1.010	3.735	0.505	0.505	0.271	8.716	0.714	1.186
Frequency	25	17	25	42	93	8	25	42	83	33	92
	∑HCH = 2.938		∑DDE = 2.673		∑DDD = 4.590	∑DDT = 12.263	∑Chlors = 1.988			∑END = 2.718	
Controls											
Mean	0.486	0.242	0.163	ND	ND	ND	0.301	0.243	ND	0.503	ND
SD	0.196	0.223	0.024	–	–	–	0.300	0.022	–	0.398	–
Frequency	20	15	15	–	–	–	25	20	–	15	–
	∑HCH = 0.728		∑DDE = 0.163			∑DDT = 0.163	∑Chlors = 0.544			∑END = 0.503	
USEPA MRL	30	40	40	40	40	50	30	50	40	50	40

LOD Limit of detection, *Hept.* heptachlor, *Meth.* methoxychlor, *endos.* endosulphan, USEPA (µg/kg)

suggestive ratios such as DDE + DDD)/∑DDTs, DDD/DDE, and, *p*,*p*-DDT/∑DDTs are extensively used (Sarkar et al. 2008). The ratio (DDE + DDD)/∑DDT > 0.5 is assumed to have undergone a long-term weathering process. If the DDD/DDE ratio is larger than 1, then the sediment is dominated by DDD, which is the result of anaerobic DDT degradation; if the ratio is less than 1, then the sediment was primarily influenced by DDE, which is the product of aerobic DDT breakdown (El Nemrn and El-Sadaawy 2016). The ratios of (DDE + DDD)/DDT in the current study ranged from 0.59 to 1.23. This indicated that the farm sediments had undergone a long-term weathering process. Furthermore, several DDD/DDE ratios in fish farm A and D sediments were higher than 1, indicating a significant DDD in the environment and anaerobic conditions in that region. However, farms B and C showed an elevated proportion of DDE, suggesting aerobic conditions prevailing in sediments from those farms. In addition, the *p*,*p*-DDT/∑DDT ratios were below 0.5 in sediment samples from farms C and D, indicating long-term degradation of *p*,*p*-DDT in the studied farms.

HCHs have been utilised as a broad-spectrum insecticide for agricultural purposes in the past. 55–80 per cent of α-HCH, 5–14 per cent of β-HCH, 8–15 per cent of γ -HCH, and 2–16 per cent of δ-HCH are found in HCHs (El Nemr et al. 2012). β-HCH and δ-HCH were detected in all farms and accounted for 100% of ∑HCH concentrations. The ∑HCH ranges from 0.728 µg/kg in the controls sediment to 10.263 µg/kg in fish farm A. Apart from fish farm A, the levels of β-HCH were higher than that of δ-HCH in all the farms. Two reasons could explain this phenomenon. Firstly, this can be attributed to the degradation of the α- and γ-isomers to the more stable β-HCH (Buah-Kwofie and Humphries 2017; Muralidharan et al. 2009). That probably explains why α- and γ-isomers were not detected in the farms. Secondly, β-HCH has low water solubility and vapour pressure and is relatively resistant to microbial degradation (Nguyen et al. 2020). The predominance of the β-HCH in the farms indicates no fresh input of the technical HCH. The reported levels of β-HCH in fish farms A, B, and C and delta-HCH for fish farm A for this study were similar to an earlier investigation by Koranteng (2015). The reported levels of β-HCH and δ-HCH in fish farm D are in agreement with that of Gbeddy et al. (2015) on the same Volta Lake. The reported β-HCH level for fish farm D in this study was similar to the 1.81 µg/kg and 1.54 µg/kg found by Ezemonye et al. (2015) and Kamel et al. (2015) in sediment from Ogbesse River in Nigeria and Manzala Lake in Egypt, respectively. The β-HCH levels found in fish farms A, B, and C in this investigation were comparable to those found on the Egyptian Mediterranean coast by El Nemr et al. (2012).

The range of ∑HCHs in the measured sediment was used to compare with studies within the world. The range was found to be in the range of measured ∑HCH in sediment from water bodies in Thailand (Sudaryanto et al. 2011) and Pakistan (Baqar et al. 2018). The range was, however, lower than measured sediment in water bodies from China (Sun et al. 2010; Zhao et al. 2010b).

Heptachlor concentration ranges from ND to 3.985 µg/kg, with the pesticides being predominant in fish farms A and accounted for about 57% of the sediment sampled. Heptachlor concentrations were generally higher in farms A and B than the other farms' sediment. This is expected as heptachlor is rapidly metabolised in sediments to the more stable epoxide (Buah-Kwofie and Humphries 2017). Heptachlor was not detected in farm C indicating the complete degradation of this compound. The range in sediment from farm A was not different from one observed by Gbeddy et al. (2015) on the same Volta Basin and Malik et al. (2011) in River Chenab, Pakistan. Heptachlor is hydrophobic and poorly soluble in water (Taiwo et al. 2019). This observation probably reflects its higher level in sediment from farm A. The heptachlor concentration recorded for fish farm D for the study was 1.080 µg/kg. This agrees with Ezemonye et al. (2015) and Kamel et al. (2015) in sediment from Ogbesse River in Nigeria and Manzala Lake in Egypt, respectively. Methoxychlor residues were highly detected in farm A (8.253 ± 5.252 µg/kg) followed by farm B (1.860 ± 1.612 µg/kg) with detection frequencies of 57% and 20%, respectively. The methoxychlor concentration found in fish farm A corresponds with that found by Musa et al. (2011) in the Yala/Nzoia River in Kenya's Lake Victoria Basin. ∑chlor concentrations from the study varied between.

ND and 12.238 µg/kg were significantly lower than concentrations from Lake Sibaya (34.0 ng/g), Kosi Bay (31.6 ng/g), and Lake St Lucia (35.1 ng/g) reported by Buah-Kwofie and Humphries (2017) from iSimangaliso Wetland Park in South Africa.

Aldrin, dieldrin, and endrin are pesticides in the cyclodiene family that are used to kill rodents, termites in the soil as well as grasshoppers. Due to their powerful insecticidal properties, these chemicals are commonly used for crop defence in cotton-growing areas, from where these harmful chemicals make their way to the aquatic environment. In this study, the average concentration of endrin for the four farms ranged from < LOD to 13.867 µg/kg. The range was within the measured sediment from Kala Shah in Pakistan (Syed and Malik 2011). Endrin was predominant in fish farms D and C and accounted for 83% and 33% of the sediment samples, respectively. The average level of endrin in this study for fish farm D complied with the level found by Musa et al. (2011) in Yala/Nzoia River within the Lake Victoria Basin, Kenya. In the environment, endrin breaks down to endrin ketone and endrin aldehyde through photodecomposition and microbial degradation (Bempah et al. 2011). This probably accounted for its low levels in fish farms A and B. The

low levels also suggest that the presence of this pesticide in the sediment was as a result of old inputs.

Concerning the endosulphans, α-endosulphan was higher than β-endosulphan in all the farms, although the water solubility of β-endosulphan is higher (Eqani 2012). This is not surprising given that the Ghanaian Environmental Protection Agency (EPA) restricted endosulphan use in the agricultural sector in December 2008 (Afful et al. 2010). Additionally, the technical mixture of endosulphan has higher rates of the α-endosulphan than its β-isomer, and that β-endosulphan is converted to α-endosulphan in environmental matrices (Schmidt et al. 2001). The range of α-endosulphan concentrations for the study was 1.555–6.000 µg/kg, which was similar to the range; (0.01–14.21 µg/kg) obtained by Kuranchie-Mensah et al. (2012) in the Nsawam stretch of the Densu River.

Levels of Polychlorinated Biphenyls in the Sediment

Six indicative PCB congeners (tri-18, 28, tetra-52, Penta-101, Hexa-153, and Hepta-180) were detected in the surface sediment from the fish farms, among which PCB 153 recorded the highest concentration of 3.328 ± 1.700 ng/g in farm D (Table 3). CB 18 and CB 180 tend to dominate the profiles in the sediment from all the farms. There were more congeners determined in the studied farm D as compared to the other farms. According to Russell et al. (2011), if the input of PCBs into the sediment of fish farms is due to the input of fish feed, the profile will be dominated by higher chlorinated PCBs, depending on the chemical composition of the fish feed. It was therefore unlikely that the PCBs were originating from the uneaten fish feed in the bottom of the cages. There was, however, a more significant proportion of tri-18 and hep-180 PCBs in the profile of all fish-farm sediments, probably suggesting mixed contributions from the atmosphere and particulate matter. The detection of some of the higher chlorinated PCBs (Penta-CB 101, Hexa-CB 153, and Hepta-CB or PCB 180) in some fish farms is near the hydro dam and urban areas, where these contaminants are most likely entering the aquatic system by surface run-off and direct effluent discharge. The higher chlorinated PCBs have a higher log Kow than the less chlorinated congeners, which may explain why those congeners have a higher concentration in the sediment samples. Because of their high log Kow, they have a higher affinity for adsorbing particulate matter, which leads to their build-up and deposition in farm sediment.

The sum of the six PCBs concentrations (∑PCBs) (ng/g) detected in sediment from the fish farms ranged from 0.172 ng/g to 6.202 ng/g, where the sum of the PCBs in fish farm D was significantly higher than the other farms. Meanwhile, the range of ∑PCBs (0.172–6.202 ng/g) in the measured sediment compared with other studies globally was within the range of ∑PCBs in Hong Kong coast (0.1–461 ng/g), Fenhe Reservoir and Watershed in China (ND–126.5 ng/g), and Haihe River in China (ND–253 ng/g) obtained by Wong et al. (2000), Li et al. (2012), and Zhao et al. (2010a), respectively. The range of the ∑PCBs for the study was, however, lower than the measured sediment of ∑PCBs in Pearl River in China (19.8–111 ng/g), Canada Basin (24–600 ng/g), and Donggang River in Taiwan (25.5–63.5 ng/g) established by Lai et al. (2015), Wang et al. (2011), and Hsieh et al. (2011), respectively.

Ecological Concerns of OCPs in Sediment

The potential risk of organochlorine and PCB compounds in sediments from fish farms in the Volta Basin was assessed based on the sediment quality guidelines (SQG) developed for freshwater. The levels of OCPs and PCBs in the sediment samples found in all four fish farms and the controls were compared with the guidelines on sediment quality (Table 4) to evaluate the potential quality of sediments and the possible risk to aquatic life in the Volta Basin.

Sum concentrations of ∑DDTs ranged from 0.163 to 12.263 µg/kg during the period of observations. Sum concentrations of DDT (∑DDTs) in fish farms A, C, and D exceeded the threshold effect concentrations (TECs) and the consensus-based threshold effect concentration (CB-TEC) except ∑DDT concentration in fish farm B and the

Table 3 Mean concentrations (ng/g) of indicator PCBs in the sediments from the fish farm

PCBs	Fish farm A Mean ± SD	Fish farm B Mean ± SD	Fish farm C Mean ± SD	Fish farm D Mean ± SD	Controls Mean ± SD
PCB 18	0.296 ± 0.0008	0.248 ± 0.1006	0.141 ± 0.0516	0.296 ± 0.0002	0.059 ± 0.0120
PCB 28	ND	ND	ND	0.400 ± 0.0758	ND
PCB 52	ND	ND	ND	0.066 ± 0.0138	ND
PCB 101	ND	0.494 ± 0.2479	0.382 ± 0.1305	ND	ND
PCB 138	ND	ND	ND	ND	ND
PCB 153	ND	0.475 ± 0.0799	0.394 ± 0.0505	3.328 ± 1.700	ND
PCB 180	0.492 ± 0.1682	0.401 ± 0.0999	0.354 ± 0.0755	2.112 ± 0.7008	0.113 ± 0.1050
∑PCBs	0.788 ± 0.1762	1.618 ± 0.6283	1.271 ± 0.3081	6.202 ± 2.4906	0.172 ± 0.187

Table 4 Ecotoxicological risk assessment of OCPs and PCB in sediment using sediment guidelines

	TECs				PECs				Pesticides concentration in sediment				
Pesticides	TEL	LEL	ERL	CB-TE	PEL	SEL	ERM	CB-PEC	FF_A	FF_B	FF_C	FF_D	CC
p,*p*′-DDE	1.42	5	2.2	6.75	6.75	190	27	31.3	–	1.48	1.113	1.510	–
p,*p*′-DDT	–	–	1	4.16	–	710	7	62.9	–	–	1.803	5.000	–
∑DDT	3.89	7	1.58	5.28	51.7	120	46.1	572	7.185	3.483	5.938	12.263	0.163
∑HCH	0.32	–	–	–	0.99	–	–	–	10.490	2.862	4.155	2.938	0.728
∑PCBs	34.1	–	22.7	–	277	–	180	–	0.788	1.618	1.271	6.202	0.172

FF_A Fish farm A, FF_B fish farm B, FF_C fish farm C, FF_D fish farm D, *CC* controls

controls that were less than TEL. None of the sediment samples exceeded consensus-based probable effect concentrations (CB-PECs) of 572 for ∑DDTs from all four areas. In all sediment samples, the values for p, p′-DDE surpassed the threshold effect level (TEL) for fish farms B and D, while p,p′-DDT surpassed the low effect range (ERL) for fish farm C and D in all sediment samples. However, in sediment samples from fish farm D, p,p′-DDT concentrations (µg/kg) surpassed the Census Based Threshold Effect Concentrations (CB-TECs) for this metabolite but were below the PECs. This comparison of the levels of DDTs with the appropriate sediment criteria for evaluating the contamination of DDTs and their metabolites shows that adverse biological effects are not likely to occur in the studied areas examined. Indoor residual spraying (IRS) of mosquitoes has been used in many parts of Ghana, especially in areas vulnerable to the epidemics of malaria. The situation tends to naturally present DDT and its metabolites in the aquatic environment, though it is no longer used in agricultural settings. As a result, routine steps must be implemented to minimise DDT pollution in aquaculture farms.

In the case of ΣHCH, all the mean concentrations of the sediment samples from the farms as well as the controls showed higher values than the threshold effect level (TEL) and the probable effect concentration (PEL), except the controls that recorded mean value less than the PEL. As shown, when the sums of HCHs were compared to the appropriate quality recommendations, the risk from HCHs was extremely high, except for HCHs from the controls. The levels of ∑HCHs should therefore be regularly monitored and primary sources established and abated.

PCBs can have harmful effects on aquatic creatures at an ERL value of 22.7 g/kg, according to Eqani (2012). The ERM value of 180 g/kg indicates that PCBs are highly likely to be hazardous to aquatic organisms. A PEL value of 277 g/kg can frequently have harmful effects on aquatic species, according to Canadian Sediment Quality Guidelines (CSQGs). At a TEL of 34.1 g/kg, on the other hand, the effects are minimal (CCME 1999). As a result, ∑PCB levels in sediments were lower than TEL, ERL, PEL, and ERM levels in this investigation, and hence, ∑PCB concentrations are unlikely to pose harm to the aquatic ecosystem.

Conclusions

Generally, eleven (11) OCPs were detected in the sediment, and the level ranged < LOD–33.0 µg/kg. The OCPs; -HCH, *o*,*p*′-DDD, *α*-endosulphan, *o*,*p*′-DDD, and heptachlor were predominant in fish farms A, B, C, D, and controls, respectively. The study revealed that the OCPs were from anthropogenic sources such as agricultural run-off, industrial and municipal waste. CB 18 and CB 180 were the predominant congeners in the entire sediment observed from the farms accounting for a detection frequency of 100% each. The levels of the OCPs and PCBs were below the MRL proposed by USEPA. Evaluating the ecological risk of the OCPs and PCBs in the surface sediment using the SQGs, it was evident that ∑HCH in the sediment from all the farms except the controls poses a health risk to the benthic organisms. Therefore, a comprehensive study followed by a remedial intervention is required to arrest the situation.

Funding No funding was received to assist with the preparation of this manuscript.

Data availability The datasets generated during the current study are not publicly available due to the University policy on data restriction until the Ph.D. thesis is completely examined. However, data are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Adeshina YA, Solomon A, Ademola AF (2019) Contamination levels of organochlorine and organophosphorous pesticide residues in water and sediment from River Owena, Nigeria. Curr J Appl Sci Technol. https://doi.org/10.9734/cjast/2019/v34i230119

Adu-Kumi S, Kawano M, Shiki Y, Yeboah PO, Carboo D, Pwamang J, Morita M et al (2010) Organochlorine pesticides (OCPs), dioxin-like polychlorinated biphenyls (dl-PCBs), polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo furans (PCDD/Fs) in edible fish from Lake Volta, Lake Bosumtwi and Weija Lake in Ghana. Chemosphere 81:675–684. https://doi.org/10.1016/j.chemosphere.2010.08.018

Afful S, Anim AK, Serfor-Armah Y (2010) Spectrum of organochlorine pesticide residues in fish samples from the Densu Basin. Res J Environ Earth Sci 2:133–138

Albanese S, De Vivo B, Lima A, Cicchella D, Civitillo D, Cosenza A (2010) Geochemical baselines and risk assessment of the Bagnoli brownfield site coastal sea sediments (Naples, Italy). J Geochem Explor 105:19–33. https://doi.org/10.1016/j.gexplo.2010.01.007

Antunes P, Gil O (2004) PCB and DDT contamination in cultivated and wild sea bass from Rio Aveiro, Portugal. Chemosphere 54:1503–1507. https://doi.org/10.1016/j.chemosphere.2003.08.029

Asante KA, Takahashi S, Itai T, Isobe T, Devanathan G, Muto M et al (2013) Occurrence of halogenated contaminants in inland and coastal fish from Ghana: levels, dietary exposure assessment and human health implications. Ecotoxicol Environ Saf 94:123–130. https://doi.org/10.1016/j.ecoenv.2013.05.008

Baqar M, Sadef Y, Ahmad SR, Mahmood A, Li J, Zhang G (2018) Organochlorine pesticides across the tributaries of River Ravi, Pakistan: human healthrisk assessment through dermal exposure, ecological risks, source fingerprints and spatio-temporal distribution. Sci Total Environ 618:291–305. https://doi.org/10.1016/j.scitotenv.2017.10.234

Barhoumi B, LeMenach K, Dévier MH, Megdiche YE, Hammammi B, Ameur WB, Hassine SB (2014) Distribution and ecological risk of polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs) in surface sediments from the Bizerte lagoon, Tunisia. Environ Sci Pollut Res 21:6290–6302. https://doi.org/10.1007/s11356-013-1709-7

Bempah CK, Archibold BK, Denutsui D, Asomaning J, Osei Tutu A (2011) Monitoring of pesticide residues in fruits and vegetables and related health risk assessment in Kumasi Metropolis, Ghana. J Environ Earth Sci 3:761–771

Bordajandi LR, Martin I, Abad E, Rivera J, Gonzalez MJ (2006) Organochlorine compounds (PCBS, PCDDS and PCDFS) in seafish and seafood from the Spanish Atlantic Southwest Coast. Chemosphere 64:1450–1457. https://doi.org/10.1016/j.chemosphere.2005.12.059

Botaro D, Torres JPM, Malm O, Rebelo MF, Henkelmann B, Schramm KW (2011) Organochlorine pesticides residues in feed and muscle of farmed Nile tilapia from Brazilian fish farms. Food Chem Toxicol 49:2125–2130. https://doi.org/10.1016/j.fct.2011.05.027

Botwe BO, Ntow WJ, Nyarko E (2012) Pesticides contamination in groundwater and streams draining vegetable plantations in the Ofinso District, Ghana. Soil Health Land Use Manag. https://doi.org/10.5772/29564

Buah-Kwofie A, Humphries MS (2017) The distribution of organochlorine pesticides in sediments from iSimangaliso Wetland Park: ecological risks and implications for conservation in a biodiversity hotspot. Environ Pollut 229:715–723. https://doi.org/10.1016/j.envpol.2017.07.031

CCME (1999) Canadian Council of Ministers of the Environment), Canadian sediment quality guidelines for the protection of aquatic life: summary tables. Canadian environmental guidelines, Winnipeg, Manitoba

Darko G, Akoto O, Oppong C (2008) Persistent organochlorine pesticide residues in fish, sediments and water from Lake Bosomtwi, Ghana. Chemosphere 72:21–24. https://doi.org/10.1016/j.chemosphere.2008.02.052

Doong RA, Sun YC, Liao PL, Peng CK, Wu SC (2002) Distribution and fate of organochlorine pesticide residues in sediments from the selected rivers in Taiwan. Chemosphere 48(2):237–246. https://doi.org/10.1016/s0045-6535(02)00066-8

Easton MDL, Luszniak D, Von der Geest E (2002) Preliminary examination of contaminant loadings in farmed salmon, wild salmon and commercial salmon feed. Chemosphere 46:1053–1074. https://doi.org/10.1016/S0045-6535(01)00136-9

El Nemr A, El-Sadaawy MM (2016) Polychlorinated biphenyl and organochlorine pesticide residues in surface sediments from the Mediterranean Sea (Egypt). Int J Sedim Res 31(1):44–52. https://doi.org/10.1016/j.ijsrc.2013.03.001

El Nemr A, Moneer AA, Khaled A, El-Sikaily A (2012) Contamination and risk assessment of organochlorines in surface sediments of Egyptian Mediterranean coast. Egypt J Aquat Res 38:7–21. https://doi.org/10.1016/j.ejar.2012.08.001

Elegbede LO, Kies F, Omolara LAA, Rashidat SD, Hakeem EB et al (2015) Effect of water quality characteristics on fish population of the Lake Volta, Ghana. Environ Anal Toxicol 5:317. https://doi.org/10.4172/2161-0525.1000317

Eqani SAMAS (2012) Organochlorine residues in the riverine ecosystem of Pakistan. Doctoral dissertation, Quaid-i-Azam University Islamabad, Pakistan

Ezemonye L, Ogbeide O, Tongo I (2015) Distribution and ecological risk assessment of pesticide residues in surface water, sediment and fish from Ogbesse River, Edo State, Nigeria. J Environ Chem Ecotoxicol 7:20–30. https://doi.org/10.5897/JECE2014.0337

Gbeddy G, Yeboah P, Carboo D, Doamekpor L, Afful S, Nartey V et al (2012) Organochlorine pesticide residues in African catfish muscle, Nile tilapia muscle and gills from the middle Volta basin, Kpando Torkor, Ghana and their potential health risks to humans. Elixir Agric 49:9724–9730

Gbeddy G, Glover E, Doyi I, Frimpong S et al (2015) Assessment of organochlorine pesticides in water, sediment, African cat fish and Nile tilapia, consumer exposure and human health implications, Volta Lake. Ghana Environ Anal Toxicol 5:297. https://doi.org/10.4172/2161-0525.1000297

Guo Y, Meng XZ, Tang HL, Zeng EY (2008) Tissue distribution of organochlorine pesticides in fish collected from the Pearl River Delta, China: implications for fishery input source and bioaccumulation. Environ Pollut 155:150–156. https://doi.org/10.1016/j.envpol.2007.10.025

Hites RA, Foran JA, Schwager SJ, Knuth BA, Hamilton MC, Carpenter DO (2004) Global assessment of polybrominated diphenyl ethers in farmed and wild salmon. Environ Sci Technol 38:4945–4949. https://doi.org/10.1021/es049548m

Hsieh CY, Lee CL, Kuo WC, Chen TC, Wang YK, Yu BY (2011) PCBs in Donggang river watershed sediments, Taiwan. J Environ Sci Health Part A 46:480–489. https://doi.org/10.1080/10934529.2011.551727

Kaipper BI, Madureira LA, Corseuil HX (2001) Use of activated charcoal in a solid-phase extraction technique for analysis of pesticide residues in tomatoes. J Braz Chem Soc 12:514–518. https://doi.org/10.1590/s0103-50532001000400012

Kamel E, Moussa S, Abonorag MA, Konuk M (2015) Occurrence and possible fate of organochlorine pesticide residues at Manzala Lake in Egypt as a model study. Environ Monit Assess 187:4161. https://doi.org/10.1007/s10661-014-4161-3

Kanzari F, Syakti AD, Asia L, Malleret L, Piram A, Mille G, Doumenq P (2014) Distributions and sources of persistent organic pollutants (aliphatic hydrocarbons, PAHs, PCBs and pesticides) in surface sediments of an industrialised urban river(Huveaune), France. Sci Total Environ 478:141–151. https://doi.org/10.1016/j.scitotenv.2014.01.065

Karikari AY (2017) Assessment of environmental impacts of cage aquaculture on Lake Volta of Ghana. Doctoral thesis, University of Science and Technology, Kumasi, Ghana

Kelly BC, Ikonomou MG, Blair JD, Morin AE, Gobas FAPC (2007) Food web-specific biomagnification of persistent organic pollutants. Science 317:236–239. https://doi.org/10.1126/science.113827

Koranteng SS (2015) Pesticides in environmental compartments of Afram arm of the Volta Basin in Ghana. Doctoral thesis, University of Ghana

Kuranchie-Mensah H, Atiemo SM, Palm LMND, Blankson-Arthur S, Tutu A, Fosu P (2012) Determination of organochlorine pesticide residue in sediment and water from the Densu river basin, Ghana. Chemosphere 86:286–292. https://doi.org/10.1016/j.chemosphere.2011.10.031

Lai Z, Li X, Li H, Zhao L, Zeng Y, Wang C et al (2015) Residual distribution and risk assessment of polychlorinated biphenyls in surface sediments of the Pearl River Delta, South China. Bull Environ Contam Toxicol 95:37–44. https://doi.org/10.1007/s00128-015-1563-z

Li YF, Macdonald RW (2005) Sources and pathways of selected organochlorine pesticides to the Arctic and the effect of pathway divergence on HCH trends in biota: a review. Sci Total Environ 342:87–106. https://doi.org/10.1016/j.scitotenv.2004.12.027

Li WH, Tian YZ, Shi GL, Guo CS, Feng YC, Yue XP (2012) Source and risk assessment of PCBs in sediments of Fenhe reservoir and watershed, China. J Environ Monit 14:1255–1262. https://doi.org/10.1039/c2em10983b

Maule AG, Gannam AL, Davis JW (2007) Chemical contaminants in fish feeds used in federal salmonid hatcheries in the USA. Chemosphere 67:1308–1315. https://doi.org/10.1016/j.chemosphere.2006.11.029

Malik RN, Rauf S, Mohammad A, Eqani SAMAS, Ahad K (2011) Organochlorine residual concentrations in cattle egret from the Punjab Province, Pakistan. Environ Monit Assess 173:325–341. https://doi.org/10.1007/s10661-010-1390-y

McKee MJ, Kromrey GB, May TW, Orazio CE (2008) Contaminant levels in rainbow trout, *Oncorhynchus mykiss*, and their diets from Missouri Coldwater Hatcheries. Bull Environ Contam Toxicol 80:450–454. https://doi.org/10.1007/s00128-008-9374-0

Montuori P, Cirillo T, Fasano E, Nardone A, Esposito F, Triassi M (2014) Spatial distribution and partitioning of polychlorinated biphenyl Sarno River and Estuary, Southern Italy. Environ Sci Pollut Res 21:5023–5035. https://doi.org/10.1007/s11356-013-2419-x

Muhayimana AS, Shihua Q, Yinghui W, Xiangsheng K, Owago OJ, Junpeng Z (2009) Distribution and sources of organochlorine pesticides (OCPs) in Karst Cave, Guilin, China. J Am Sci 5(1):35–43

Muralidharan S, Dhananjayan V, Jayanthi P (2009) Organochlorine pesticides in commercial marine fishes of Coimbatore, India and their suitability for human consumption. Environ Res 109:15–21. https://doi.org/10.1016/j.envres.2008.08.006

Musa S, Gichuki JW, Raburu PO, Aura CM (2011) Organochlorine and organophosphorus pesticide residues in water and sediment from Yala/Nzoia River within Lake Victoria Basin, Kenya. J Ecol Nat Environ 3:392–399. https://doi.org/10.5897/JENE.9000078

Navas JM, Merino R, Jiménez B, Rivera J, Abad E, Zanuy S, Carrillo M (2005) Organochlorine compounds in liver and concentrations of vitellogenin and 17β-estradiol in plasma of sea bass fed with a commercial or with a natural diet. Aquat Toxicol 75:306–315. https://doi.org/10.1016/j.aquatox.2005.07.014

Nguyen VH, Smith SM, Wantala K, Kajitvichyanukul P (2020) Photocatalytic remediation of persistent organic pollutants (POPs): a review. Arab J Chem 13:8309–8337. https://doi.org/10.1016/j.arabjc.2020.04.028

Ntow WJ (2005) Pesticide residues in Volta Lake, Ghana. Lakes Reserv Res Manag 10:243–248. https://doi.org/10.1111/j.1440-1770.2005.00278.x

Perugini M, Manera M, Tavoloni T, Lestingi C, Pecorelli I, Piersanti A (2013) Temporal trends of PCBs in feed and dietary influence in farmed rainbow trout (*Oncorhynchus mykiss*). Food Chem 141:2321–2327. https://doi.org/10.1016/j.foodchem.2013.05.062

Russell M, Robinson CD, Walsham P, Webster L, Moffat CF (2011) Persistent organic pollutants and trace metals in sediments close to Scottish marine fish farms. Aquaculture 319:262–271. https://doi.org/10.1016/j.aquaculture.2011.06.030

Sakan S, Ostojić B, Đorđević D (2017) Persistent organic pollutants (POPs) in sediments from river and artificial lakes in Serbia. J Geochem Explor 180:91–100. https://doi.org/10.1016/j.gexplo.2017.06.008

Sarkar SK, Bhattacharya BD, Bhattacharya A, Chatterjee M, Alam A, Satpathy KK, Jonathan MP (2008) Occurrence, distribution and possible sources of organochlorine pesticide residues in tropical coastal environment of India: an overview. Environ Int 34(7):1062–1071. https://doi.org/10.1016/j.envint.2008.02.010

Schmidt WF, Bilboulian S, Rice CP, Fettinger JC, McConnell LL, Hapeman CJ (2001) Thermodynamic, spectroscopic, and computational evidence for the irreversible conversion of β-to α-endosulfan. J Agric Food Chem 49:5372–5376. https://doi.org/10.1021/jf0102214

Shaw SD, Berger ML, Brenner D, Carpenter DO, Chia-Swee Hong CS, Kannan K (2008) Polybrominated diphenyl ethers (PBDEs) in farmed and wild salmon marketed in the Northeastern United States. Chemosphere 71:1422–1431. https://doi.org/10.1016/j.chemosphere.2008.01.030

Solomon A (2016) Determination of organochlorine pesticide residues in water and sediment samples from selected areas of River llaje, Nigeria. Chem Sci Int J 11:1–6. https://doi.org/10.9734/ACSJ/2016/22274

Sun J, Feng J, Liu Q, Li Q (2010) Distribution and sources of organochlorine pesticides (OCPs) in sediments from upper reach of Huaihe River, East China. J Hazard Mater 184:141–146. https://doi.org/10.1016/j.jhazmat.2010.08.016

Sudaryanto A, Isobe T, Takahashi S, Tanabe S (2011) Assessment of persistent organic pollutants in sediments from Lower Mekong River Basin. Chemosphere 82:679–686. https://doi.org/10.1016/j.chemosphere.2010.11.004

Syed JH, Malik RN (2011) Occurrence and source identification of organochlorine pesticides in the surrounding surface soils of the Ittehad Chemical Industries Kalashah Kaku, Pakistan. Environ Earth Sci 62:1311–1321. https://doi.org/10.1007/s12665-010-0618-z

Taiwo AM (2019) A review of environmental and health effects of organochlorine pesticides residues in Africa. Chemosphere 220:1126–1140. https://doi.org/10.1016/j.chemosphere.2019.01.001

Veljanoska-Sarafiloska EM, Jordanoska M, Stafilov T (2013) Presence of DDT metabolites in water, sediment and fish muscle tissue from Lake Prespa, Republic of Macedonia. J Environ Sci Health B 48:548–558. https://doi.org/10.1080/03601234.2013.774879

Wang HS, Du J, Leung HM, Leung AOW, Liang P, Giesy JP et al (2011) Distribution and source apportionments of polychlorinated biphenyls (PCBs) in mariculture sediments from the Pearl River Delta, South China. Mar Pollut Bull 63:516–522. https://doi.org/10.1016/j.marpolbul.2011.02.009

Williams AB (2013) Residue analysis of organochlorine pesticides in water and sediments from Agboyi Creek, Lagos. Afr J Environ Sci Technol 7:267–273. https://doi.org/10.5897/AJEST12.214

Wong CKC, Yeung HY, Cheung RYH, Yung KKL, Wong MH (2000) Ecotoxicological assessment of persistent organic and heavy metal contamination in Hong Kong coastal sediment. Arch Environ Contam Toxicol 38:486–493. https://doi.org/10.1007/s002449910064

Wong MH, Leung AOW, Chan JKY et al (2005) A review on the usage of POP pesticides in China, with emphasis on DDT Loadings in human milk. Chemosphere 60:740–752. https://doi.org/10.1016/j.chemosphere.2005.04.028

Yu H, Zhang YBZ, Giesy JP, Zeng EY (2011) Persistent halogenated compounds in aquaculture environments of South China: implications for global consumers' health risk via fish consumption. Environ Int 37:1190–1195. https://doi.org/10.1016/j.envint.2011.04.012

Zhao L, Hou H, Zhou Y, Xue N, Li H, Li F (2010a) Distribution and ecological risk of polychlorinated biphenyls and organochlorine pesticides in surficial sediments from Haihe River and Haihe Estuary Area, China. Chemosphere 78(10):1285–1293. https://doi.org/10.1016/j.chemosphere.2009.12.007

Zhao Z, Zhang L, Wu J, Fan C, Shang J (2010b) Assessment of the potential mutagenicity of organochlorine pesticides (OCPs) in contaminated sediments from Taihu Lake, China. Mutat Res Genet Toxicol Environ Mutagen 696:62–68. https://doi.org/10.1016/j.mrgentox.2009.12.013