Vol 6 No 4 December 2025 Pages 16-22 e-ISSN 2708-5694

Journal of Agriculture, Food and Environment (JAFE)

Journal Homepage: https://journal.safebd.org/index.php/jafe

https://doi.org/10.47440/JAFE.2025.6403

Research Article

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Bioaccumulated polychlorinated biphenyls (PCBs) levels in three aquatic fauna specimens obtained from a continually perturbed fresh water mangrove swamp location in Southern Nigeria

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Article History

Received: 07 October 2025

Accepted: 30 November 2025

Published: 31 December 2025

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Keywords

Aquatic fauna, Bioaccumulated PCBs, Crab, Falcorp swamp, Mudskipper, Periwinkle

How to cite: Odigie O, Olomukoro JO, Obayagbona ON 2025: Bioaccumulated polychlorinated biphenyls (PCBs) levels in three aquatic fauna specimens obtained from a continually perturbed fresh water mangrove swamp location in Southern Nigeria. J. Agric. Food Environ. 6(4): 16-22.

A B S T R A C T

This study evaluated the presence of 15 polychlorinated biphenyls (PCB) congeners in three aquatic faunal organisms; mudskipper (*Periopthalmus barbarous*), crab (*Sesarma alberti*) and periwinkle (*Tympanotonus fuscatus*) obtained from different sampling points in the Falcorp mangrove swamp located in Delta State, Nigeria. Gas chromatography was used in the determination of PCB concentrations in the faunal specimens. The resulting PCB data obtained were analyzed using descriptive and inferential statistical tests. The PCB 2,2',3,3',4,5',6,6'-Octachlorobiphenyl was not detected in any sample while the observed maximal values were: mudskipper - 2,2',3,3',4,4',6-Heptachlorobiphenyl (0.1794mg/kg); crab - 2,3,3',4,4',5',6- Heptachlorobiphenyl and 2,2',3,3',4,4',6 -Heptachlorobiphenyl (0.1107mg/kg); and 4,4'-Dichlorobiphenyl (0.0402mg/kg). The detection of bioaccumulated PCBs in the respective aquatic fauna has raised important inquires pertaining to likely long-term negative effects of PCB contamination on ecosystem health as well as public health safety as these aquatic faunae are commonly consumed among residents living within the vicinity of the swamp. Results of this research has also highlighted an urgent need for continuous environmental monitoring by public and concerned stakeholders as well as an increased stringent regulatory oversight of the release of persistent pollutants such as PCBs into different environmental matrices particularly mangrove wetlands.

INTRODUCTION

The group of synthetic organic chemical moieties known as polychlorinated biphenyls (PCBs) has been widely used across various industrial sectors due to their properties as electrical insulators, their chemical stability, as well as their thermal resistance (Montano *et al*., 2022). PCBs are known to consist of 209 different congeners that differ in their respective chlorination levels (Othman *et al*., 2022). With reference to increased evidence pertaining to their environmental persistence, ability to bioaccumulate, and harmful effects on both ecosystems as well as human health, numerous national Governments have prohibited or heavily restricted their usage, despite their extensive application (Montano *et al*., 2022).

PCBs are released into the environment through various means, including improper disposal of PCB-containing equipment, leaks or accidental spills during production and use, and combustion processes. Once they enter the environment, these substances exhibit high chemical stability, preventing physical, chemical, or biological degradation from occurring (Zhu *et al*., 2022). As a result, PCBs can remain in soil, water, and air for extended periods, often traveling long distances through the atmosphere (Ijenyo and Okoro, 2023). Furthermore, due to their hydrophobic nature, PCBs strongly bind to organic matter, facilitating their accumulation in sediments and living organisms (Kaifie *et al.*, 2020).

Aquatic ecosystems are particularly vulnerable to contamination because of the risks posed by industrial discharges, urban runoff, and atmospheric deposition that can introduce PCBs into water bodies (Ngoubeyou *et al.*, 2022). In these habitats, PCBs are known to gradually seep into the water column and accumulate in the tissues of aquatic organisms as well as sediments wherein they can remain for many years. This bioaccumulation process is known to allow PCBs to move through various trophic levels, leading to biomagnification across different trophic levels (Montano *et al.*, 2022).

The Niger Delta ranks among the largest wetlands globally, providing a habitat for diverse flora and fauna and serving as a crucial hub for Nigeria's oil and gas industry, as such holding noteworthy ecological and economic importance (Olufemi *et al.*, 2020). However, this region has become a focal point for environmental degradation due to industrial activities such as transportation, oil drilling, and refining (Odigie and Olomukoro, 2020). PCBs are a notable group persistent chemical contaminants in the area, detected in sediments, water, flora and fauna respectively. Studies have indicated that elevated levels of PCBs are present in the Niger Delta region particularly near urban centers, oil installations, and industrial locations (Iwegbue *et al.*, 2020; Odigie and Olomukoro, 2020a; Ossai *et al.*, 2023). The accumulation of PCBs in these organisms can pose a health risk to fish and other aquatic species, as well as to the communities that are reliant on them as a source of both monetary income and dietary protein respectively.

Mangrove ecosystems play crucial roles such as carbon storage, coastal protection, and providing breeding grounds for aquatic species, making them among the most productive and biologically diverse habitats. In the Niger Delta, mangrove habitats are vital for supporting local livelihoods and preserving biodiversity (Aransiola *et al.*, 2024). However, these ecosystems are highly susceptible to pollution, particularly from PCBs. At the individual level, PCBs can disrupt immune responses, reproductive systems, and endocrine functions in aquatic organisms (Odigie and Olomukoro, 2020b).

Extended exposure to PCBs has been linked to reduced fertility, heightened susceptibility to diseases, and developmental abnormalities (Montano *et al.*, 2022). For instance, PCBs can disrupt hormonal balance in fish, inhibit growth, and lead to tissue bioaccumulation, all of which can influence predator-prey relationships within the ecosystem (Chris and Anyanwu, 2022). At the ecosystem level, PCBs contribute to habitat degradation by altering both the composition and dynamics of mangrove ecosystems. As they accumulate in mangrove sediments, PCBs can serve as a long-lasting source of pollution that adversely affects benthic organisms and the overall health of the ecosystem (Ukwu *et al.*, 2023).

Fish, crabs and other aquatic species often serve as primary sources of protein and income for communities residing near these habitats (Aransiola *et al.*, 2024). Individuals who consume seafood contaminated with PCBs face the risk of bioaccumulation, which could result to the development of negative health outcomes such as; cancer, neurological conditions as well as disruptions to the endocrine system (Ukwu *et al.*, 2023).

The examined three representative aquatic species: *Tympanotonus fuscatus* (periwinkle), *Periopthalmus barbarous* (mudskipper), and *Sesarma alberti* (West African Sesarmid Crab)—are commonly found throughout the freshwater mangrove swamps in the Niger Delta region of Southern Nigeria (Odigie and Olomukoro, 2021). The study focuses on the Falcorp mangrove swamp, which is located in the western part of the Niger Delta's freshwater mangrove belt. The swamp has been affected by various human activities, including the dumping of petrochemical waste from the proximal located Warri petroleum refinery and vandalization of oil pipelines as well as oil bunkering activities (Odigie and Olomukoro, 2021).

The suitability of utilizing these aquatic faunae as bio-indicators of heavy metal bioaccumulation was demonstrated by Odigie and Olomukoro (2021). This trend necessitated a follow up study focusing on the utilization of these representative fauna as potential bio-indicators of PCB bioaccumulation within the anthropogenically perturbed mangrove habitat. Additionally, seasonal variations in the biota related PCB levels were also evaluated.

MATERIALS AND METHODS

Study area and collection of aquatic fauna

As previously indicated by Odigie and Olomukoro (2020a) and Odigie and Olomukoro (2020b), the Falcorp Mangrove Swamp which is the study area is located in Warri South Local Government Area (LGA) of southern Delta State, Nigeria. The mapped geo referenced locational details as well as other locational attributes of the swamp has been previously described by Odigie and Olomukoro (2020a) and Odigie and Olomukoro (2020b).

With respect to this study, five sampling stations earlier described by Odigie and Olomukoro (2020a) and Odigie and Olomukoro (2021) were revisited between February 2022 to July 2023. As previously detailed by Odigie and Olomukoro (2020a) as well as Odigie and Olomukoro (2021), the distance between each of these stations was about 600 m. The geo referenced co-ordinates of the respective sampling locations have been earlier described by Odigie and Olomukoro (2020a) and Odigie and Olomukoro (2021).

At each station, duplicate samples each of mudskipper, periwinkle and crab were collected with the aid of highly skilled local fishermen residing around the swamp as previously reported by Odigie and Olomukoro (2021). The collected faunal specimens were humanely handled and transported to the laboratory for PCB analysis.

Analytical procedures for PCB detection

Each of the three animal specimens was homogenised separately (around 2 g d.w.), extracted using a 50:50 (v/v) acetone: hexane combination, and then sonicated in an ultrasonic bath (2×3 ml + 8×2 ml, 90 W, 15 min) before being subjected to repeated centrifugation for 10 mins at 2,500 rpm. The combined extracts were dissolved in hexane after being dried off by an argon stream (1.5 ml). A 0.5 cc aliquot of the solution was run through each of the three columns which contained Florisil (1 g, bed 9×30 mm) with the objective of lipid elimination. Earlier, hexane (2×1.5 ml

+ 2×1 ml) had been used to condition each of these columns. Also, 3×1 ml + 0.5 ml of acetonitrile was used to elute PCBs. The acetonitrile portions were combined and dried *via* evaporation beneath a stream.

The PCB content of the respective faunal extract was determined with the aid of a Gas Chromatography (GC) system equipped with an Electron Capture Detector (ECD). The name and the operating conditions of the GC column have previously been described by Obayagbona *et al.* (2025). Fifteen (15) PCB congeners that were to be detected for each sample included; 4,4'-Dichlorobiphenyl (1-chloro-4-(4-chlorophenyl)benzene), 2,3,4,4'5-Pentachlorobiphenyl, 2,2',3,3',4,5-Hexachlorobiphenyl, 2,2',3,4,4',5-Hexachlorobiphenyl, 2,2',4,4',5,5'-Hexachlorobiphenyl, 2,2',3,3',4,4',6-Heptachlorobiphenyl, 2,2',3,4,4',5',6-Heptachlorobiphenyl, 2,2',3,4,5,5',6-Heptachlorobiphenyl, 2,3,3',4,4',5,5'-Heptachlorobiphenyl, 2,3,3',4,4',5',6-Heptachlorobiphenyl, 2,2',3,3',4,5',6,6'-Octachlorobiphenyl, 2,2',3,3',4,5,5',6'-Octachlorobiphenyl, 2,2',3,4,4',5,5',6-Octachlorobiphenyl, 2,2',3,3',4,4',5,5',6-Nonachlorobiphenyl and Decachlorobipheny (2,2',3,3',4,4',5,5',6,6'-decachlorobiphenyl). The concentration of each PCB in a sample was calculated directly from the GC-ECD using the Data Analysis Software as well as formula earlier described by Noriega *et al.* (2004).

Statistical analyses

Descriptive statistics were used to summarize the PCB data derived for the respective sampled station. Additionally, the mean PCB data sets were subjected to student T test and Kruskal Wallis non parametric statistical test using SPSS 20.0 software. This was done to determine if the observed differences in the data sets were statistically significant at 95% and 99% probability levels. Multivariate analysis of the data sets encompassing PCA and cluster tests was conducted using PAST 4.03 statistical software.

RESULTS

PCBs in aquatic biota

Table 1 revealed the mean bioaccumulated PCB concentrations for the three aquatic faunal species. The observed differences between the various PCB congeners in the tissues of each of the animal specimens was very significant (*P<0.001*) (Table 1).

Table 1: Concentrations of biota associated PCBs

Parameter (Unit: mg/Kg)	Mudskipper	Crab	Periwinkle	P-value	Significance
	$\bar{X}$±S.E	$\bar{X}$±S.E	$\bar{X}$±S.E		
1-chloro-4-(4-chlorophenyl)benzene	0.0409±0.0024[b]	0.0331±0.0022[a]	0.0402±0.0021[b]	0.037	*P<0.05**
2,3,4,4'5-Pentachlorobiphenyl	0.0388±0.0044	0.0244±0.0037	0.0327±0.0116	0.403	*P>0.05*
2,2',3,3',4,5-Hexachlorobiphenyl	0.0147±0.0022[a]	0.0089±0.0009[b]	0.0063±0.0012[b]	0.002	*P<0.01***
2,2',3,4,4',5-Hexachlorobiphenyl	0.0415±0.0190[b]	0.0517±0.0105[a]	0.0127±0.0008[c]	0.029	*P<0.05**
2,2',4,4',5,5'-Hexachlorobiphenyl	0.0023±0.0000	0.0000±0.0000	0.0053±0.0007	0.152	*P>0.05*
2,2',3,3',4,4',6-Heptachlorobiphenyl	0.1794±0.0697	0.1107±0.0317	0.0000±0.0000	-	-
2,2',3,4,4',5',6-Heptachlorobiphenyl	0.0394±0.0000	0.0071±0.0028	0.0062±0.0041	0.370	*P>0.05*
2,2',3,4,5,5',6-Heptachlorobiphenyl	0.0394±0.0000[a]	0.0071±0.0028[b]	0.0062±0.0041[b]	0.020	*P<0.05**
2,3,3',4,4',5,5'-Heptachlorobiphenyl	0.0060±0.0025	0.0000±0.0000	0.0005±0.0000	0.551	*P>0.05*
2,3,3',4,4',5',6-Heptachlorobiphenyl	0.1793±0.0697[a]	0.1107±0.0317[a]	0.0000±0.0000[b]	0.020	*P<0.05**
2,2',3,3',4,5',6,6'-Octachlorobiphenyl	ND	ND	ND	-	-
2,2',3,3',4,5,5',6'-Octachlorobiphenyl	0.0313±0.0018[b]	0.0507±0.0084[a]	0.0062±0.0011[c]	0.005	*P<0.01***
2,2',3,4,4',5,5',6-Octachlorobiphenyl	0.0271±0.0011[a]	0.0039±0.0013[b]	0.0000±0.0000[c]	0.000	*P<0.001****
2,2',3,3',4,4',5,5',6-Nonachlorobiphenyl	0.0068±0.0024	0.0011±0.000	0.0000±0.0000	0.539	*P>0.05*
2,2',3,3',4,4',5,5',6,6'-decachlorobiphenyl	0.0031±0.0008	0.0022±0.0010	0.0034±0.0009	0.699	*P>0.05*

Note: *P>0.05*-There is no significant difference, ND: Not detected, *P<0.01*-There is a high significant difference**, P<0.001-The significant difference is high ***, *P<0.05*- There is a significant difference*

Seasonal variations in PCB concentrations

The seasonal fluctuations of bioaccumulated PCBs in the three aquatic faunal species are depicted in Figures 1 to 3. For the examined mudskipper tissues, it was revealed that during the dry season, 2,2',3,4,4',5',6-Heptachlorobiphenyl had the highest value (0.19 mg/kg) and 2,2',4,4',5,5'-Hexachlorobiphenyl and 2,2'3,4,4',5,5',6-Heptachlorobiphenyl had the lowest value (0.01 mg/kg). Similarly, it was found that during the wet season, 2,2',3,4,4',5',6-Heptachlorobiphenyl had the highest value (0.17 mg/kg) and 2,2',4,4',5,5'-Hexachlorobiphenyl and 2,2'3,4,4'5,5',6-Heptachlorobiphenyl had the lowest value (0.00 mg/kg).

For the periwinkle samples, it was revealed that during the dry season, 2,2',3,4,4',5',6-Heptachlorobiphenyl had the highest value (0.19 mg/kg) while 2,2',3,3',4,4',5,5'-Hexachlorobiphenyl, 2,2'3,3',4,4',6,6', 6-Heptachlorobiphenyl, 2,3,3'4,4',5,5'-Heptachlorobiphenyl, 2,3,3',4,4',5,5'-Heptachlorobiphenyl, and 2,2',3,3',4,5',6,6'-Octachlorobiphenyl had the lowest value (0.00 mg/kg). Likewise, it was found that during the wet season, 2,2',3,4,4',5',6-Heptachlorobiphenyl had the highest value (0.06 mg/kg) while 2,2',3,3',4,4',5,5'-Hexachlorobiphenyl, 2,2'3,3',4,4',6-Heptachlorobiphenyl, 2,3,3'4,4',5,5'-Heptachlorobiphenyl, 2,3,3',4,4',5,5'-Heptachlorobiphenyl, 2,3,3',4,4',5,5'-Heptachlorobiphenyl, 2,3,3',4,4',5,5'-Heptachlorobiphenyl, and 2,2',3,3',4,5',6,6'-Octachlorobiphenyl had the lowest value (0.00 mg/kg).

For the examined crab specimens, it was observed that in the dry season, the highest value (0.05 mg/kg) was observed for 2, 3,4,4',5'-Pentachlorobiphenyl and the lowest (0.00 mg/kg) values were observed for 2,2',3,3'4,4',5',6-Heptachlorobiphenyl, 2,2'3,4,4',5,5',6-Heptachlorobiphenyl, 2,2',3'4,4',5,5'-Heptachlorobiphenyl, 2,2'3,3',4,5'6,6'-Octachlorobiphenyl and 2,2',3,4,4',5,5',6,-Octachlorobiphenyl. Similarly, it was observed that in the wet season, the highest value (0.03 mg/kg) was observed for

4,4'-Dichlorobiphenyl and the lowest (0.00 mg/kg) value was documented for 2,2',3,3'4,4',5',6-Heptachlorobiphenyl, 2,2'3,4,4',5,5',6-Heptachlorobiphenyl, 2,2',3'4,4',5,5'-Heptachlorobiphenyl, 2,2'3,3',4,5'6,6'-Octachlorobiphenyl and 2,2',3,4,4',5,5',6,-Octachlorobiphenyl.

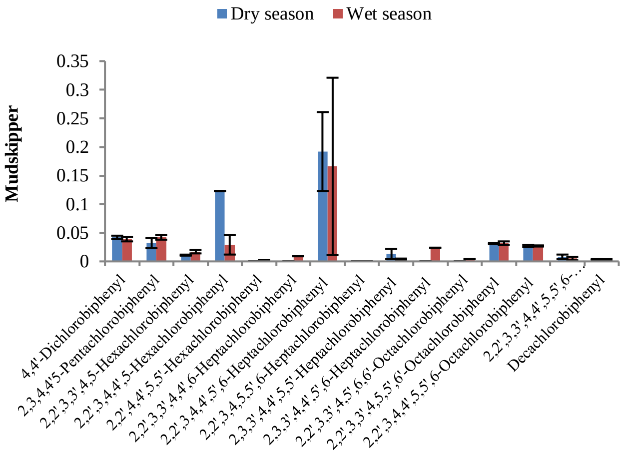

Figure 1: Seasonal fluctuations of PCBs in mudskipper specimens

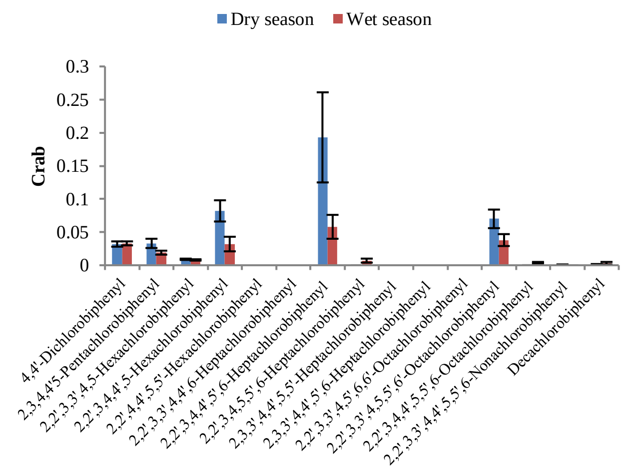

Figure 2: Seasonal fluctuations of PCBs in crab specimens

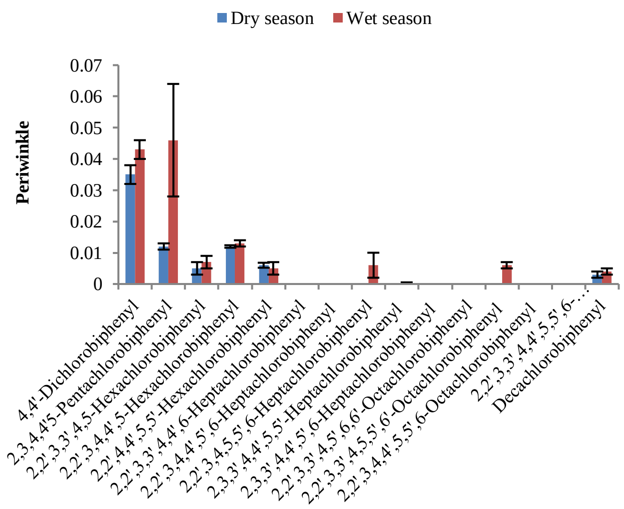

Figure 3: Seasonal fluctuations of PCBs in periwinkle specimens

Multivariate analysis for PCBs in biota

Table 2 revealed the PCA outcomes anchored on the PCBs congeners' correlation matrix. The data sets with 15 PCB congeners examined in the animal specimens were subjected to PCA (Fig. 4). The PCA data sets produced 26 variables with Eigenvalues < 1 under 15 components (PC1-PC15). Each of these factors were responsible for 100.02 % of the variance in aquatic biota. The following were the contributions: 80.58, 9.68, 5.81, 1.97, 0.68, 0.55, 0.25, 0.19, 0.16, 0.09, 0.03, 0.02, 0.01, 0.00, and 0.00 percent were accounted for by components 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, and 15. The important parameters in each component were: 1; 2,2'3,4,4',5'-Heptachlorobiphenyl, 2; 2,2'3,4,4',5- Hexachlorobiphenyl and 2,2'3,3',4,5,5',6-Octachlorobiphenyl, 3; 2,3,4,4',5- Pentachlorobiphenyl and 2,2'3,4,4',5- Hexachlorobiphenyl, 4; 2,2'3,3',4,5,5',6-Octachlorobiphenyl, 5; 4,4- Dichlorobiphenyl, 2,2'3,4,4',5-Hexachlorobiphenyl and 2,2'3,3',4,5,5',6-Octachlorobiphenyl, 6; 2,2'3,4,4',5- Hexachlorobiphenyl, 2,2'3,4,4',5,5'- Heptachlorobiphenyl and 2,2'3,4,4',5,5'6-Octachlorobiphenyl; 7; 2,2'3,4,4',5,5',6- Octachlorobiphenyl and 2,2'3,3',4,4',5,5',6- Nonachlorobiphenyl, 8; 2,2'3,3', 4,5- Hexachlorobiphenyl, 2,3,3',4,4',5,5'-Heptachlorobiphenyl and 2,2'3,3',4,4',5,5',6-Nonachlorobiphenyl, 9; 4,4'-Dichlorobiphenyl, 2,2'3,4,4',5,5'- Heptachlorobiphenyl and 2,2'3,3',4,4',5,5',6- Nonachlorobiphenyl, 10; 2,2'3,4,4',5,5'6- Heptachlorobiphenyl and 2,3,3,4,4',5',6-Heptachlorobiphenyl, 11; 4,4' Decachlorobiphenyl, 12; 2,2',4,4',5- Hexachlorobiphenyl and 2,2'3,3'4,4',5',6-Heptachlorobiphenyl, 13: 2,2'3,4,4',5,5'-Hexachlorobiphenyl, 14; 2,2'3,3',4,4',6-Heptachlorobiphenyl and 15; 2,2'3,3'4,5,5'6,6'-Octaachlorobiphenyl.

Figures 4 and 5 revealed the scatter plot as well as the relationship of the PCBs congeners in the aquatic biota. Positive clusters of 2,2'3,4,4',5- Hexachlorobiphenyl, 2,2'3,4',5,5',6- Octachlorobiphenyl, 2,2'4,4',5,6,6'-Heptachlorobiphenyl and 2,3,4,4',5- Pentachlorobiphenyl with the biota in component 1 were observed.

Positive correlation was observed between 2,3,4,4'5-Pentachlorobiphenyl, 2,2',4,4',5,5'-Hexachlorobiphenyl, 2,3,3',4,4',5',6-Heptachlorobiphenyl, and 2,2',3,4,5,5',6-Heptachlorobiphenyl, while a negative relationship existed between 4,4'-Dichlorobiphenyl, 2,2',3,3',4,5-Hexachlorobiphenyl, 2,2',3,3',4,4',6-Heptachlorobiphenyl, 2,3,3',4,4',5,5'-Heptachlorobiphenyl, 2,2',3,3',4,5',6,6'-Octachlorobiphenyl, 2,2',3,4,4',5,5',6-Octachlorobiphenyl, 2,2',3,3',4,4',5,5',6-Nonachlorobiphenyl and Decachlorobiphenyl (Fig. 6).

Table 2: Eigenvectors and Eigenvalues of the respective PCBs components

PCBs	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9	PC 10	PC 11	PC 12	PC 13	PC 14	PC 15
1-chloro-4-(4-chlorophenyl)benzene	-0.02	-0.04	0.08	0.02	**0.89**	-0.20	-0.36	-0.03	**0.15**	0.10	-0.04	0.05	-0.02	0.00	0.00
2,3,4,4'5-Pentachlorobiphenyl	0.03	-0.52	**0.85**	0.07	-0.08	-0.02	0.05	-0.02	-0.05	-0.01	0.01	0.00	0.01	0.00	0.00
2,2',3,3',4,5-Hexachlorobiphenyl	0.00	-0.01	0.02	0.19	-0.01	**0.55**	-0.55	**0.42**	-0.24	-0.32	-0.09	0.01	0.11	0.00	0.00
2,2',3,4,4',5-Hexachlorobiphenyl	0.26	**0.57**	**0.39**	-0.61	0.11	0.22	0.09	0.03	-0.06	-0.04	0.02	-0.02	0.01	0.00	0.00
2,2',4,4',5,5'-Hexachlorobiphenyl	0.00	0.00	-0.01	-0.03	-0.03	0.01	0.05	-0.08	0.00	0.08	-0.21	**0.79**	**0.56**	0.00	0.00
2,2',3,3',4,4',6-Heptachlorobiphenyl	0.00	0.00	0.01	0.01	-0.02	0.12	-0.03	-0.04	0.10	0.02	0.07	0.20	-0.26	**0.88**	0.30
2,2',3,4,4',5',6-Heptachlorobiphenyl	**0.96**	-0.22	-0.17	0.08	0.02	-0.03	-0.02	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.00
2,2',3,4,5,5',6-Heptachlorobiphenyl	-0.01	-0.02	0.02	0.06	-0.09	**0.48**	-0.15	-0.35	**0.54**	**0.37**	-0.08	-0.30	0.29	0.00	0.00
2,3,3',4,4',5,5'-Heptachlorobiphenyl	-0.01	-0.01	0.00	0.06	0.06	0.10	0.19	**0.61**	-0.12	**0.74**	0.10	0.01	-0.01	0.00	0.00
2,3,3',4,4',5',6-Heptachlorobiphenyl	0.00	-0.01	0.01	0.03	-0.05	0.29	-0.06	-0.11	0.24	0.06	0.18	**0.49**	-0.64	-0.30	-0.27
2,2',3,3',4,5',6,6'-Octachlorobiphenyl	0.00	0.00	0.00	0.01	-0.01	0.04	-0.01	-0.02	0.04	0.01	0.03	0.08	-0.10	-0.37	**0.92**
2,2',3,3',4,5,5',6'-Octachlorobiphenyl	0.12	**0.60**	0.30	**0.68**	-0.11	-0.23	-0.07	-0.02	0.08	0.04	-0.01	0.02	0.00	0.00	0.00
2,2',3,4,4',5,5',6-Octachlorobiphenyl	-0.01	0.00	-0.04	**0.33**	**0.41**	**0.46**	**0.61**	-0.19	-0.25	-0.17	0.09	-0.04	0.05	0.00	0.00
2,2',3,3',4,4',5,5',6-Nonachlorobiphenyl	-0.01	-0.03	0.02	0.01	0.06	-0.02	**0.33**	**0.50**	**0.66**	-0.35	-0.27	-0.01	0.00	0.00	0.00
2,2',3,3',4,4',5,5',6,6'-decachlorobiphenyl	-0.01	-0.01	0.00	-0.01	0.00	-0.05	-0.04	0.11	0.21	-0.16	**0.90**	0.05	0.31	0.00	0.00
Eigenvalue	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% variance	**80.58**	**9.68**	**5.81**	**1.97**	**0.68**	**0.55**	**0.25**	**0.19**	**0.16**	**0.09**	**0.03**	**0.02**	**0.01**	**0.00**	**0.00**

NB: Bolded values were above standards. Grimm and Yarnold, (2000) described loadings > 0.71 as being excellent, and loadings < 0.32 as very poor. Nair *et al.*, (2010) indicated that the component with the maximal Eigenvalue was interpreted to be the most significant and should be one or greater for proper considerations in PCA studies. Factor loadings values of > 0.75, between 0.75–0.5 and 0.5–0.3 are respectively categorized as strong, moderate and weak with respect to their absolute values.

Cluster analysis, Euclidean similarity and distance indices of PCBs

Table 3 revealed the similarity and dissimilarity as indicated by Euclidean distance and the combination of cluster anchored on Ward method as indicated in Fig. 7. According to the respective cluster combinations, the PCB attributes in all the biota were completely dissimilar, having values that were < 1.

Table 3: Euclidean similarity and distance indices of the respective fauna associated PCB congeners

	Mudskipper	**Crab**	**Periwinkle**
Mudskipper	0.00		
Crab	0.09	0.00	
Periwinkle	0.05	0.13	0.00

Ward-Euclidean: 0 and < 1; total dissimilarity, ≥ 1; total similarity, critical significance level (C) = 0.05.

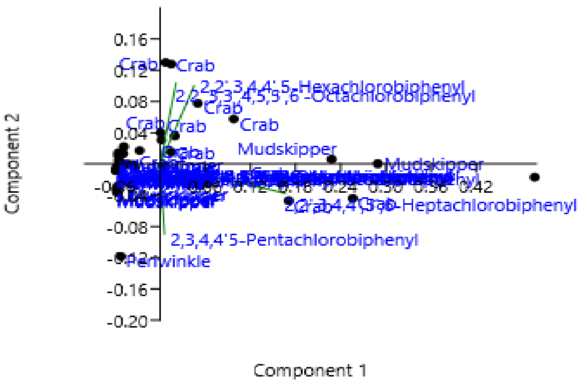

Figure 4: Scatterplot for bioaccumulated PCBs

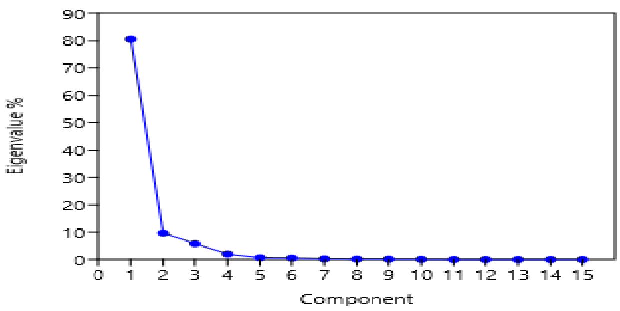

Figure 5: Screenplot for the bioaccumulated PCBs

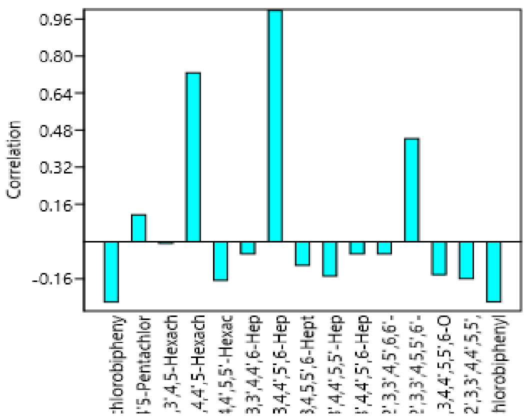

Figure 6: Correlation of the bioaccumulated PCBs

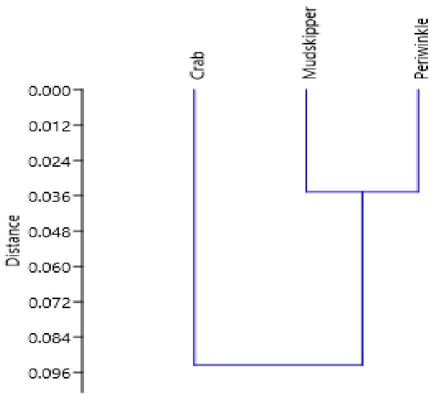

Figure 7: Cluster analysis of the bioaccumulated PCBs

DISCUSSION

Bioaccumulated PCBs

The mean bioaccumulated PCB concentrations documented for the respective fauna obtained from the Falcorp mangrove habitat were very low. The observed variations in the bioaccumulated PCB congeners for the representative fauna was significant. Notwithstanding these differences, the measured bioaccumulated PCB concentrations documented in this study contrasted with values reported for other areas, such as Shanghai (Wang *et al.*, 2022), Bonny (Ukwo *et al.*, 2023) and Lagos (Nkwoji *et al.*, 2024). A likely reason for this difference would be the differing levels of anthropogenic activities between these urban areas and the Falcorp swamp. The low bioaccumulated PCB levels observed in this study is in tandem with previous studies that revealed comparable patterns of PCB bioaccumulation in aquatic species, especially in environments continually exposed to modest industrial activity (Ukwo *et al.*, 2023; Nkwoji *et al.*, 2024). PCB levels fluctuated and peaked during both the dry and rainy seasons suggesting that pollution levels vary spatially throughout the ecosystem. It was observed that whereas crab tissues showed significant variances ($P<0.05$) in PCB levels, mudskipper and periwinkle tissues did not show any significant seasonal fluctuations ($P>0.05$). It has been reported that the primary causes of PCB contamination and subsequent bioaccumulation in fauna and flora are anthropogenic activities exemplified by industrial operations and runoffs from terrestrial areas subjected to agricultural activities (Othman *et al.*, 2022).

Principal component analysis (PCA) of PCBs congeners in biota

The main sources and trends of bio-concentrated PCB values were found using PCA. The majority of the variation was explained by three principal components (PC1, PC2, and PC3), which explained 80.58 %, 9.68 %, and 5.81 % of the data, respectively. Every component had a specific PCB congener connected with it: 2,2'3,4,4',5'-Heptachlorobiphenyl dominated PC1, 2,2'3,4,4',5-Hexachlorobiphenyl and 2,2'3,3',4,5,5',6-Octachlorobiphenyl dominated PC2, and 2,3,4,4',5-Pentachlorobiphenyl and 2,2'3,4,4',5-Hexachlorobiphenyl dominated PC3. These findings would imply that organo-chlorine contaminants, which are frequently linked to industrial and agricultural sources, have a significant impact on the pollution. Similar research conducted around the world has connected anthropogenic actions, such as incorrect garbage disposal and pesticide use, to the bioaccumulation of these PCB moieties in both aquatic sediments and biota (Rocha *et al.*, 2021; Eze *et al.*, 2023; Zhang *et al.*, 2023). Although the eigenvalues for all components were below 1, indicating limited individual influence, the scatter plot revealed significant clustering of certain PCB congeners in specific biota. The PCA analysis further showed positive correlations between some congeners, while others were negatively correlated. The dendrogram, which emphasised clear groupings, supported this pattern. Although crab and mudskipper showed some clustering, the periwinkle displayed separate contamination paths, possibly reflecting changes in environment or feeding patterns.

CONCLUSION

This study examined PCBs bioaccumulation profiles in mudskipper, crab as well as periwinkle specimens collected from several sampling sites within the Falcorp mangrove swamp. The detection of bioaccumulated PCBs in the respective aquatic fauna has raised important inquires pertaining to likely long-term effects of PCB contamination on ecosystem health as well as public health safety as these aquatic fauna are commonly consumed among people residing around the vicinity of the swamp. The results of this study have also highlighted an urgent need for continuous environmental monitoring by public and concerned stakeholders and increased stringent regulatory oversight of the release of persistent pollutants such as PCBs into different environmental matrices especially mangrove wetlands.

COMPETING INTERESTS

The authors declared that there are no competing interests.

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