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Bioaccumulation of polychlorinated biphenyls (PCBs) in *Pseudotolithus senegalensis* from the coastal waters of Apam and Shama, Ghana: implications for human health risk

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Abstract

Polychlorinated biphenyls (PCBs) are legacy persistent organic pollutants that remain a concern in aquatic ecosystems despite restrictions on their production and use. This study evaluated PCB bioaccumulation and associated human health risks in the demersal fish *Pseudotolithus senegalensis* (cassava croaker) from Apam and Shama on the coast of Ghana. A total of 20 fish (40 liver and skeletal muscle samples) and 12 composite water samples were analysed. Selected PCB congeners were quantified using gas chromatography-tandem mass spectrometry (GC-MS/MS) following QuEChERS extraction and grouped as di-, tri-, tetra-, penta-, and hexa-PCBs according to degree of chlorination. Mean total PCB concentrations in water ranged from 0.675 to 2.972 µg/L, while tissue concentrations ranged from undetectable levels to 7.220 µg/kg, with concentrations generally higher in muscle than liver. PCB composition and bioaccumulation varied with degree of chlorination and location. At Shama, hexa-PCBs exhibited the highest group-specific BAFs in both June (47.76) and August (9.01), whereas at Apam the highest BAFs were observed for tri-PCBs in June (26.07) and di-PCBs in August (22.66). Mean total-PCB BAFs ranged from 0.409 to 2.388 across locations and sampling periods. Lifetime Cancer Risk (LCR) and Hazard Index (HI) values remained below U.S. Environmental Protection Agency thresholds of 10^{-6} – 10^{-4} and 1, respectively, indicating low estimated carcinogenic and non-carcinogenic risks under the exposure assumptions used. The contrasting chlorination-specific profiles demonstrate that PCB bioaccumulation in *P.*

senegalensis varies spatially and cannot be adequately characterized by total PCB concentrations alone.

Keywords: Bioaccumulation; Ghanaian coast; human health risk; legacy pollution; polychlorinated biphenyls (PCBs); *Pseudolithus senegalensis*

1 Introduction

Pollution is one of the most pressing environmental challenges of the Anthropocene that forms part of the triple planetary crisis, along with climate change and biodiversity loss (Miao & Nduneseokwu, 2024). For over two decades, persistent organic pollutants (POPs) have been a global concern due to their persistence in the environment, toxicity, tendency to bioaccumulate, and harmful effects on both ecological and human health (Mwakalapa et al., 2018). Polychlorinated biphenyls (PCBs), a class of POPs that have been widely studied for their possible effects on human health and the environment, are among the most concerning (Mahan, 1988; UNEP, 2001). The Stockholm Convention on Persistent Organic Pollutants defines PCBs as a class of aromatic chemicals that are created in such a way that up to ten chlorine atoms can substitute for the hydrogen atoms on the biphenyl molecule, which is made up of two benzene rings joined by a single carbon-carbon bond (UNEP, 2001; Fiedler et al., 2019).

PCBs possess high thermal conductivity, high dielectric constants, and chemical stability, properties that contributed to their widespread use as dielectric and heat-transfer fluids in transformers, capacitors, and electric motors (Mahan, 1988; UNEP, 2001; Afful et al., 2013). They were extensively manufactured between the 1930s and 1970s, but growing evidence of their persistence, bioaccumulation, and toxicity led to the cessation of production in the 1970s (Johnson et al., 1964). Their subsequent inclusion among the Stockholm Convention's original “dirty dozen” persistent organic pollutants in 2001 further underscored the need for their elimination, although they continue to occur as legacy pollutants due to their long half-lives (Zhang et al., 2018; Mortimer & Reichelt-Brushett, 2023).

PCBs continue to be detected in aquatic ecosystems because their strong affinity for organic matter and lipids promotes persistence in sediments, bioaccumulation in aquatic organisms, and biomagnification through food webs (Norstrom, 2002; Blocksom et al., 2010; Xia et al., 2012; Klaus et al., 2016). In Africa, their continued occurrence has been linked to challenges in chemical governance, environmental monitoring, and the management of obsolete PCB-containing equipment (Akinrinade et al., 2024). In Ghana, PCB contamination has been reported in transformer oils, plastic resin pellets, freshwater fish, and coastal sediments,

indicating ongoing secondary emissions from aging electrical infrastructure and inadequately managed waste streams (Buah-Kwofie et al., 2011; Dodoo et al., 2012; Afful et al., 2013; Agbo & Abaye, 2016; Botwe et al., 2017). However, information on PCB contamination in commercially important marine fish species remains limited, despite the importance of marine fisheries to food security and livelihoods, highlighting the need for further investigation along the Ghanaian coast.

Fish tissue contamination is widely used as an indicator of the biological accumulation of persistent pollutants and as a predictor of contaminant exposure risks to higher trophic levels, including humans and piscivorous organisms (Blocksom et al., 2010). The demersal fish *Pseudotolithus senegalensis* (cassava croaker) is an ecologically and socioeconomically important species and a suitable sentinel organism for monitoring PCB contamination in Ghanaian coastal waters. It is among the country's most commercially important demersal fish species and is currently listed as Endangered on the IUCN Red List due to population declines associated with overfishing and habitat degradation (Chao & Trewavas, 1990; Nunoo & Nascimento, 2021). Its close association with benthic habitats, including muddy, sandy, and rocky substrates, increases its exposure to sediment-bound contaminants, which constitute a major environmental reservoir for hydrophobic PCBs (Dachs & Méjanelle, 2010; Dodoo et al., 2012). Furthermore, its benthic feeding habits facilitate contaminant uptake through both dietary pathways and interactions with contaminated sediments, making it a useful indicator of PCB contamination in coastal ecosystems.

Although 209 PCB congeners exist, their environmental fate and bioaccumulation vary with molecular structure and degree of chlorination (Norstrom, 2002; Jahromi et al., 2014). Lower-chlorinated PCBs are generally more volatile and water-soluble, whereas higher chlorination increases hydrophobicity, persistence, and affinity for organic matter and biological lipids (Fisk et al., 1998; Dachs & Méjanelle, 2010). Consequently, examining PCB composition across chlorination groups can provide insights into environmental partitioning and biological accumulation that may not be apparent from total PCB concentrations alone (Frame et al., 1996; Breivik et al., 2002). However, such chlorination-dependent patterns remain poorly characterized in tropical West African coastal ecosystems.

This study investigated PCB occurrence and bioaccumulation in *Pseudotolithus senegalensis* from two contrasting coastal environments in Ghana, with particular emphasis on differences associated with degree of chlorination. Selected PCB congeners were quantified and grouped

into di-, tri-, tetra-, penta-, and hexa-chlorinated PCBs. The study specifically assessed the distribution of these PCB groups in water and fish tissues, evaluated spatial and tissue-specific bioaccumulation patterns, and estimated the carcinogenic and non-carcinogenic health risks associated with consumption of *P. senegalensis*.

2 Materials and Methods

2.1 Study Area

The study was carried out in the coastal towns of Apam and Shama in the Central and Western Regions of Ghana, respectively (Figure 1). Apam (5°17'N, 0°44'W) in the Central Region is a historic fishing town along the Gulf of Guinea with shallow continental shelf waters (<30 m) and sandy–mud substrates suitable for demersal species such as *P. senegalensis* (Obodai et al., 2022). The local economy is dominated by artisanal fishing, small-scale fish processing, and dense residential settlements. The main fish landing site at Apam serves as a central hub where artisanal fishers offload their daily catch from nearshore and offshore fishing grounds, and supports active fish trading and processing activities.

Shama (5°00'N, 1°39'W), located at the mouth of the Pra River in the Western Region, represents a river-dominated estuarine system with tidal mixing, mudflats, and mangroves. The area has a mixed economy that includes fishing, agriculture, and small-scale trading, with the Pra Estuary serving as a vital ecological and economic feature. The Shama landing site serves as a central hub where artisanal fishers offload their daily catch from nearshore and offshore fishing grounds. The landing site supports active fish trading and processing activities.

Samples were collected from the Apaa Lagoon and Pra Estuary in Apam and Shama, respectively, and the sea.

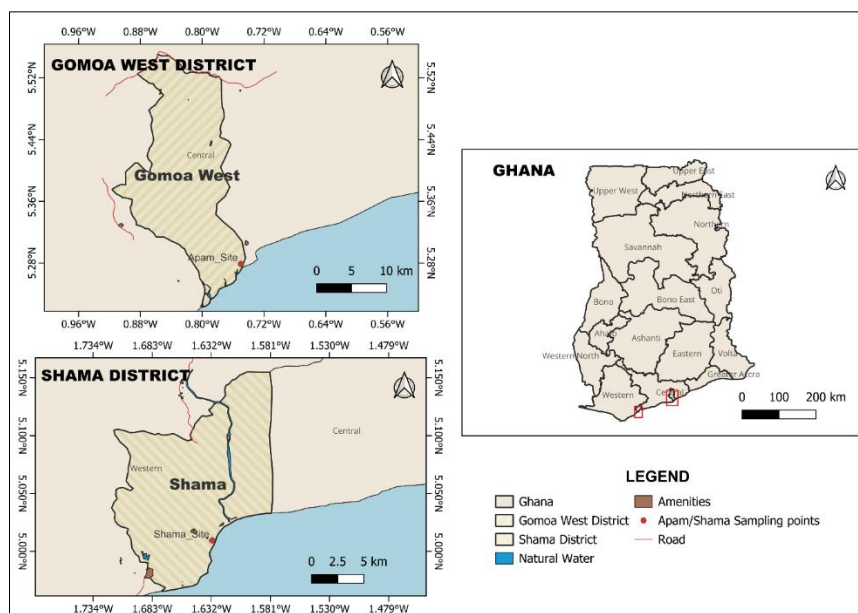


Figure 1: Map showing the study sites of Apam and Shama along the coast of Ghana

2.2 Sample Collection Procedures

Sampling was conducted in June 2024 (representing the peak of the major rainy season and immediately before the national closed fishing season in July) and August 2024 (following the implementation of the closed fishing season). These periods were strategically selected to capture potential seasonal variations in PCB loadings and bioavailability influenced by rainfall-driven runoff. The sample collection procedure involved taking in situ water quality parameters and collecting water and fish samples. Before water sample collection, in situ water quality parameters (temperature, dissolved oxygen, pH, total dissolved solids, and salinity) were measured at an average depth of 0.4 m using a pre-calibrated multi-parameter water quality checker (Horiba U-50 series). Water sampling was conducted during two sampling rounds at two study sites (Apam and Shama). At each site, three sampling stations were established, comprising two estuarine stations and one marine station. During each sampling round, three replicate water samples were collected at each station using a Van Dorn water sampler and transferred into 500 mL polyethylene bottles. The samples were transported on ice to the Fisheries and Coastal Research Laboratory at the Department of Fisheries and Aquatic Sciences, University of Cape Coast, and stored at 4 °C until analysis.

Prior to analysis, the three replicate samples collected from each station were thoroughly mixed to form a single composite sample representative of the station. Consequently, three composite samples were obtained per site during each sampling round, resulting in a total of 12 composite water samples for pollutant analysis. Composite sampling was employed to obtain representative estimates of pollutant concentrations at each sampling station while minimizing the influence of short-term variability among replicate samples. The resulting composite samples were used to characterize spatial and temporal patterns of contamination and to estimate bioaccumulation factors in the study areas.

During each sampling round, *Pseudotolithus senegalensis* specimens were purchased from beach seine fishers at the Apam and Shama landing sites after species identification using a field taxonomic guide. A total of 20 fish specimens were collected, comprising 10 individuals from each study site (5 individuals per sampling round). Immediately after collection, the fish were wrapped in aluminium foil, placed in self-sealing plastic bags, and transported on ice in a cooler box to the Fisheries and Coastal Research Laboratory at the Department of Fisheries and Aquatic Sciences, University of Cape Coast. Upon arrival at the laboratory, the fish were

rinsed with distilled water to remove external debris and minimize contamination. Morphometric measurements, including body weight (g), standard length (cm), and total length (cm), were then recorded. Fulton's condition factor (K) was subsequently calculated to evaluate the health and overall condition of the fish (Onwuka & Onuabuchi, 2022). The k-factor was calculated using the formula:

$$K = \frac{W \times 100}{L^3}$$

where W is the weight of the fish (in g), and L^3 is the total length of the fish (in cm).

Following morphometric measurements, liver and skeletal muscle tissues were excised from each fish using clean stainless-steel dissection instruments. The isolated tissues were weighed, wrapped individually in aluminium foil, placed in well-labelled self-sealing plastic bags, and stored at -16°C until chemical analysis. Separate storage of tissue samples was maintained to prevent cross-contamination and ensure traceability throughout the analytical process.

2.3 Laboratory Analysis

Fish tissue and composite water samples were transported to the Food and Drugs Control Laboratory, Zambia, for PCB analysis. A total of 40 fish tissue samples and 12 composite water samples were analysed for selected PCB congeners using gas chromatography–tandem mass spectrometry (GC-MS/MS). The target congeners were PCB-4, PCB-10, PCB-28, PCB-52, PCB-101, PCB-118, PCB-138, and PCB-153. For reporting and interpretation, the quantified congeners were grouped according to degree of chlorination as follows: di-PCBs (PCB-4 and PCB-10), tri-PCBs (PCB-28), tetra-PCBs (PCB-52), penta-PCBs (PCB-101 and PCB-118), and hexa-PCBs (PCB-138 and PCB-153). Concentrations of congeners within each chlorination group were summed to obtain the corresponding group concentration.

PCB extraction was performed using the Quick, Easy, Cheap, Efficient, Rugged, and Safe (QuEChERS) method following the protocols of Lehotay (2006) and Cloutier et al. (2017). Briefly, 5 g of homogenised tissue was extracted with acetonitrile containing 1% acetic acid in the presence of magnesium sulphate and sodium acetate. The extract was subjected to dispersive solid-phase clean-up using Z-Sep, C18, calcium chloride, and magnesium sulphate before filtration through a polytetrafluoroethylene (PTFE) syringe filter. The cleaned extract was analysed using GC-MS/MS. Individual PCB congeners were identified based on chromatographic retention times and mass spectral characteristics relative to PCB reference standards and quantified using calibration curves prepared from certified PCB standards.

2.3.1 Quality Assurance and Quality Control

Quality assurance and quality control procedures were implemented throughout sample preparation and instrumental analysis. All glassware and sample containers were cleaned, solvent-rinsed, and air-dried prior to use. Procedural blanks, matrix spikes, and replicate analyses were included to assess contamination, recovery, and analytical precision. No target PCBs were detected in procedural blanks. Matrix spike recoveries ranged from 75% to 115%, while relative standard deviations for replicate analyses were generally below 20%. Limits of detection (LOD) and quantification (LOQ) were determined using signal-to-noise ratios of 3:1 and 10:1, respectively. Instrument calibration was performed using multi-point calibration curves prepared from certified reference standards, yielding coefficients of determination (R^2) greater than 0.99 for all analytes.

2.4 Statistical Analysis

Field data and laboratory analysis results were organised and managed in Microsoft Excel and analysed using R. Descriptive statistics (mean, standard deviation, maximum, median, and minimum) were calculated for both field data and laboratory results to examine the structure of the datasets. The data were then subjected to the Shapiro-Wilk normality test at a 0.05 significance level to determine whether they were normally distributed. The test indicated that not all datasets were normally distributed. Consequently, non-parametric tests were employed to explore relationships in the data. Kruskal-Wallis and Mann-Whitney tests were conducted at a 0.05 significance level to compare pollutant concentrations in fish tissues and between the two locations, respectively. Where statistically significant differences were observed ($p < 0.05$), post-hoc analyses were performed to identify the specific differences while controlling for the likelihood of false positives. Pairwise comparisons were conducted using the Wilcoxon rank sum test, with p-values adjusted using the Bonferroni method. Finally, all analysed results were visualised to provide graphical representations of data structure, relationships, and comparisons.

2.5 Bioaccumulation and Human Health Risk Assessment

The total pollutant concentrations in fish tissues and water samples were determined to assess bioaccumulation. Bioaccumulation was quantified using the Bioaccumulation Factor (BAF) by dividing the lipid-corrected sum of PCB concentrations in fish tissues by the sum of PCB concentrations in water (Borgå & Ruus, 2022). The following formula was used to calculate the BAF:

$$BAF_{PCB} = \frac{C_{fish}}{C_{water}}$$

219

221 where:

- 222 • C_{fish} is the lipid-corrected sum of PCB concentrations in fish tissues; and
- 223 • C_{water} is the sum of PCB concentrations in water.

224 The BAF was calculated for each fish sample collected from the two study locations. In
 225 addition, group-specific BAFs were calculated for di-, tri-, tetra-, penta-, and hexa-PCBs using
 226 the concentration of each PCB chlorination group in fish tissue relative to its corresponding
 227 concentration in water.

228 The carcinogenic risk was evaluated using the Lifetime Cancer Risk (LCR), which estimates
 229 the probability of developing cancer over a lifetime due to continuous exposure to contaminants
 230 (Yadav et al., 2020). The LCR was computed as follows:

$$LCR = CDI \times SF$$

232 where:

- 233 • CDI (Chronic Daily Intake) represents the estimated daily exposure to the contaminant
 234 over a lifetime ($\mu g/kg/day$).
- 235 • SF (Cancer Slope Factor) is a contaminant-specific parameter ($mg/kg/day^{-1}$) that
 236 quantifies the risk associated with exposure to a carcinogen. An SF of 2.0 was used
 237 following USEPA standards (U.S. EPA, 1996).

238 The CDI was calculated using the formula:

$$CDI = \frac{(C \times IR \times EF \times ED)}{(BW \times AT)}$$

240 where:

- 241 • C = Contaminant concentration in fish ($\mu g/kg$).
- 242 • IR = Ingestion rate of fish (kg/day).
- 243 • EF = Exposure frequency ($days/year$).
- 244 • ED = Exposure duration ($years$).
- 245 • BW = Body weight of the consumer (kg).
- 246 • AT = Averaging time ($days$) (for carcinogens, AT = lifetime in days, typically 70 years
 247 $\times 365$ days).

248 The concentrations of the pollutants (C) were obtained from laboratory analysis, while the
 249 values for the other metrics were adopted from the United States Environmental Protection
 250 Agency (USEPA) guidelines on the assessment of risks for adults (U.S. EPA, 2011). The

Ingestion Rate (IR) was estimated at 0.020 kg/day; Exposure Frequency (EF) was 365 days/year; Exposure Duration (ED) was 30 years; Body Weight (BW) was 70 kg; and the Averaging Time (AT) was 22,550 days. According to the United States Environmental Protection Agency (USEPA) guidelines, an LCR value between 10^{-6} and 10^{-4} is considered within an acceptable risk range. Values exceeding 10^{-4} indicate a significant cancer risk, requiring risk management interventions.

Non-carcinogenic health risks were assessed using the Hazard Index (HI), which provides a measure of the potential for adverse health effects resulting from long-term exposure to pollutants. The HI was calculated using the formula:

$$HI = \frac{MDI}{TDI}$$

where:

- MDI (Maximum Daily Intake) represents the estimated daily intake of the contaminant through fish consumption ($\mu g/kg/day$).
- TDI (Tolerable Daily Intake) is the reference dose ($\mu g/kg/day$) below which no adverse health effects are expected.

An HI value less than 1 indicates that the exposure level is within safe bounds, while an HI value larger than 1 suggests that there may be a danger of negative health impacts and that additional research and mitigation strategies are required.

3 Results

3.1 Physicochemical Parameters

Physicochemical measurements revealed distinct environmental characteristics between Apam and Shama. Temperature, pH, and dissolved oxygen (Figure 2) did not differ significantly between sites ($p > 0.05$). In contrast, total dissolved solids (TDS) and salinity were significantly higher in Apam (TDS: 28.02 ± 9.58 ppt; salinity: 30.83 ± 11.68 ppt) than in Shama (TDS: 4.49 ± 4.28 ppt; salinity: 3.41 ± 2.95 ppt; $p < 0.05$).

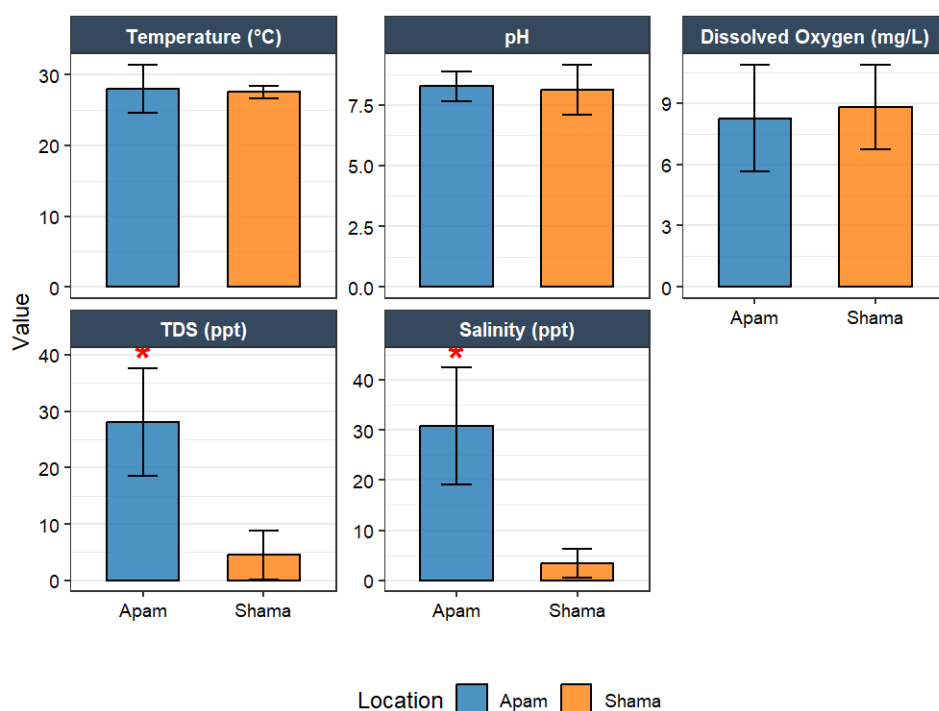


Figure 2. Physicochemical parameters in Apam and Shama. Panels show (A) temperature, (B) pH, (C) dissolved oxygen, (D) total dissolved solids, and (E) salinity. Bars represent mean $\pm$ SD, with asterisks (*) indicating significant differences ($p < 0.05$).

3.2 Fish Morphometrics

There was a significant difference ($p < 0.05$) in fish morphometric parameters and Fulton's condition factor (K) between fish samples collected in Apam and Shama (Figure 3). Mean fish weight was 349.18 ± 97.27 g at Apam and 116.66 ± 149.68 g at Shama. The mean standard length was 27.98 ± 2.53 cm at Apam and 19 ± 7.13 cm at Shama. Total length averaged 32.95 ± 3.04 cm at Apam and 23.39 ± 7.97 cm at Shama. Mean values of Fulton's condition factor (K) were 0.95 ± 0.05 at Apam and 0.63 ± 0.05 at Shama.

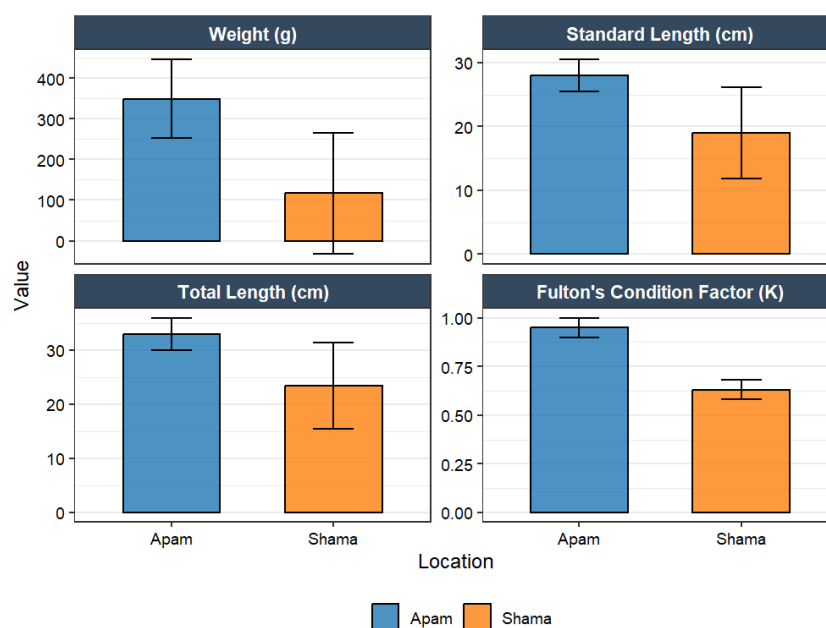


Figure 3. Mean morphometrics and Fulton's condition factor (K) of *P. senegalensis* from Apam and Shama. Fish from Apam were larger and in better condition (higher K) than those from Shama, with Shama showing greater variability in weight and length.

3.3 PCB Concentrations in Water

Significant differences in PCB chlorination-group concentrations were observed between the two study areas (Figure 4), with Apam generally exhibiting higher concentrations than Shama. Penta-PCBs had the highest mean concentration at Apam ($0.909 \pm 0.920 \mu\text{g/L}$), while di-PCBs had the lowest ($0.058 \pm 0.078 \mu\text{g/L}$). At Shama, penta-PCBs also had the highest mean concentration ($0.302 \pm 0.467 \mu\text{g/L}$), while hexa-PCBs had the lowest ($0.028 \pm 0.021 \mu\text{g/L}$). In terms of relative composition, penta-PCBs contributed the largest proportion of total PCBs at Apam (37.0%), whereas tetra-PCBs predominated at Shama (50.0%).



Figure 4: Mean concentrations of PCB chlorination groups in water from Apam and Shama (Di_CB = Dichlorobiphenyls, Hexa_CB = Hexachlorobiphenyls, Penta_CB = Pentachlorobiphenyls, Tetra_CB = Tetrachlorobiphenyls, Tri_CB = Trichlorobiphenyls)

Total PCB concentrations varied between locations and sampling periods (Figure 5). At Apam, the mean total PCB concentration increased from 1.945 µg/L in June to 2.972 µg/L in August, whereas at Shama it decreased from 1.121 µg/L in June to 0.675 µg/L in August.

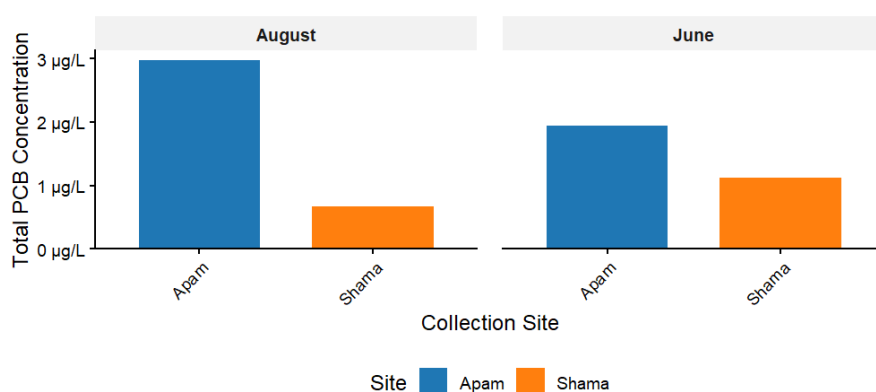


Figure 5. Mean total PCB concentrations (ΣPCBs) in water from Apam and Shama during the June and August sampling periods.

3.4 PCB Concentrations in Fish Tissues

PCBs were detected in fish tissues from both locations, with total concentrations generally higher in muscle than in liver (Table 1). At Apam, mean ΣPCB concentration was 1.934 ± 1.611 µg/kg in muscle and 0.191 ± 0.602 µg/kg in liver, with maximum concentrations of 5.253 and 1.905 µg/kg, respectively. At Shama, PCBs were not detected in liver, while muscle concentrations averaged 1.857 ± 2.246 µg/kg and ranged from 0.177 to 7.220 µg/kg.

Table 1: PCB concentrations (µg/kg) in *P. senegalensis* tissues from Apam and Shama.

Site	Tissue	N	Mean ΣPCBs ± SD (µg/kg)	Minimum	Maximum
Apam	Liver	10	0.190 ± 0.602	0.000	1.905
Apam	Muscle	10	1.934 ± 1.611	0.000	5.253
Shama	Liver	10	0.000 ± 0.000	0.000	0.000
Shama	Muscle	10	1.857 ± 2.246	0.177	7.220

3.5 Bioaccumulation of PCBs

Group-specific BAFs varied by degree of chlorination and location (Table 2). At Apam, the highest BAFs were recorded for tri-PCBs in June (26.07) and di-PCBs in August (22.66), while at Shama, hexa-PCBs had the highest BAFs in both June (47.76) and August (9.01). BAFs for the remaining PCB groups ranged from 0.04 to 7.24 at Apam and from 0.40 to 4.46 at Shama.

Table 2: Group-specific bioaccumulation factors (BAFs) for PCB chlorination groups in *P. senegalensis* from Apam and Shama

Site	Sampling Period	Di-PCBs	Tri-PCBs	Tetra-PCBs	Penta-PCBs	Hexa-PCBs
Apam	June	7.24	26.07	0.23	0.77	1.02
Apam	August	22.66	0.93	0.05	0.04	0.78
Shama	June	2.51	3.44	0.44	1.17	47.76
Shama	August	4.46	3.98	1.00	0.40	9.01

The calculated mean BAF_{PCB} at Apam in June was 1.560 ± 1.061 , with a range of 0.374 to 2.701, whereas the second sampling in August showed a lower mean of 0.409 ± 0.376 , with values ranging from 0.000 to 0.999 (Figure 6). In Shama, the mean BAF_{PCB} was 2.388 ± 2.629 before the closed season, ranging from 0.347 to 6.441, while a lower mean of 1.538 ± 1.471 , ranging from 0.262 to 3.148, was recorded after the closed season.

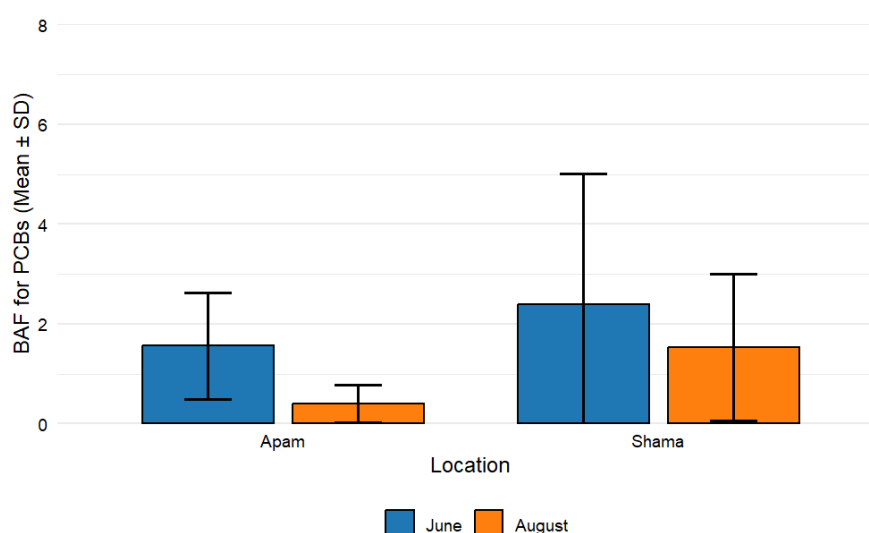


Figure 6. PCB bioaccumulation factors in fish from Apam and Shama before (blue) and after (orange) the closed season.

3.6 Human Health Risk Assessment

The carcinogenic and non-carcinogenic health risk assessment results are presented in Figure 7. The Lifetime Cancer Risk (LCR) and Hazard Index (HI) values varied between Apam and Shama. In Apam, the mean LCR_{PCB} was of $5.20 \times 10^{-10} \pm 4.49 \times 10^{-10}$ while the mean HI_{PCB} was $3.03 \times 10^{-5} \pm 2.62 \times 10^{-5}$. In Shama, the mean LCR_{PCB} was $4.55 \times 10^{-10} \pm 5.51 \times 10^{-10}$ while the mean HI_{PCB} was $2.65 \times 10^{-5} \pm 3.21 \times 10^{-5}$.

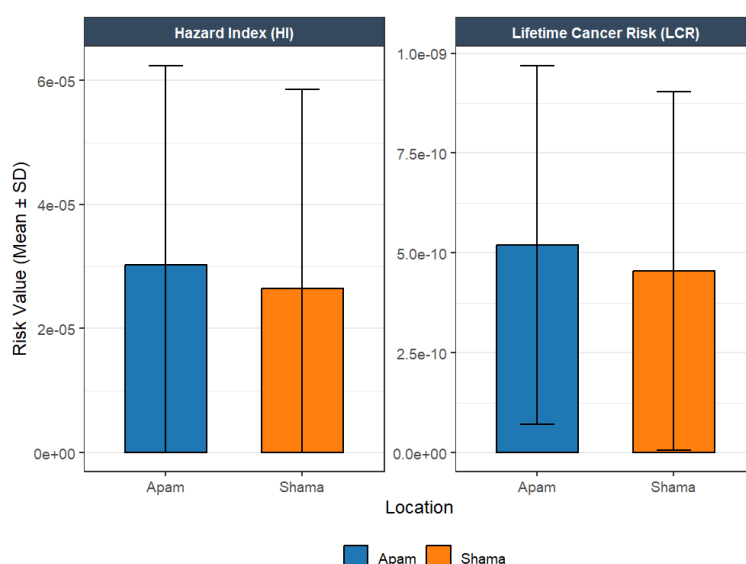


Figure 7. PCB health risk assessment in *P. senegalensis* from Apam and Shama. (A) Lifetime Cancer Risk (LCR) and (B) Hazard Index (HI) are shown as mean $\pm$ SD. All values are well below their respective safety thresholds, indicating negligible carcinogenic and non-carcinogenic risks. Apam shows slightly higher mean values, while Shama exhibits greater variability, particularly for HI.

4 Discussion

This study establishes that the PCB concentration levels in *P. senegalensis* are a direct reflection of site-specific environmental pressures. The ongoing bioavailability of PCBs in Ghana's coastal waters is driven by a complex interplay between seasonal dynamics and watershed-scale inputs, which together dictate the extent of bioaccumulation in these demersal fish. Differences in physicochemical characteristics between the sites (Figure 2) further support contrasting exposure environments. Observed differences in Fulton's condition factor and bioaccumulation patterns suggest that these environmental factors not only affect fish health but also shape the potential for human and ecological risk. These findings highlight the enduring impact of legacy contaminants in Ghana's coastal ecosystems and provide a foundation for interpreting site-specific differences in bioavailability, exposure pathways, and ecological consequences.

4.1 Fulton's Condition Factor

Fulton's condition factor (K) is a widely used indicator of fish health and habitat quality (Nash et al., 2006). Fish from Shama exhibited lower condition factors than those from Apam, suggesting comparatively poorer physiological condition. Similar reductions in condition factor have been associated with environmental stressors such as habitat degradation, limited food availability, and contaminant exposure (Adeogun et al., 2016; Osei et al., 2021). Although PCBs can impair growth and energy storage through endocrine and metabolic disruption (Khan, 2003), no physiological biomarkers or toxicological endpoints were measured in the present study. Consequently, the lower condition factor observed in Shama cannot be attributed directly to PCB exposure.

Shama is located downstream of the Pra River, which receives inputs from agriculture, illegal alluvial gold mining, and domestic effluents (Nti, 2023). These activities may contribute to environmental stress in aquatic organisms (Duker et al., 2024). However, fish condition is influenced by multiple interacting factors, including habitat quality, prey availability, fishing pressure, seasonal variability, and contaminant exposure (Osei et al., 2021). Therefore, the differences in condition factor between sites likely reflect the combined influence of chemical and ecological stressors rather than PCBs alone.

4.2 PCB Contamination in Water and Fish Tissues

PCB homologous groups were detected in both water and *P. senegalensis* tissues at Apam and Shama, confirming the continued occurrence of these legacy pollutants in Ghanaian coastal ecosystems decades after their ban. Similar contamination has been reported in other Ghanaian aquatic systems, including the Benya, Brenu, and Fosu lagoons (Dodoo et al., 2012; Bruce-Vanderpuije et al., 2019). Significant differences in salinity and total dissolved solids between the two study sites indicate contrasting hydrological conditions that may influence contaminant partitioning, retention, and bioavailability (Duker et al., 2024), thereby contributing to the observed spatial differences in PCB accumulation.

The accumulation of PCBs in *P. senegalensis* is consistent with its demersal ecology and close association with bottom sediments, which are recognized as major reservoirs of hydrophobic contaminants. Similar sediment-associated PCB accumulation has been reported in wild *Oreochromis niloticus* from Lake Kariba, Zambia (Simukoko et al., 2023). Although PCBs often accumulate at higher concentrations in the liver due to its role in metabolism and detoxification (Fisk et al., 1998; van der Oost et al., 2003), muscle tissues contained higher

PCB concentrations than liver tissues in the present study. This atypical pattern may reflect species-specific lipid distribution or metabolic differences in *P. senegalensis*. Similar observations have not been widely reported for other demersal fishes, where PCB concentrations are typically higher in the liver (Silva Barni et al., 2016; Magalhães et al., 2017), highlighting the influence of species ecology and physiology on contaminant distribution.

A limitation of the present study is that PCB concentrations in sediments were not measured. Given the strong affinity of PCBs for sediments and the demersal feeding habits of *P. senegalensis*, sediment-associated exposure pathways may not have been fully characterized. Nevertheless, the detection of PCBs in both water and fish tissues indicates that these contaminants remain bioavailable in Ghanaian coastal ecosystems and continue to enter aquatic food webs.

4.3 PCB Bioaccumulation

The bioaccumulation factors (BAFs) of PCBs varied across locations and sampling rounds, indicating spatial and temporal variation in PCB accumulation (Figure 6). Shama exhibited higher BAFs despite lower PCB concentrations in water, suggesting that accumulation was influenced by factors beyond water-column concentrations alone. Similar observations have been reported in Lake Chapala, Mexico, where PCB accumulation in fish species such as *Chirostoma* spp., *Cyprinus carpio*, and *Oreochromis aureus* was more closely associated with sediment-related exposure pathways than with concentrations in water (Oregel-Zamudio et al., 2021).

Group-specific BAFs further revealed contrasting patterns with degree of chlorination. At Shama, hexa-PCBs had the highest BAFs in both June (47.76) and August (9.01), consistent with the greater persistence and bioaccumulation potential generally associated with higher-chlorinated PCBs (Jahromi et al., 2014; Rimayi et al., 2017). The particularly high June BAF should, however, be interpreted cautiously because hexa-PCB concentrations in Shama water were very low. In contrast, the highest BAFs at Apam occurred for tri-PCBs in June (26.07) and di-PCBs in August (22.66), indicating that increasing chlorination did not consistently correspond to greater bioaccumulation across locations. Site-specific factors such as hydrology, watershed inputs, and habitat characteristics may contribute to these contrasting accumulation patterns (Simukoko et al., 2023).

The ecology of *P. senegalensis* may also influence PCB exposure. As a demersal species, it feeds in close association with bottom substrates where hydrophobic contaminants can

accumulate. Although sediment PCB concentrations were not measured in the present study, sediment-associated exposure may therefore have contributed to the observed patterns. Similar sediment-related accumulation pathways have been reported in other aquatic ecosystems (Oregel-Zamudio et al., 2021; Simukoko et al., 2023).

Overall, the BAFs demonstrate that PCBs were bioavailable to *P. senegalensis* at both locations, while the group-specific patterns indicate that bioaccumulation varied with both degree of chlorination and location. The contrasting profiles between Apam and Shama highlight the value of considering PCB composition alongside total PCB concentrations when assessing contaminant exposure and bioaccumulation in coastal ecosystems.

4.4 Health Risks of Consuming *P. senegalensis*

From a public health perspective, the risk indices derived from fish consumption (Figure 7) indicate that consuming *P. senegalensis* from both study sites is unlikely to pose significant carcinogenic or non-carcinogenic health risks under the exposure scenarios considered in this study. Similar findings have been reported in Ghana (Adu-Kumi et al., 2010; Asante et al., 2011; Dodoo et al., 2012) and along the Chinese coast (Xia et al., 2012), where PCB concentrations in fish generally remained within internationally accepted safety limits. However, exposure risks may not be uniform across all population groups. Frequent fish consumers and fish-dependent households may experience higher exposure levels than those estimated under typical consumption scenarios (Panseri et al., 2019). These observations highlight the importance of continued biomonitoring of fish tissues as indicators of human exposure to environmental contaminants.

While the estimated risks to consumers were low, a low human health risk does not necessarily imply negligible ecological impact. In South American shallow lakes, PCB exposure has been associated with tissue damage, endocrine disruption, and abnormal vitellogenin expression in fish (Silva Barni et al., 2016). Such sublethal effects can reduce individual fitness and population resilience, highlighting the importance of considering ecological as well as human health endpoints when evaluating the consequences of PCB contamination.

Across West Africa, PCB contamination remains a concern, although levels and associated risks vary among species and locations. For example, imported fish in Nigeria contained predominantly tetra-, penta-, and hexa-PCBs and posed low to moderate cancer risks (Iwegbue et al., 2025), while *Clarias gariepinus* from Nigerian waters exhibited PCB concentrations that occasionally exceeded regulatory limits (Ololade et al., 2025). These differences underscore

the influence of local environmental conditions, species ecology, and contaminant sources on PCB accumulation and risk. Consequently, continued biomonitoring, effective management of obsolete PCB-containing equipment, and remediation of contaminated environmental reservoirs remain important for protecting public health and sustaining coastal fisheries in Ghana. Continued implementation of the Stockholm Convention and periodic effectiveness evaluations will be critical for reducing the long-term burden of PCB contamination in the region (EPA Ghana, 2018; UNEP, 2023; Mortimer & Reichelt-Brushett, 2023).

5 Conclusion

This study evaluated the occurrence, tissue distribution, bioaccumulation, and potential human health risks of selected PCBs in *Pseudotolithus senegalensis* from Apam and Shama. PCBs were detected in water and fish tissues at both sites, with concentrations generally higher in skeletal muscle than in liver. Bioaccumulation varied by location and degree of chlorination: hexa-PCBs exhibited the highest group-specific BAFs at Shama, whereas tri- and di-PCBs had the highest BAFs at Apam in June and August, respectively. These contrasting patterns indicate that PCB bioaccumulation was site-specific and not consistently related to increasing chlorination. Screening-level estimates of carcinogenic and non-carcinogenic risks were below the respective USEPA benchmark values, indicating low estimated risks from consuming *P. senegalensis* under the exposure scenario assessed. Continued monitoring incorporating sediment analysis, broader spatial and seasonal coverage, and individual congener-level reporting would improve understanding of PCB exposure and bioaccumulation in Ghanaian coastal ecosystems.

5.1 Limitations

This study has several limitations. First, the relatively small sample size and inclusion of only two coastal locations limit the spatial representativeness of the findings. Second, although selected PCB congeners were quantified and grouped by degree of chlorination, the study did not cover the full range of PCB congeners that may occur in the coastal environment. Third, sediment and dietary PCB concentrations were not measured, limiting the ability to determine the relative contribution of water, sediment, and food-web exposure to the observed bioaccumulation patterns. This is particularly relevant for *P. senegalensis* because of its demersal ecology and the strong association of hydrophobic PCBs with sediments. Finally, the human health risk assessment relied on USEPA exposure assumptions because population-specific fish consumption and exposure data were unavailable for the study area. The risk estimates should therefore be interpreted within the assumptions used.

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Conflicts of Interest

The author reports no conflicts of interest.

Authors' Contribution

CJP: Conceptualisation, Resources and Funding Acquisition, Data Collection, Analysis, Visualisation and Curation, Writing the Original Draft Manuscript, Review and Editing; EA: Supervision, Conceptualisation, Resources and Funding Acquisition, Project Administration, Review and Editing; PKM: Supervision, Conceptualisation, Resources and Funding Acquisition, Project Administration, Review and Editing; HB: Data Curation and Visualisation; Writing the Original Draft Manuscript, Review and Editing. All authors read and approved the final manuscript.

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Data Availability

The data that support the findings of this study are available from the corresponding authors, Chisomo Jim Phiri and Paul Kojo Mensah, upon reasonable request.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation Process

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language editing, improving clarity, and enhancing the overall presentation of the manuscript. After using this tool, the authors critically reviewed, revised, and edited the content as necessary and take full responsibility for the content of the published article.

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