



Society of Petroleum Engineers

SPE-221640-MS

Distribution and Health Risk Assessment of Polycyclic Aromatic Hydrocarbons in Silver Catfish from Escravos Estuary, Nigeria

Abraham O. Ekperusi and Amaka Michael, Department of Environmental Management and Pollution, Faculty of Environmental Management, Nigeria Maritime University, Okerenkoko, Delta State;; Henrietta C. Chukwurah, Department of Science Laboratory Technology, Federal Polytechnic, Orogun, Delta State, Nigeria;; Naomi M. Sunday and David O. Asiwa, Department of Environmental Management and Pollution, Faculty of Environmental Management, Nigeria Maritime University, Okerenkoko, Delta State.

Copyright 2024, Society of Petroleum Engineers DOI [10.2118/221640-MS](https://doi.org/10.2118/221640-MS)

This paper was prepared for presentation at the SPE Nigeria Annual International Conference and Exhibition held in Lagos, Nigeria 5 - 7 August 2024.

This paper was selected for presentation by an SPE program committee following review of information contained in an abstract submitted by the author(s). Contents of the paper have not been reviewed by the Society of Petroleum Engineers and are subject to correction by the author(s). The material does not necessarily reflect any position of the Society of Petroleum Engineers, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper without the written consent of the Society of Petroleum Engineers is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 300 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgment of SPE copyright.

Abstract

Polycyclic aromatic hydrocarbons (PAHs) are important components of crude oil that require regular monitoring due to their interaction with the environment, biota and humans. There has been a growing literature on the impact of PAHs on the flora and fauna from both freshwater and coastal ecosystems in the Niger Delta region. However, studies on the potential health risks associated with consuming seafood contaminated with hydrocarbons are limited. In this study, we investigated the tissue distribution and the potential human health risk associated with PAHs in silver catfish, *Chrysichthys nigrodigitatus* collected from the Escravos estuary, a major oil and gas processing zone in Nigeria. Varying concentrations of PAH congeners were reported in the tissues of silver catfish with the highest level reported in the liver compared to the gills and the rest of the fish. Fluorene (36.62%), naphthalene (22.62%) and anthracene (15.19%) were the dominant congeners in fish tissues. The values of PAHs especially carcinogenic congeners were higher than the maximum permissible limits for fishery products which indicate potential concern for public health, but the estimated daily intake for adults and children was below the reference dose values for selected PAH congeners, while the hazard ratio was less than 1. Increasing industrial activities and poor regulation could lead to possible long-term human health risks from the consumption of seafood exposed to PAHs from the estuary. There is a need for the regular monitoring of domestic and industrial effluents entering the estuary to mitigate potential impact on seafood and human health.

Introduction

Crude oil is one of the most important products in global trade due to its critical role in providing a vital energy source for the modern economy. Among the complex classes of compounds present in crude oil, polycyclic aromatic hydrocarbons (PAHs) are of significant interest due to their interaction with the environment, biota and human health (USEPA, 1993; Tongo et al., 2016; Akinnusotu et al., 2023). Although PAHs can enter the environment through various natural sources, anthropogenic activities like

petrochemical production, industrial emissions from fossil fuel use as well as vehicular emissions are some of the major sources of PAHs in the global environment (USEPA, 1993; Tongo et al., 2016; Akinnusotu et al., 2023). Over 100 PAHs have been described for their commercial purposes, of which 16 are categorised as priority pollutants because of their toxicological effect on biota (USEPA, 1993; Akinnusotu et al., 2023). PAHs have a wide range of impacts on the environment, biota and human health, they are commonly implicated for their carcinogenic, mutagenic and teratogenic effects on animals and humans (USEPA, 1993; Tongo et al., 2016; Ibe et al., 2021; Akinnusotu et al., 2023). In 2005, PAHs were ranked 7th on the scale of global chemicals deemed harmful with significant risk to human health (Christopher, 2008; Ibe et al., 2021). PAHs are highly lipophilic compounds which makes them extremely soluble in organic solvents. This unique property makes PAHs pervasive in air, soil, sediments, water and biota (Adekunle et al., 2018; Ambade et al., 2023). The diverse use of hydrocarbons as an energy source releases PAHs into the environment via multiple sources (Wang et al., 2017; Akinnusotu et al., 2023), but dietary intake through food consumption remains the major source of human exposure to PAHs (Phillips, 1999; Tongo et al., 2016; Akinnusotu et al., 2023). Seafoods are essential tools for the monitoring of organic contaminants due to the bioaccumulation potentials of several species to PAHs. Their prevalence in the environment and potential movement across the food chain has warranted regular monitoring for food safety and the protection of public health (Phillips, 1999; Olayinka et al., 2019; Pang et al., 2021; Akinnusotu et al., 2023; Tongo et al., 2016). Although, there are several researches on PAHs contamination and health risks in the global north, there are still data gaps in the south, especially in Africa, where regular monitoring programmes are limited. In this study, we investigated the prevalence of PAHs in the tissues of the silver catfish, a commonly consumed and readily available seafood product in the Niger Delta region and the potential risk associated with human health.

Materials and Methods

Study Area

The Escravos estuary is an intrusion of fresh and saltwater ecosystems that empties into the Gulf of Guinea section of the Atlantic Ocean from the Niger Delta region of Nigeria. The area features several creeks and mangrove swamp ecosystems. The region is characterised by two distinct seasons. Rainfall and flooding are prevalent in the wet season, disrupting the economic livelihoods and social well-being of the people. The estuary is the main route for shipping goods and petroleum products to Delta State. The estuary is named after the Escravos terminal, one of the main oil and gas processing terminals in Nigeria. The estuary serves as a vital fishing ground for artisanal fishers from island communities and a transport route to several towns in the mainland within the region. The major occupations in the area include fishing, lumbering, farming, petty trading, and oil servicing operations (Figure 1).

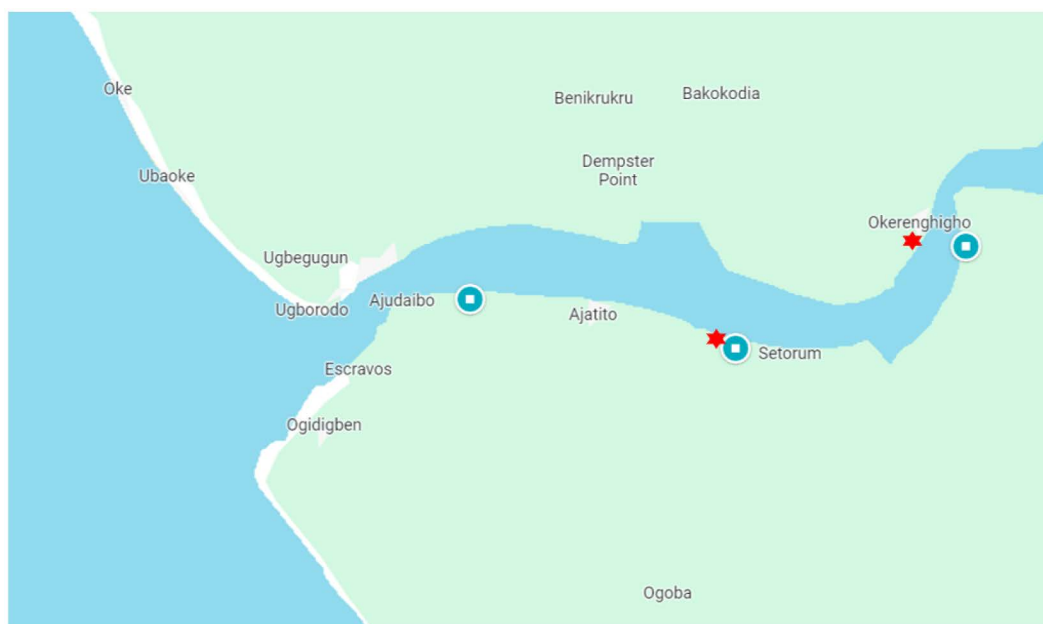


Figure 1—Map of the study area showing the study sites in red dots along the Escravos estuary.

Fish Sample Collection

Samples of silver catfish were purchased from the daily catch of artisanal fishers between 06:00 and 09:00 hours at the landing jetties in Kurutie (Latitude 5°34'56.61" N, Longitude 5°20'31.12" E) and Okerenkoko (Latitude 5°37'44.42" N, Longitude 5°23'32.36" E) island communities along the estuary (Figure 1). The samples were rinsed with the water from the estuary, wrapped in aluminium foil and put in ice pack before being transported to the laboratory for analysis. Fish samples of similar morphometric characteristics were collected in triplicates from the estuary. A total of 18 samples from the two sites were collected for the study. At the lab, the samples were kept in cold storage at −20°C before analysis.

Sample Extraction and Analysis

At the laboratory, the fish were defrosted, cleaned in de-ionised water, weighed and dissected using a surgical kit and the target organ for analysis such as the liver, gills and the rest of the fish were collected, weighed and kept in a glass jar after labelling. The samples were blended using a clean blender and about 10 g of anhydrous sodium sulphate (Na_2SO_4) was added to dehydrate the sample. Extraction was done using 20 ml of dichloromethane using a Soxhlet extraction apparatus for 5 h and evaporated to near dryness. Cleanup of extracts was done using 20 ml of dichloromethane in a chromatographic column, packed at the bottom with glass wool, 2 g of silica gel and anhydrous Na_2SO_4 . Extracts were evaporated to 1 ml and loaded in vials. The extracts were analysed for PAH congeners such as Naphthalene (NaP), Acenaphthylene (AcPY), Acenaphthene (AcP), Fluorene (Flu), Anthracene (Ant), Phenanthrene (Phe), Fluoranthene (FL), Pyrene (Pyr), Benzo[a]anthracene (BaA), Chrysene (Chr), Benzo[b]fluoranthene (BbFL), Benzo[k]fluoranthene (BkFL), Benzo[a]pyrene (BaP), Dibenzo[ah]anthracene (DBA), Indeno[123-cd]pyrene (Ind) and Benzo[ghi]perylene (BP) using gas chromatography with flame ionisation detector (GC-FID, Agilent A series, Agilent Corporation, United States). Samples were injected using a micro syringe in a splitless mode. The starting temperature of the GC was 60 °C for 2 min and was raised to 300 °C with a run time of 22 min. The carrier gas used was helium. A standard mixture of the 16 priority PAHs was prepared and used for the analysis.

Quality Assurance and Quality Control

All the glassware used were rinsed with de-ionised water and ethanol before use. All solvents used were analytical grades. High grade PAHs (> 97% purity) standards were used for analysis (Sigma-Aldrich GmbH, Germany). All laboratory equipment used for analysis were regularly calibrated before use. Sample analysis includes blanks and quality control to guarantee accuracy and minimize errors. Recoveries and surrogates PAH congeners range between > 80% and 100%. The signal-to-noise ratio of the blanks was multiplied by 3 and 10 to determine the limits of detection (LOD) and quantitation (LOQ).

Human Health Risk Assessment

The possible human health risk associated with consuming *C. nigrodigitatus* contaminated with PAH congeners was computed using the estimated daily intake (EDI) and hazard ratio (HR). The EDI was calculated using the [equation 1](#).

$$EDI = C \times FIR / BW \quad (1)$$

where EDI is the estimated daily intake of the silver catfish in mg kg⁻¹ day⁻¹, C is the PAHs concentration in silver catfish in mg kg⁻¹, FIR is the fish ingestion or consumption rate using the Food and Agricultural Organization's Food Balance Sheets for Nigeria (FAO, 2022) and BW is the average body weight for Nigerians, which is 60.7kg for adults (Walpole et al., 2012) and 30kg for children (Goon et al., 2012). The hazard ratio was calculated following [equation 2](#).

$$HR = EDI / RfD \quad (2)$$

where, RfD is the reference dose factor following the United States Environmental Protection Agency's reference dose for PAH congeners such as naphthalene (0.02), acenaphthene (0.06), fluorene (0.04), anthracene (0.3), fluoranthene (0.04) and pyrene (0.03), ([USEPA, 1993](#)).

Data Analysis

Data analysis was performed using SPSS version 21. Data for individual PAH congeners, total ($\sum_{16}$ PAHs) and carcinogenic PAH congeners ($\sum_8$ PAHs) were summarised into descriptives such as mean, standard error and range. A one-way analysis of variance (ANOVA) was used to determine the level of significance at a probability of 0.05 (95% confidence level).

Results and Discussion

Concentration of PAH Congeners in Silver Catfish

The result showed varying mean concentrations of PAH congeners in silver catfish from the estuary. The highest mean total concentration of individual PAH congeners was reported with fluorene (0.355±0.154 mg kg⁻¹), followed by naphthalene (0.220±0.079 mg kg⁻¹), anthracene (0.147±0.094 mg kg⁻¹), phenanthrene (0.048±0.007 mg kg⁻¹), acenaphthene (0.045±0.010 mg kg⁻¹), acenaphthylene (0.035±0.006 mg kg⁻¹), benzo[a]pyrene (0.024±0.005 mg kg⁻¹), benzo[ghi]perylene (0.017±0.003 mg kg⁻¹), benzo[b]fluoranthene (0.016±0.003 mg kg⁻¹), pyrene (0.013±0.003 mg kg⁻¹), fluoranthene (0.013±0.002 mg kg⁻¹), benzo[k]fluoranthene (0.012±0.002 mg kg⁻¹), benzo[a]anthracene (0.008±0.003 mg kg⁻¹), chrysene and dibenzo[ah]anthracene (0.006±0.002 mg kg⁻¹) and indeno[123cd]pyrene (0.004±0.001 mg kg⁻¹). In this study, fluorene, naphthalene and anthracene were the dominant congeners making up 36.62%, 22.69% and 15.19% of PAH congeners ([Figure 2](#)) respectively. No significant differences were reported in the mean values of PAHs in silver catfish from both study sites and the values of PAH congeners reported in the silver catfish, *C. nigrodigitatus* from the Escravos estuary were higher than the maximum permissible limit for fishery products ([European Commission, 2017](#)), except for benzo[a]anthracene, chrysene, dibenzo[ah]anthracene, and indeno[123cd]pyrene. In their study of fish samples from selected

markets in southern Nigeria, [Tongo et al. \(2016\)](#) reported naphthalene in *Tilapia zilli* (33.3%) and *Scomber scombrus* (32.7%) and benzo[b]fluoranthene in *Clarias gariepinus* (28.5%) and *Ethmalosa fimbriata* (41.5%) as the dominant congeners respectively.

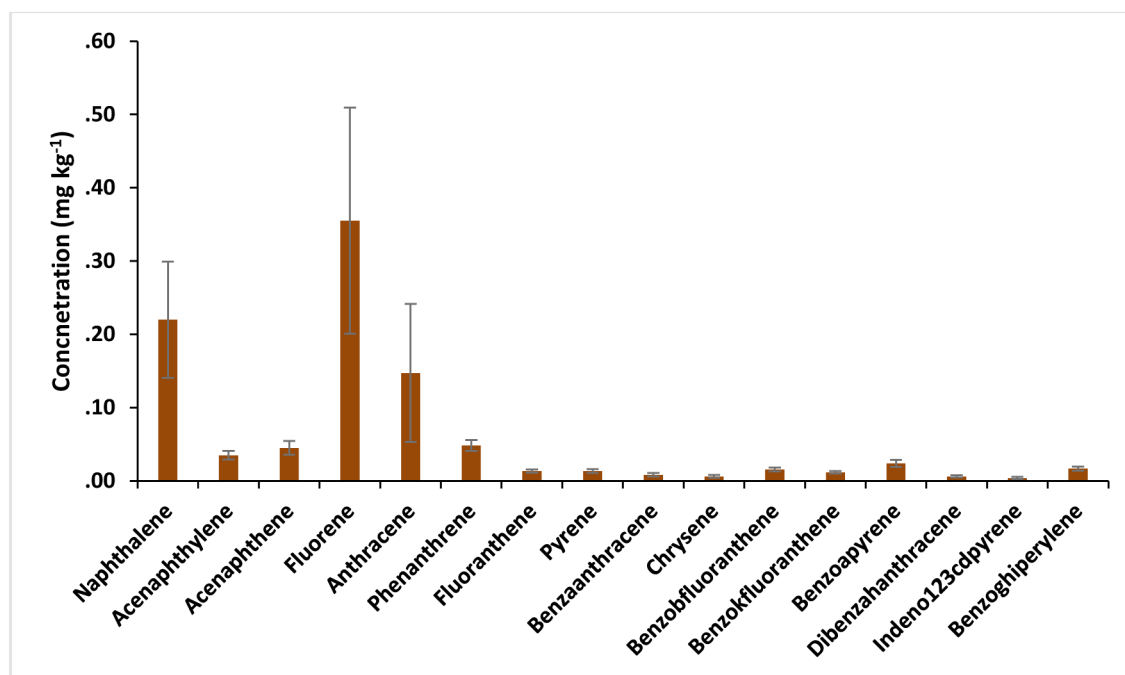


Figure 2—Summary concentration of PAH congeners (mean±SE) in silver catfish collected from the Escravos Estuary in September 2023.

Tissues Distribution of PAHs in Silver Catfish

The total $\sum_{16}$ PAHs in the whole fish from both study sites, was higher in Kurutie (3.023 mg kg⁻¹) compared to Okerenkoko (2.793 mg kg⁻¹), with no significant differences between both sites ($p > 0.05$, $F = 0.411$). Udofia et al. (2021) reported higher values for *C. nigrodigitatus* (4.55 to 6.36 mg kg⁻¹) in Akwa Ibom State. Similarly, [Tongo et al. \(2016\)](#) reported a higher concentration in *S. scombrus* (3.585) in Benin City, compared to our study. The increased levels of total PAH from silver catfish in Akwa Ibom may be connected with the sample location within estuaries with a history of frequent oil spill incidents. Also, the increased levels in the $\sum_{16}$ PAHs congeners reported in Benin City compared to our study, may be associated with the fish processing method which required the involves firewood for fish smoking. Firewood smoking has been implicated to introduce hydrocarbons into fishery products aside from regular exposure from the aquatic ecosystem ([Yusuf et al., 2015](#); [Tongo et al., 2016](#)). Concerning the tissues of the silver catfish, the total $\sum_{16}$ PAHs concentration in the liver, gills and the rest of the fish were 0.963, 1.023 and 1.037 mg kg⁻¹ for Kurutie and 1.993, 0.460 and 0.340 mg kg⁻¹ for Okerenkoko respectively.

The concentration of the individual PAH congeners in the tissues of fish across the two study sites is shown in [Table 1](#). In Kurutie, naphthalene (0.480±0.350 mg kg⁻¹), fluorene (0.093±0.029 mg kg⁻¹) and acenaphthene (0.063±0.024 mg kg⁻¹) were the highest for the liver, fluorene (0.663±0.643 mg kg⁻¹), naphthalene (0.083±0.058 mg kg⁻¹) and anthracene (0.063±0.039 mg kg⁻¹) for the gills and naphthalene (0.513±0.256 mg kg⁻¹), fluorene (0.257±0.213 mg kg⁻¹) and anthracene (0.047±0.015 mg kg⁻¹) for the rest of the fish, whereas in Okerenkoko, fluorene (0.893±0.670 mg kg⁻¹), anthracene (0.650±0.546 mg kg⁻¹) and naphthalene (0.133±0.086 mg kg⁻¹) for the liver, fluorene (0.123±0.093 mg kg⁻¹), naphthalene (0.083±0.063 mg kg⁻¹) and acenaphthene (0.043±0.024 mg kg⁻¹) for the gills, and fluorene (0.100±0.075 mg kg⁻¹), acenaphthene (0.053±0.043 mg kg⁻¹) and acenaphthylene (0.040±0.025 mg kg⁻¹) for the rest of the fish respectively.

Table 1—Summary result of PAH congeners (mean±SE) in tissues of silver catfish collected from the Escravos estuary in September 2023

PAHs	Liver	Gills	RoF*	Liver	Gills	RoF
	Kurutie			Okerenkoko		
Naphthalene	0.480±0.350	0.083±0.058	0.513±0.256	0.133±0.086	0.083±0.063	0.027±0.017
Acenaphthylene	0.043±0.013	0.023±0.009	0.033±0.015	0.043±0.020	0.027±0.012	0.040±0.025
Acenaphthene	0.063±0.024	0.023±0.009	0.037±0.020	0.050±0.025	0.043±0.024	0.053±0.043
Fluorene	0.093±0.029	0.663±0.643	0.257±0.213	0.893±0.670	0.123±0.093	0.100±0.075
Anthracene	0.057±0.009	0.063±0.039	0.047±0.015	0.650±0.546	0.043±0.009	0.023±0.009
Phenanthrene	0.060±0.010	0.050±0.035	0.043±0.020	0.063±0.015	0.043±0.019	0.030±0.012
Fluoranthene	0.017±0.003	0.010±0.006	0.010±0.006	0.027±0.003	0.010±0.006	0.007±0.003
Pyrene	0.017±0.007	0.010±0.006	0.010±0.010	0.023±0.009	0.013±0.003	0.007±0.003
Benzo[a]anthracene	0.007±0.003	0.010±0.010	0.010±0.010	0.013±0.009	0.010±0.000	0.000±0.000
Chrysene	0.010±0.006	0.007±0.007	0.007±0.007	0.010±0.006	0.003±0.003	0.000±0.000
Benzo[b]fluoranthene	0.020±0.010	0.013±0.003	0.017±0.012	0.017±0.003	0.010±0.006	0.017±0.003
Benzo[k]fluoranthene	0.017±0.007	0.013±0.003	0.007±0.003	0.017±0.003	0.007±0.003	0.010±0.000
Benzo[a]pyrene	0.037±0.027	0.020±0.010	0.027±0.009	0.030±0.010	0.013±0.003	0.017±0.003
Dibenzo[h]anthracene	0.010±0.006	0.003±0.003	0.010±0.006	0.007±0.003	0.007±0.003	0.000±0.000
Indeno[123cd]pyrene	0.010±0.006	0.007±0.003	0.003±0.003	0.000±0.000	0.003±0.003	0.000±0.000
Benzo[ghi]perylene	0.023±0.009	0.023±0.009	0.007±0.003	0.017±0.007	0.020±0.006	0.010±0.000

*Rest of the fish

Tissue Distribution for Carcinogenic and Non-Carcinogenic PAHs

In this study, we computed the values for the mean $\sum_8$ PAH carcinogenic (benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, dibenzo[ah]anthracene, indeno[123cd]pyrene and benzo[ghi]perylene) and non-carcinogenic (naphthalene, acenaphthylene, acenaphthene, fluorene, anthracene, phenanthrene, fluoranthene, pyrene) congeners in the tissues of the silver catfish, *C. nigrodigitatus* from the estuary. The sum of the carcinogenic PAHs in silver catfish was 0.553 mg kg⁻¹, while that for non-carcinogenic was 5.264 mg kg⁻¹. The values reported for the total carcinogenic PAHs in our study were higher than those reported in smoke fish in Benin City (Tongo et al., 2016). In the respective tissues, it was 0.243, 0.170 and 0.140 mg kg⁻¹ for the liver, gills, and the rest of the fish for carcinogenic PAHs, whereas it was 2.713, 1.314 and 1.237 mg kg⁻¹ for non-carcinogenic PAHs respectively (Figure 3).

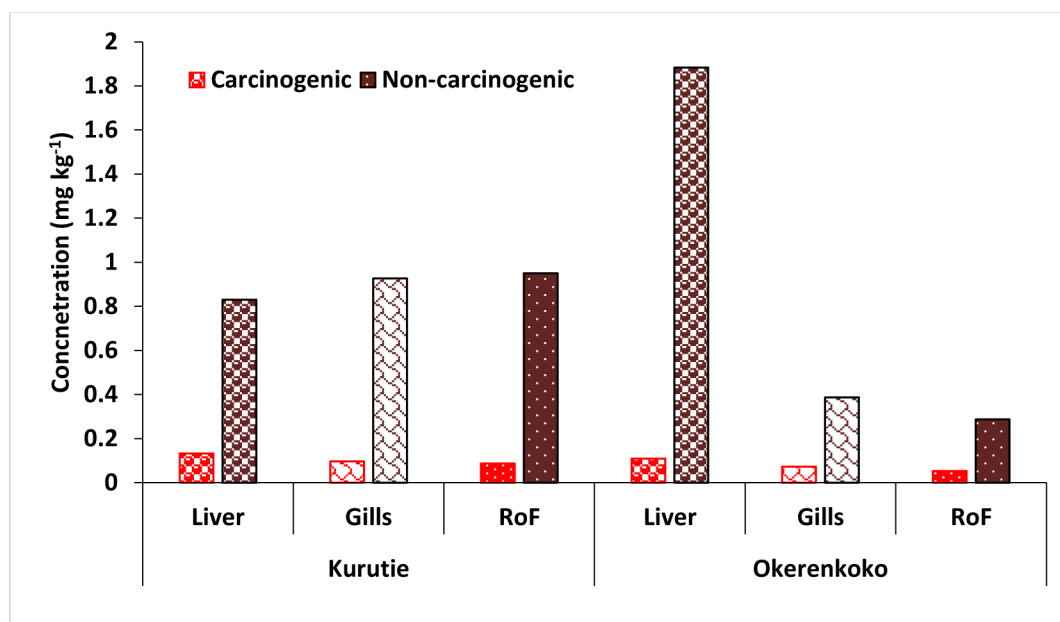


Figure 3—Graph of carcinogenic and non-carcinogenic PAHs in the various tissues of silver catfish collected from the Escravos estuary in September 2023.

Among the individual congeners, benzo[a]pyrene was the highest (0.143 mg kg^{-1}) followed by benzo[ghi]perylene (0.100 mg kg^{-1}), and benzo[b]fluoranthene (0.093 mg kg^{-1}) while the least was indeno[123cd]pyrene (0.023 mg kg^{-1}) for carcinogenic PAHs, whereas, for non-carcinogenic congeners, fluorene (2.130 mg kg^{-1}) was the highest, followed by the naphthalene (1.320 mg kg^{-1}) and anthracene (0.883 mg kg^{-1}) and the least were fluoranthene and pyrene (0.080 mg kg^{-1}) respectively. The levels of carcinogenic PAH congeners were higher than the acceptable limits (European Commission, 2005), which indicates potential concern for public health for the consumption of silver catfish from the estuary. In conformity with our study, both Udofia et al. (2021) and Tongo et al. (2016) reported benzo[a]pyrene as the dominant carcinogenic PAH congeners in *C. nigrodigitatus* collected from Akwa Ibom State and *C. gariepinus* and *E. fimbriata* collected from markets in Benin City with the concentrations higher than the maximum acceptable limit (0.005 mg/kg) in smoked fish (Tongo et al., 2016).

Health Risk Assessment of PAHs from Silver Catfish

Seafood provides a regular source of protein to coastal communities and urban dwellers across Nigeria. In this study, we evaluated the human health risk associated with consuming silver catfish contaminated with PAHs from the estuary. The estimated daily intake (EDI) values were compared against the PAH congeners (naphthalene, acenaphthene, fluorene, anthracene, fluoranthene and pyrene) with available RfD values. The EDI values reported in our study for adults and children (Table 2) were below the RfD values (USEPA, 1993) for the selected PAH congeners in both study locations, while the hazard ratio was less than 1. The EDI values reported in our study were lower than those reported in freshwater catfish (*C. gariepinus*) collected from markets in Benin City (Tongo et al., 2016). The low EDI and hazard ratio (< 1) observed in our study reflect no immediate risk from the daily consumption of silver catfish from the estuary. Low EDI values below the reference doses were also reported in smoked freshwater catfish from Benin City (Tongo et al., 2016) and fish samples collected from Ovia River, both in Edo State (Tongo et al., 2017). Low values were also reported for Mullet fish (*Mugil cephalus*) collected from Bonny estuary (Tongo et al., 2018). Ossai et al. (2023) reported that the EDI and hazard index for all seafood collected from Orashi River in Rivers State were within the maximum permissible limit recommended by the European Food and Safety Agency and the United States Environmental Protection Agency. The prevalence of PAHs within safe limits underscores the biodegradation potentials of hydrocarbons when released into the environment. However, increased

effluents from industrial activities in the region could lead to possible long-term human health risk effects from consuming seafood exposed to PAHs from the estuary.

Table 2—Summary values for EDI and HR for silver catfish collected from the Escravos estuary.

Risk Indicator	Category	NaP	AcP	Flu	Ant	FL	Pyr
Kurutie							
EDI	Adult	0.41E-03	0.05E-03	0.40E-03	0.06E-03	0.01E-03	0.01E-03
	Children	0.85E-03	0.10E-03	0.80E-03	0.12E-03	0.03E-03	0.03E-03
HR	Adult	0.02	0.80E-03	9.90E-03	0.20E-03	0.36E-03	0.48E-03
	Children	0.04	1.62E-03	0.02	0.40E-03	0.73E-03	0.98E-03
Okerenkoko							
EDI	Adult	0.09E-03	0.06E-03	0.44E-03	0.05E-03	0.02E-03	0.02E-03
	Children	0.19E-03	0.12E-03	0.88E-03	0.11E-03	0.03E-03	0.03E-03
HR	Adult	4.75E-03	0.96E-03	0.01	0.18E-03	0.42E-03	0.56E-03
	Children	9.61E-03	1.94E-03	0.02	0.36E-03	0.85E-03	1.13E-03
	RfD	0.02	0.06	0.04	0.3	0.04	0.03

Conclusion

Polycyclic aromatic hydrocarbons are important components of crude oil that requires regular monitoring due to their interaction with the environment, biota and human health. In this study, we investigated the tissue distribution and the potential human health risk associated with PAHs in silver catfish, *C. nigrodigitatus* collected from the Escravos estuary. Varying concentrations of PAHs congeners were reported in the silver catfish with fluorene, naphthalene and anthracene the dominant congeners. Among the tissues, the highest level of PAHs was reported in the liver compared to the gills and the rest of the fish. Non-carcinogenic PAHs were significantly higher than carcinogenic congeners, with the values of carcinogen congeners higher than the maximum permissible limits for fishery products. The EDI values reported in our study for adults and children were below the RfD values for the selected PAH congeners in both study locations, while the hazard ratio was less than 1. However, increased effluents from domestic and industrial activities in the region could lead to possible long-term human health risk effects from the consumption of seafood exposed to PAHs from the estuary.

Conflict of Interest

The authors declare no conflict of interest

Acknowledgement

We are grateful to the Tertiary Education Trust fund (TETFund) under the Federal Ministry of Education for providing the funding (TETF/DR&D/CE/UNIV/NMU/IBR/2023/VOL.1) for this study under the Institutional Based Research (IBR) grant for tertiary institutions in Nigeria.

References

- Adekunle, J.A.O., Oyekunle, I.J.O., Obisesan, O.R. and Maxakato, N.W. 2018. Determination of polycyclic aromatic hydrocarbons (PAHs) and organochlorine pesticides (OCPs) in some personal care products in Nigeria. *Nigeria. Toxicol. Rep.* **5**: 994–1001. doi:10.1016/j.toxrep.2018.10.003

- Akinnusotu, A., Ukpebor, J.E. and Okieimen, F.E. 2023. Source, distribution, and risk assessment of polycyclic aromatic hydrocarbons in sediment and fish samples from River Owan, Edo State, Nigeria. *Front. Toxicol.* **5**:1250943. doi:10.3389/ftox.2023.1250943
- Ambade, B., Sethi, S.S. and Chintalacheruvu, M.R. 2023. Distribution, risk assessment, and source apportionment of polycyclic aromatic hydrocarbons (PAHs) using positive matrix factorization (PMF) in urban soils of East India. *Environ. Geochem. Health* **45**(2): 491–505. doi:10.1007/s10653-022-01223-x
- Christopher, M. 2008. Polycyclic aromatic hydrocarbons (PAHs) in urban soil: Florida risk assessment perspective. *Int. J. Soil Sedim. Water* **1**(2): 1–14
- European Commission 2005. Commission recommendation on the further investigation into the levels of polycyclic aromatic hydrocarbons in certain foods. Notified under document number C (2005/256) (2005/108/EC) *Off. J. Eur. Union.* **314**: 4–9
- European Commission 2017. Commission Regulations (EC) No 1881/2006 of 19 December 2006, setting maximum levels for certain contaminants in foodstuffs, 02006R1881 - EN - 28.07.2017. *Off. J. Eur. Union.* **364**: 1–28
- Ibe, F.C., Duru, C.E., Isiuku, B.O. and Akalazu, J.N. 2021. Ecological risk assessment of the levels of polycyclic aromatic hydrocarbons in soils of the abandoned sections of Orji Mechanic Village, Owerri, Imo State, Nigeria. *Bull. Natl. Res. Cent.* **45**: 18. <https://doi.org/10.1186/s42269-021-00485-2>
- Olayinka, O.O., Adewusi, A.A., Olujimi, O.O. and Aladesida, A.A. 2019. Polycyclic aromatic hydrocarbons in sediment and health risk of fish, crab and shrimp around Atlas Cove, Nigeria. *J. Health Pollut.* **9**(24): 191204. doi:10.5696/2156-9614-9.24.191204
- Ossai, C., Frazzoli, C., Ekhatior, O.C. and Orisakwe, O.E. 2023. Assessment of Polycyclic Aromatic Hydrocarbons (PAHs) in Seafood from Orashi River in Omoku, Rivers State of Nigeria and Human Health Risk Assessment. *Polycycl. Aromat. Comp.* 1–18. <https://doi.org/10.1080/10406638.2023.227012>
- Pang, L., Zhang, S., Wang, L., Yang, T. and Wang, S. 2021. Pollution characteristics and risk assessment of polycyclic aromatic hydrocarbons in the sediment of Wei River. *Environ. Earth Sci.* **80**(5): 203–211. doi:10.1007/s12665-021-09483-z
- Phillips, D.H. 1999. Polycyclic aromatic hydrocarbons in the diet. *Mutat. Res./Genet. Toxicol. Environ. Mutagenesis.* **443**(1): 139–147
- Rey-Salgueiro, L., Garcia-Falcón, M.S., Soto-Gonzalez, B. and Simal-Gándara, J. 2009. The occurrence of polycyclic aromatic hydrocarbons and their hydroxylated metabolites in infant foods. *Food Chem.* **115**: 814–819
- Simko, P. 2002. Determination of polycyclic aromatic hydrocarbons in smoked meat products and smoke flavouring food additives. *J. Chromatogr. B.* **770**(1-2): 3–18
- Tongo, I., Ogbeide, O., Ezemonye, L. 2016. Human health risk assessment of polycyclic aromatic hydrocarbons (PAHs) in smoked fish species from markets in Southern Nigeria. *Toxicol. Rep.* **4**: 55–61. doi:10.1016/j.toxrep.2016.12.006
- Tongo, I., Ezemonye, L. and Akpeh, K. 2017. Distribution, characterization, and human health risk assessment of polycyclic aromatic hydrocarbons (PAHs) in Ovia River, Southern Nigeria. *Environ. Monit. Assess.* **189**(6): 247 <https://doi.org/10.1007/s10661-017-5931-5>
- Tongo, I., Etor, E.E. and Ezemonye, L.I.N. 2018. Human Health Risk Assessment of PAHs in Fish and Shellfish from Amariaria Community, Bonny River, Nigeria *J. Appl. Sci. Environ. Manage.* **22**(5): 731–736. <https://dx.doi.org/10.4314/jasem.v22i5.19>
- Udofia, U.S., Ameh, C., Miller, E., Ekpenyong, M.S. 2021. Investigating the origin and tissue concentration of polycyclic aromatic hydrocarbons in seafood and health risk in Niger Delta, Nigeria. *Environ. Sci. Processes Impacts.* **23**: 1803–1814. doi: 10.1039/D1EM00249J
- United States Environmental Protection Agency 1993. *Provisional Guidance for Quantitative Risk Assessment of Polycyclic Aromatic Hydrocarbons*. EPA/600/R-93/089. Office of Research and Development, United States Environmental Protection Agency, Washington, DC
- Wang, J., Liu, J., Ling, W., Huang, Q. and Gao, Y. 2017. Composite of PAH-degrading endophytic bacteria reduces contamination and health risks caused by PAHs in vegetables. *Sci. Total Environ.* **598**: 471–478. doi: 10.1016/j.scitotenv.2017.04.126
- Yusuf, K.A., Ezechukwu, L.N., Fakoya, K.A., Akintola, L.S., Agboola, J.I. and Omoleye T.O. 2015. Influence of fish smoking methods on polycyclic aromatic hydrocarbons content and possible risks to human health. *Afr. J. Food Sci.* **9**(3): 126–135