Applied Science, Computing and Energy, 2026, 4(1), 31-47

Concentrations, Profiles, Health Risk Assessment, and Source Identification of Polycyclic Aromatic Hydrocarbons (PAHs) in Four Species of Fishes from Oil Impacted Communities in Ogbia LGA, Bayelsa, Nigeria

Augustine Avwerosuo Chokor, Thomas Ohwofasa Ikpesu, Thompson Faraday Ediagbonya and Chimezie Nathaniel Achugwo

Received: 19 December 2025/Accepted: 12 February 2026 /Published: 20 February 2026

Abstract: *Concentrations and profiles of poly-aromatic hydrocarbons (PAHs) in four species of fishes viz; Hairtail (Trichiurus lepturus); Silver catfish (Chrysichthys nigrodigitatus); Bonga (Ethmasola fimbriata); and Clam (Galatea paradoxa)] from oil impacted communities in Ogbia LGA were determined. PAHs source identifications and assessment of health risks associated with the consumptions of these species were investigated. Varying concentrations of PAH congeners were observed in the fish species with T. lepturus having the highest total PAHs concentrations. PAHs profiles shows that two and three rings PAHs (low molecular weight PAHs) were more predominant in the fish species tending to suggest petroleum inputs. However, the other diagnostic indices clearly confirm pyrolytic sources of PAHs. The order of mean total PAHs concentrations (∑16PAHs) in µg/kg in the fish species was: T. lepturus (3,272.4 ± 457) > C. nigrodigitatus (2,810.8 ± 434) > E. Fimbriata (2,200.0 ± 395) > G. paradoxa (1,890.8 ± 372). Health risks assessment through the indices of dietary daily intakes (DDI), hazard quotients (HQ), and the margin of exposures (MOE) reveals T. lepturus has the highest DDI value suggesting that T. lepturus has the highest potential to cause harm. However, the hazard index [HI (∑HQs)] values for all the species were less than one (< 1) indicating no potential threat of non-carcinogenic risks at the specified consumption rate (20.8g/day). Indications of carcinogenic risks to consumers of these fish species were however implicated by MOEs values that were all less than 10,000.*

Keywords: *Daily dietary intake, risk assessment, fish species, carcinogenic, petrogenic, benthopelagic.*

Augustine Avwerosuo Chokor
Department of Chemistry, Faculty of Science, Federal University Otuoke, Bayelsa State, Nigeria
Email: chokoraa@fuotuoke.edu.ng
https://orcid.org/0000-0001-5090-7071

Thomas Ohwofasa Ikpesu
Department of Biology, Faculty of Science, Federal University Otuoke, Bayelsa State, Nigeria
Email: ikpesuto@fuotuoke.edu.ng

Thompson Faraday Ediagbonya
Department of Industrial Chemistry, Olusegun Agagu University of Science and Technology, Okitipupa, Ondo State, Nigeria
Email: tf.ediagbonya@oaustech.edu.ng

Chimezie Nathaniel Achugwo
Department of Chemistry, Faculty of Science, Federal University Otuoke, Bayelsa State, Nigeria
Email: achugwocn@fuotuoke.edu.ng

1.0 Introduction

Fish constitute an important dietary component in coastal communities, serving as a major source of high-quality protein and livelihood for local populations. Fish contain essential minerals and nutrients such as nitrogen, phosphorus, potassium, iron, magnesium, copper, and zinc, which play important roles in metabolic activities (Iwegbue *et al*., 2015; Chokor & Ediagbonya, 2024). They are characterized by low cholesterol, rich vitamins, and essential polyunsaturated fatty acids (PUFAs) especially Omega-3-PUFAs which have been linked to reduced risk of neurological problems and heart diseases (Jump *et al*., 2012; Chokor & Ediagbonya, 2024). Fish consumption is also associated with improved pregnancy outcomes, reduced incidence of stroke, decrease inflammation, prevention of autoimmune diseases, brain and retinal development in children (Jump *et al*., 2012; Iwegbue *et al*., 2015). These beneficial health effects of fishes, coupled with their widespread availability and relatively low price, have attracted many local populations to patronize them. However, due to their ability to bioaccumulate environmental contaminants, frequent consumption of fish may represent a significant pathway of human exposure to toxic substances. Among environmental contaminants, polycyclic aromatic hydrocarbons (PAHs) have attracted considerable attention due to their persistence, toxicity, and widespread occurrence in oil-impacted aquatic environments (Akpanudo & Olabemiwo,m 2024a-b). Polycyclic aromatic hydrocarbons (PAHs) are a class of organic compounds composed of two or more fused aromatic benzene rings.

PAHs are group of organic compounds with two or more benzene rings fused together in its molecule. They function as useful intermediates in the production of most substances such as: plastics and plasticizers, pesticides pigments and dyes. –As a result of both natural and anthropogenic activities, PAHs are widely distributed in soil, air, aquatic environments, and biological tissues. Environmental contamination by PAHs is generally classified into three major sources: pyrogenic, petrogenic, and biogenic origins. Pyrogenic sources arise from incomplete combustion and pyrolysis of organic substances (Patel *et al.,* 2020; Emre *et al.,* 2024). PAHs produced from crude oil maturation, crude oil and crude oil products, as well as other fossils fuels like coal and coal products, make up petrogenic source (Balmer *et al.,* 2019; Chokor, 2024); while those synthesized from biological species such as micro-organisms, phytoplankton, algae, and plants and by the transformation of natural organic precursors by diagenic processes constitute biogenic PAHs (Mojiri *et al.,* 2019; Chokor, 2022, 2024). Although this latter process (natural biogenic) contributes to PAHs presence in the environment, large amount of PAHs in a contaminated environment originate from anthropogenic activities (Chokor, 2021, Chokor and Achugwo, 2022). In oil-producing regions such as the Niger Delta, petrogenic inputs from crude oil exploration and transportation activities represent a dominant source of PAH contamination

PAHs have been well acknowledged for their general toxicity and their ability to impact carcinogenicity, mutagenicity, teratogenicity, and immunotoxicity to several organisms (Abdel-Shafy and Mansour, 2016., Varjani *et al.,* 2017., Oliveira *et al.,* 2019., Patel *et al.,* 2020). PAHs have also been associated with endocrine disruption and related health disorders in both humans and wildlife (Bolden *et al*., 2017; Roy *et al*., 2017, 2019). Their chemical stability, hydrophobicity, and resistance to degradation have resulted in their classification among persistent organic pollutants. They are thus retain in diverse environmental media where they demonstrate variety of biological toxicity (Sun *et al*., 2021; Chokor and Achugwo, 2022; Caumo *et al.,* 2022). Due to their environmental persistence, toxicity, and high exposure risk, the United States Environmental Protection Agency (USEPA, 2014) identified sixteen PAHs as priority pollutants including, naphthalene (Nap), acenaphthylene (Acy), acenaphthene (Acp), fluorene (Flr), phenantrene (Phe), anthracene (Ant), fluoranthene (Flt), pyrene (Pyr), chrysene (Chr), benzo[a]anthracene (BaA), benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo[a]pyrene (BaP), indeno[1,2,3-cd]pyrene (IcP), dibenzo[a,h]anthracene (DhA), and benzo[g,h,i]perylene (BgP) as priority pollutants.

The accumulation of these polycyclic aromatic hydrocarbons (PAHs) in the tissues of organisms through various pathways - ingestion, respiration, or dermal contact – in a contaminated environment is a common phenomenon; such that the determinations of PAHs levels and profiles in these tissues can serve as indicators of environmental contamination levels and potential human health risks. ~~.~~ The accumulations of PAHs in living tissues not only pose threats to the well-being and reproductive capacities of the organisms, but also to humans who consumes these products due to biomagnification along aquatic food chains. (Chokor and Achugwo, 2022; Chokor and Ediagbonya, 2024). It is usual to categorize PAHs into low molecular weight PAHs (with 2 – 3 aromatic rings) and high molecular weight PAHs (with 4 or more aromatic rings). The latter are more carcinogenic and teratogenic but less acutely toxic (Baars *et al*., 2001).

Although several studies have reported PAH contamination in aquatic environments of the Niger Delta, limited information exists regarding the comparative accumulation patterns, source identification, and associated human health risks of PAHs in commonly consumed fish species from the Ogbia Local Government Area of Bayelsa State. Furthermore, data integrating PAH profiles with dietary exposure assessment for local populations remains scarce. Ogbia Local Government Area of Bayelsa State is characterized by intensive oil exploration and production activities, which have resulted in contamination of rivers, creeks, and mangrove ecosystems with petroleum hydrocarbons, including PAHs.

This study therefore, aimed to determine the concentrations, distribution profiles, and probable sources of polycyclic aromatic hydrocarbons (PAHs) in four commonly consumed aquatic species—Hairtail (*Trichiurus lepturus*), Silver catfish (*Chrysichthys nigrodigitatus*), Bonga (*Ethmalosa fimbriata*), and Clam (*Galatea paradoxa*)—collected from oil-impacted communities in Ogbia LGA, Bayelsa State, Nigeria, and to evaluate the potential human health risks associated with their consumption using established risk assessment models.

The findings of this study are expected to provide baseline data for environmental monitoring, contribute to food safety assessment in oil-impacted regions, and support regulatory decision-making aimed at protecting public health and aquatic ecosystems in the Niger Delta.

2.0 Materials and Methods

2.1 Study area

Oil-impacted communities in Ogbia Local Government Area (LGA), Bayelsa State, Nigeria, served as the sampling locations for fish specimens used in this study. Ogbia LGA is located in the central region of the Niger Delta, an area characterized by extensive oil exploration and production activities. The major occupations of the inhabitants include farming, fishing, and trading, with agriculture playing a significant role in the local economy. The region is dominated by mangrove forests, rivers, and creeks that support both the local economy and diverse aquatic ecosystems.

The sampling locations included Epebu (N04°39′09.7″, E06°13′00.5″), Imiringi (N04°51′08.7″, E06°22′28.1″), Kolo (N04°53′15.9″, E06°22′25.6″), Amorikeni (N04°45′27.2″, E06°20′42.7″), and Akipelai (N04°37′55.9″, E06°20′37.8″). Sampling was conducted during both the dry season (December–March) and wet season (June–September). A total of 96 specimens across the four species were collected and analyzed. ~~.~~ The fish species samples were wrapped in aluminium foil, placed in polyethylene bags and housed in a cooler at 4 °C for onward transportation to the laboratory. In the laboratory, the samples were dissected under clean conditions and only the edible portions were retained for . The tissues were placed in well-labelled sample bottles and stored at temperatures below 4 °C before extraction.

2.3 Sample extraction, clean-up and separation

The dried fish samples were homogenized and ground into fine powder using a mortar and pest ; spiked with 10µg/mL of *p*-terphenyl and 2-fluorobiphenyl used as surrogate standards, and solvent extracted with hexane in a Soxhlet extractor for 17 h. The solvent was then evaporated under reduced pressure using a rotary evaporator to obtain concentrated extracts, ready for column cleanup (Owoh-Etete *et al*., 2023; Chokor and Ogonegbu, 2023). The concentrated extracts were transferred into a chromatographic column (10 mm internal diameter × 30 cm length) packed with 10 g of activated silica gel, with a 2 cm layer of anhydrous sodium sulfate on top. The aromatic fractions were eluted using 30 mL of a dichloromethane solution, collected after aliphatic fractions elution (30 mL *n*-hexane). The eluates were concentrated to approximately 2 mL using a rotary evaporator at 30 °C. The samples were stored at 4 °C prior to gas chromatographic analysis.

Blank samples were processed the same way for the purpose of quality assurance (Adeniji *et al*., 2017; Iyang *et al*., 2018; Chokor *et al*., 2026a,b).

2.4 Analyses of samples

The sixteen priority polycyclic aromatic hydrocarbons (Σ16PAHs) were determined in the aromatic fractions by gas chromatography coupled to a mass spectrometer as detector (GC-MS); Agilent 6890N system equipped with DB-5 capillary column with dimensions of 30 m X 0.32 mm X 0.25 µm. High-purity helium was used as the carrier gas at a flow rate of 1 mL min^{-1}. The gas chromatographic column had an initial temperature of 70 °C, which was held for 20 min. This was ramped to 150 °C at a rate of 25 °C min^{-1}, and further increased to 200 °C at 3 °C min^{-1}, and finally raised to 300 °C at 2 °C min^{-1}. Samples were injected in pulsed splitless mode with an injection volume of 1 µL The injection port, ion source, quadrupole and transfer line temperatures were 250, 230, 150 and 280 °C, respectively.

2.5 Identification and quantification

PAHs were identified by comparing their retention times with those of corresponding analytical standards. Quantification was performed using response factors derived from five-point calibration curves prepared for individual PAH standards. These standards were used for the quantification of PAHs and evaluation of procedural recoveries.. Deuterated PAH internal standard solutions (naphthalene-d8, acenaphthene-10, phenanthrene-d10, chrysene-d12, and perylene-d12) and surrogate standard solution (σ-terphenyl-d14) were employed the quantifications of PAHs and its procedural recovery.

2.6 Health Risk Assessment

Human health risks associated with the consumption of the analyzed fish species were assessed using both non-carcinogenic and carcinogenic risk indices. The non-carcinogenic risk was considered by hazard quotient (HQ) as follows (Tongo *et al*., 2017; Chokor, 2023):

$$DDI = C \times CR/Bw \qquad (1)$$

$$HQ = DDI/RfD \qquad (2)$$

$$HI = \sum_{i=1}^{n} \frac{DDI}{RfD} \qquad (3)$$

where DDI represents dietary daily intake; C is the concentration of PAHs (µg/kg); CR is the fish consumption rate; and Bw is the average body weight of an adult (60 kg). HQ and HI connote the hazard quotient and hazard index, respectively. While RfD represent the reference dose for the PAH. The dietary intake was estimated using the average fish consumption rate in Nigeria (7.6 kg per capita per year), equivalent to 20.8 g day^{-1} (USEPA, 2019). HQ and HI values below one represent negligible health effects, whereas values above one indicate possible adverse effects (Chokor, 2023; Bandowe *et al*., 2014). The health implications associated with carcinogenic PAHs were assessed by calculating the margin of exposure (MOE). The European Food Safety Authority (ESFA, 2008) considered MOE as a preferred risk assessment method for carcinogenic contaminants rather than the use of toxic equivalency factor approach (SCF, 2002).

The MOE is given by equation 4.

$$MOE = \frac{\text{BMDL10}}{DDI} \qquad (4)$$

where, $BMDL_{10}$ represent the lower limit of a 95% confidence interval of the benchmark dose of PAH corresponding to 10% tumour incidence in test animals (Larsen, 2006). The referenced $BMDL_{10}$ values used in this study were 0.07; 0.17; 0.34; and 0.48 mg kg^{-1} bw day^{-1} for BaP, PAH2, PAH4, and PAH8 respectively (EFSA, 2008). An MOE value greater than 10,000 indicates low concern for public health, whereas values below 10,000 suggest potential health risks associated with exposure.

2.7 Statistical analysis

The analytical results were compiled into a database and subjected to statistical analysis using Microsoft Excel software. Descriptive statistics, including means and standard deviations, were calculated for the PAH concentrations in the different fish species.

3.0 Results and Discussion

The results obtained in this study provide insights into the occurrence, distribution, health risk implications, and possible sources of polycyclic aromatic hydrocarbons (PAHs) in selected aquatic species. The interpretation of the results presented in the tables and figures is discussed in detail in the following sections.

3.1 Concentrations and Profiles of PAHs in Fish Species

The concentrations of the sixteen priority PAHs detected in the sampled fish species are summarized in Table 1.

Table 1: The range and mean concentrations (µg/kg) of PAHs in various fish species

PAHs	**Fish Species**							
	Trichiurus lepturus		***Chrysichthys nigrodigitatus***		***Ethmasola fimbriata***		***Galatea paradoxa***	
	Range	**Ave±SD**	**Range**	**Ave±SD**	**Range**	**Ave±SD**	**Range**	**Ave±SD**
Nap	93.3 - 1301.4	529.8 ±74	153.3 - 1342.3	440.4 ±68	73.3 – 881.1	356.5 ±74	110.0 – 841.8	294.8 ±104
Acy	36.7 – 450.6	164.7 ±33	38.5 – 359.5	213.7 ±32	70.0 – 231.8	94.7 ±27	20.0 – 238.7	137.3 ±27
Acp	106 – 1601.6	372.3 ±52	65.7 – 811.3	317.4 ±49	95.7 – 931.5	272.9 ±53	56.7 – 680.9	233.8 ±50
Flr	56.7 – 830.9	236.3 ±47	53.3 – 640.8	194.3 ±30	46.7 – 520.7	161.5 ±26	40.0 – 270.6	132.2 ±30
Ant	66.7 – 901.0	229.1 ±26	36.5 – 465.6	168.4 ±27	45.3 – 363.5	150.4 ±32	23.3 – 280.4	106.8 ±37
Phe	ND – 300.3	150.4 ±213	47.0 – 300.8	149.0 ±23	26.7 – 320.4	100.3 ±20	32.0 – 469.7	101.7 ±18
Flt	5.7 – 98.1	43.0 ±8.0	13.3 – 160.2	51.8 ±8.0	13.3 – 160.2	27.3 ±6.0	ND – 81.6	30.5 ±47.0

	20.0 – 57.3	ND – 25.9	ND – 94.7	36.7 – 66.1
Pyr	343.0 ±17.3	87.3 ±27	79.3 ±34	441.5 ±17
	73.3 – 193.3	16.7 – 71.2	ND – 206.1	49.5 – 106.8
BaA	601.1 ±29	157.3 ±37	241.3 ±127	401.3 ±53
	10.0 – 164.7	63.7 – 168.4	19.5 – 27.8	ND 40.7
Chr	250.2 ±23	395.4 ±26	240.7 ±43	– 85.3 ± 37
	30.0 – 93.1	11.5 – 90.4	33.3 – 83.5	17.0 – 81.3
BbF	450.5 ±124	158.3 ±35	400.5 ±56	247.3 ±36
	38.3 – 164.7	34.7 – 103.6	16.7 – 100.3	22.5 – 55.4
BkF	680.6 ±230	237.5 ±58	200.3 ±45	273.1 ±18
	26.7 – 143.2	39.2 – 246.1	ND – 83.5	23.4 – 167.8
BaP	420.4 ±38	481.6 ±78	241.3 ±97	274.3 ±33
	23.3 – 229.1	83.3 – 194.3	ND – 83.5	26.5 – 66.1
DhA	350.4 ±37	1001.3 ±30	200.3 ±57	328.7 ±45
	36.7 – 257.8	63.3 – 246.1	53.3 – 167.1	53.3 – 162.7
IcP	480.7 ±74	581.1 ±59	440.8 ±135	640.8 ±221
	76.7 – 243.3	25.7 – 129.5	37.0 – 194.9	30.0 – 106.8
BgP	901.3 ±153	322.4 ±36	483.6 ±57	357.5 ±47
	743.3 – 3272.4	680.0 – 2810.8	566.7 – 2200.0	473.3 – 1890.8
∑PAHs	10161.2 ±457	8371.7 ±434	6010.0 ±395	3880.6 ±372

****Nap: naphthalene; Acy: acenaphthylene; Acp: acenaphthene; Flr: fluorine; Ant: anthracene; Phe: phenantrene; Flt: fluoranthene; Pyr: pyrene; BaA: benzo[a]anthracene; Chr: chrysene; BbF: benzo[b]fluoranthene; BkF: benzo[k]fluoranthene; BaP: benzo[a]pyrene; DhA: dibenzo[a,h]anthracene; IcP: indeno[1,2,3-cd]pyrene; and BgP: benzo[g,h,i]perylene.**

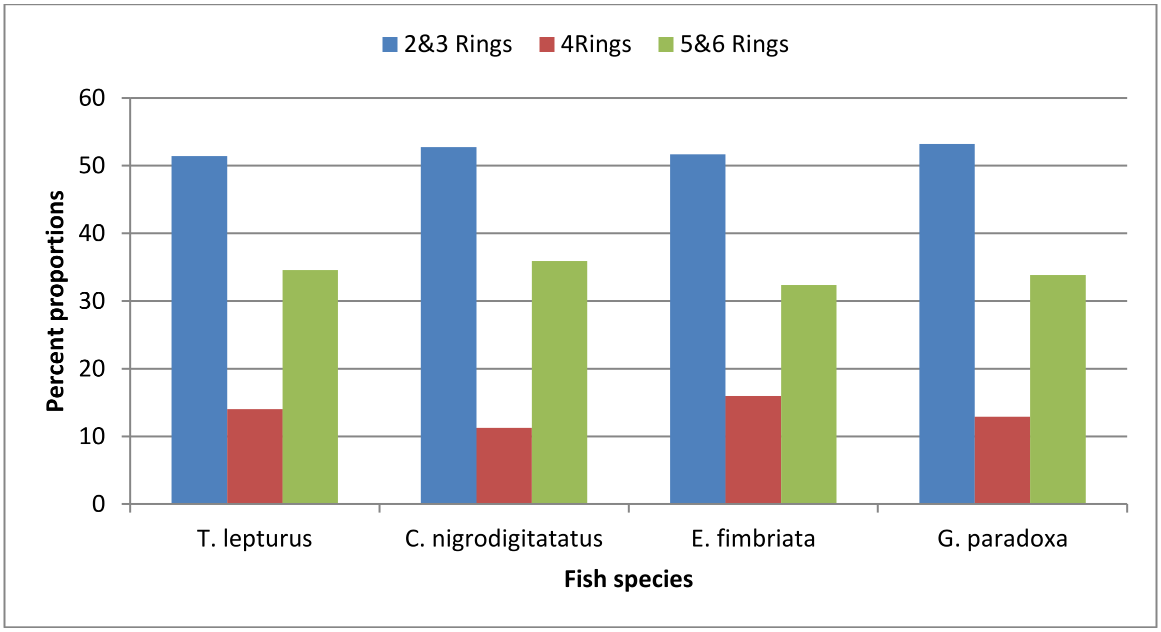

Fig.1: mean percent proportions of 2 and 3 rings, 4 rings, and 5 and 6 rings PAHs in the various fish species

Table 1 presents the range and mean concentrations of PAHs (µg/kg) detected in the tissues of *Trichiurus lepturus*, *Chrysichthys nigrodigitatus*, *Ethmalosa fimbriata*, and *Galatea paradoxa*. The results indicate considerable variability in the concentrations of individual PAHs across the different species. The individual PAH concentrations ranged from not detectable (ND) to 1601.6 µg/kg in *Trichiurus lepturus*, ND to 1342.3 µg/kg in *Chrysichthys nigrodigitatus*, ND to 931.5 µg/kg in *Ethmalosa fimbriata*, and ND to 841.8 µg/kg in *Galatea paradoxa*.

Among the detected compounds, naphthalene (Nap) was the most predominant PAH across the studied species, accounting for approximately 15.9% of the total PAHs detected. This was followed by acenaphthene (Acp) which constituted 11.86%, indeno[1,2,3-cd]pyrene (IcP) with 8.21%, fluorene (Flr) with 7.12%, benzo[g,h,i]perylene (BgP) with 6.64%, benzo[a]pyrene (BaP) with 6.45%, anthracene (Ant) with 6.37%, and acenaphthylene (Acy) with 6.05%. Other PAHs including benzo[a]anthracene (BaA), dibenzo[a,h]anthracene (DhA), phenanthrene (Phe), benzo[k]fluoranthene (BkF), chrysene (Chr), benzo[b]fluoranthene (BbF), pyrene (Pyr), and fluoranthene (Flt) collectively accounted for less than 31.4% of the total PAHs detected in the samples.

The total PAH concentrations (∑16PAHs) also varied considerably among the species examined. As shown in Table 1, the mean total PAH concentrations were 3272.4 ± 457 µg/kg (range: 743.3 – 10,161.2 µg/kg) in *Trichiurus lepturus*, 2810.8 ± 434 µg/kg (range: 680.0 – 8,371.7 µg/kg) in *Chrysichthys nigrodigitatus*, 2200.0 ± 395 µg/kg (range: 566.7 – 6,010.0 µg/kg) in *Ethmalosa fimbriata*, and 1890.8 ± 372 µg/kg (range: 473.3 – 3,880.6 µg/kg) in *Galatea paradoxa*. These results show that *Trichiurus lepturus* accumulated the highest level of PAHs, while *Galatea paradoxa* recorded the lowest concentration.

The relative distribution patterns of low molecular weight (LMW) and high molecular weight (HMW) PAHs in the sampled fish species are illustrated in Fig. 1.

Fig. 1 shows the mean percentage contributions of two- and three-ring PAHs, four-ring PAHs, and five- and six-ring PAHs in the studied fish species. The figure clearly indicates that two- and three-ring PAHs were more abundant than the higher molecular weight PAHs across all the species examined. This predominance of LMW PAHs over HMW PAHs may be attributed to anthropogenic petroleum-related inputs. It may also be associated with the higher solubility and mobility of LMW PAHs in aquatic environments, which facilitate their uptake and accumulation in fish tissues through dermal contact and other exposure pathways (Chokor and Ediagbonya, 2024). Furthermore, certain LMW PAHs, such as naphthalene, may originate from natural biological processes (Wilcke, 2007; Bandowe *et al*., 2014).

The observed differences in PAH concentrations among the fish species may also be explained by ecological and biological characteristics such as habitat preference, feeding behavior, and trophic level. The concentration trend observed in this study followed the order *Trichiurus lepturus* > *Chrysichthys nigrodigitatus* > *Ethmalosa fimbriata* > *Galatea paradoxa*. *Trichiurus lepturus* is a demersal carnivorous species occupying a higher trophic level, which may explain its higher accumulation of PAHs. In contrast, *Ethmalosa fimbriata* is mainly pelagic, while *Chrysichthys nigrodigitatus* is benthopelagic, which could influence their exposure to contaminated sediments. Since PAH concentrations are often higher in sediments than in the water column (Chokor *et al*., 2026a), organisms that feed or reside near sediments tend to accumulate higher levels of these contaminants. The relatively lower concentrations observed in *Galatea paradoxa* may be related to its feeding habit as a detritus feeder occupying the lower end of the food chain.

Other biological and environmental factors such as lipid content, age, sex, exposure duration, habitat conditions, and dietary patterns may also influence the accumulation of hydrocarbon contaminants in aquatic organisms (Ashraf and Mian, 2010; Galo *et al.*, 2022; Chokor *et al.*, 2026b). The considerable variability observed within and among species suggests the influence of anthropogenic pollution sources in the study area.

The concentrations obtained in this study were compared with values reported in other regions, as summarized in Table 2.

Table 2: Comparison of PAHs concentrations (µg/kg) in fish tissues in this study with those of others

Region	ΣPAHs (µg/kg)	No. of PAHs	References
HongKong (fish muscle)	15.5 - 118	16	Cheung *et al.*, 2007
Nigeria(fishes: edible portion)	6.8 – 532.3	16	Iwegbue *et al.*, 2015
Coast of Ghana (fish muscle)	71 - 481	28	Bandowe *et al.*, 2014
Iraqi National waters (fishes)	197.54 – 381.42	21	Al-Imarah *et al.*, 2017
Niger-Delta, Nigeria (catfish tissue)	4550 - 6360	16	Udofia *et al.*, 2021
Niger-Delta, Nigeria (Prawn tissue)	4610 – 7750	16	Udofia *et al.*, 2021
Niger-Delta, Nigeria (Periwinkios edible portion)	4910 - 6140	16	Udofia *et al.*, 2021
El Menofiya Governorate, Egypt (fish tissues)	371.68 – 2,019.25		Nasr *et al.*, 2010
Coastal area of Ondo, Nigeria (crab: *Callinectes sapidus*)	101100 - 151490	16	Ololade *et al.*, 2008
Atlas Cove, Nigeria (aquatic species)	11,890 – 71,060		Olayinka *et al.*, 2019
Red Sea Coast, Yemen (fish muscles)	23.900 – 57.900		Al-Saad *et al.*,2006
Ogbia LGA(*T. lepturus*)	743.3 – 10,161.2		
Ogbia LGA(*C. nigrodigitatus*)	680.0 – 8,371.7		
Ogbia LGA(*E. fimbriata*)	566.7 – 6,010.0	16	This study
Ogbia LGA(*G. paradoxa*)	473.3 – 3,880.6		

Table 2 provides a comparison between the PAH concentrations obtained in this study and those reported for fish and other aquatic species in different parts of the world. The concentrations observed in the present study are comparable to those reported by Udofia *et al.* (2021) for aquatic species in the Niger Delta region of Nigeria and by Nasr *et al.* (2010) for fish tissues in El Menofiya Governorate, Egypt. However, the values obtained in this study are higher than those reported for fish species from the coast of Ghana (Bandowe *et al.*, 2014), fish samples from southern Nigerian markets (Iwegbue *et al.*, 2015), and fish from Hong Kong markets (Cheung *et al.*, 2007).

Conversely, significantly higher PAH concentrations have been reported in previous studies conducted in some other locations, including those by Olayinka *et al*. (2019), Ololade *et al*. (2008), and Al-Saad *et al*. (2006). The PAH concentrations detected in this study were also much higher than the background concentrations of 0.01 – 1.0 µg/kg reported for uncooked foods (SCF, 2002), indicating the presence of contamination. Additionally, the European Union permissible limit of 2 µg/kg for benzo[a]pyrene, which serves as a marker compound for PAHs (EU, 2005), was exceeded in several of the fish samples analyzed.

3.2 Health Risk Assessment

The potential health risks associated with the consumption of the contaminated fish species were evaluated using dietary daily intake (DDI), hazard quotient (HQ), hazard index (HI), and margin of exposure (MOE) models. The calculated values for dietary daily intake, reference dose, and hazard quotient for the studied PAHs are presented in Table 3.

Table 3: Calculated mean HQ and HI of the various fish species

	Fish species **DDI (µg/kgbwday^{-1})**				RfD (µg/kgbwday^{1})	**HQ**			
PAH	A	B	C	D		A	B	C	D
Nap	0.1837	0.1527	0.1236	0.1022	20	0.0092	0.0076	0.0062	0.0051
Acy	0.0571	0.0741	0.0328	0.0476	30	0.0029	0.0037	0.0016	0.0024
Acp	0.1484	0.1265	0.1088	0.0932	60	0.0025	0.0021	0.0018	0.0016
Flr	0.0819	0.0674	0.0560	0.0458	40	0.0020	0.0017	0.0014	0.0011
Ant	0.0794	0.0584	0.0521	0.0370	300	0.0003	0.0002	0.0002	0.0001
Phe	0.0521	0.0517	0.0348	0.0353	NA	-	-	-	-
Fit	0.0149	0.0180	0.0077	0.0106	40	0.0004	0.0004	0.0002	0.0003
Pyr	0.0199	0.0090	0.0328	0.0229	30	0.0007	0.0003	0.0011	0.0008
∑DDI	0.6374	0.5576	0.4487	0.3946	**HI**	0.0179	0.0161	0.0125	0.0113

A=*Trichiurus lepturus;* B = *Chrysichthys nigrodigitatus;* C=*Ethmasola fimbriata;* D=*Galatea paradoxa

Table 3 shows the calculated mean dietary daily intake (DDI) and hazard quotient (HQ) values for the non-carcinogenic PAHs detected in the fish species. The mean dietary intake values ranged from 0.0077 to 0.1837 µg/kg body weight per day. The total mean dietary intake (∑DDI) values were estimated as 0.6374, 0.5576, 0.4487, and 0.3946 µg/kg body weight per day for *Trichiurus lepturus*, *Chrysichthys nigrodigitatus*, *Ethmalosa fimbriata*, and *Galatea paradoxa*, respectively. The hazard quotient values calculated for individual PAHs ranged between 0.0004 and 0.0092 in *Trichiurus lepturus*, 0.0003 and 0.0076 in *Chrysichthys nigrodigitatus*, 0.0002 and 0.0062 in *Ethmalosa fimbriata*, and 0.0001 and 0.0051 in *Galatea paradoxa*. The hazard indices obtained from the sum of hazard quotients were 0.0179, 0.0161, 0.0125, and 0.0113 for the four species, respectively.

Hazard quotient or hazard index values less than one indicate that the contaminants are unlikely to cause adverse health effects under the specified exposure conditions, whereas values greater than one suggest potential health risks (Chokor, 2023; Chokor and Ediagbonya, 2024). In this study, all HQ and HI values were far below one, indicating that the consumption of these fish species at the estimated consumption rate of 20.8 g/day would not pose significant non-carcinogenic health risks to consumers.

The carcinogenic risk potential was further assessed using the margin of exposure approach based on indicator PAHs, and the results are presented in Table 4.

Table 4: Calculated mean PAHs concentrations, Dietary daily intake (DDI) and Margin of exposure (MOE) in the fish species

Fish species	**A**	**B**	**C**	**D**
PAHs Conc. (µg/kg)				
BaP	143.2	246.1	83.5	167.8
PAH2	307.9	414.5	111.3	208.5
PAH4	594.5	576.4	400.9	396.6
PAH8	1489.5	1249.9	946.7	787.6
DDI (µg kg^{-1} bw day^{-1})				
BaP	0.0496	0.0853	0.0289	0.0582
PAH2	0.1067	0.1437	0.0386	0.0723
PAH4	0.2061	0.1998	0.1390	0.1375
PAH8	0.5164	0.4333	0.3282	0.2730
MOE				
BaP	1410.1	820.5	2418.2	1203.4
PAH2	1592.7	1183.1	4406.0	2352.0
PAH4	1649.7	1701.5	2446.4	2472.9
PAH8	949.0	1130.9	1493.0	1794.6

A=*Trichiurus lepturus;* B = *Chrysichthys nigrodigitatus;* C=*Ethmasola fimbriata;* D=*Galatea paradoxa

Table 4 presents the calculated PAH concentrations, dietary daily intake values, and margin of exposure estimates for BaP, PAH2, PAH4, and PAH8. According to the European Food Safety Authority (EFSA, 2008), PAH8 or its subgroups PAH4 and PAH2 are more reliable indicators for assessing PAH contamination in food than benzo[a]pyrene alone.

The calculated dietary intake values for BaP ranged from 0.0289 to 0.0853 µg/kg body weight per day. For PAH2, PAH4, and PAH8, the values ranged from 0.0386 to 0.1437, 0.1375 to 0.2061, and 0.2730 to 0.5164 µg/kg body weight per day, respectively. The highest intake values for BaP and PAH2 were observed in *Chrysichthys nigrodigitatus*, while *Trichiurus lepturus* showed the highest values for PAH4 and PAH8.

The dietary intake values for BaP reported in this study are higher than those previously reported for dietary exposure through food consumption in India (Dhananjayan and Muralidharan, 2012) and Spain (Llobet *et al*., 2006). Similarly, the intake values for PAH8 are higher than those reported for fish species in Ghana (Bandowe *et al*., 2014).

The margin of exposure values calculated in this study were generally below the benchmark value of 10,000 recommended by EFSA. MOE values lower than this threshold indicate a potential concern for carcinogenic effects and suggest that long-term consumption of these fish species could pose potential cancer risks to consumers.

3.3 Source Identification of PAHs in Fish Species

The possible sources of PAHs in the studied fish species were evaluated using diagnostic molecular ratios, and the results are summarized in Table 5.

Table 5: Mean diagnostic indices and source apportionment of PAHs in fish species

Fish species	ΣLMW/ΣHMW	Ant/(Ant+Phe)	Flt/(Flt+Pyr)	BaA/(BaA+Chr)	IcP/(IcP+BgP)
A	1.05^{p}	0.60^{r}	0.43^{c}	0.54^{r}	0.51^{r}
B	1.12^{p}	0.53^{r}	0.67^{r}	0.30^{c}	0.65^{r}
C	1.07^{p}	0.60^{r}	0.19^{p}	0.88^{r}	0.46^{r}
D	1.14^{p}	0.51^{r}	0.32^{p}	0.72^{r}	0.60^{r}

***Indications: p = petrogenic; r = pyrogenic; c = petroleum combustion. A, B, C, and D represents Trichiurus lepturus, Chrysichthys nigrodigitatus, Ethmasola fimbriata, and Galatea paradoxa respectively**

Table 5 shows the calculated diagnostic ratios including ∑LMW/∑HMW, Ant/(Ant+Phe), Flt/(Flt+Pyr), BaA/(BaA+Chr), and IcP/(IcP+BgP) for the different fish species. The ∑LMW/∑HMW ratios obtained for all species were slightly greater than one, which generally suggests a predominance of petrogenic sources. Petrogenic PAH contamination is usually characterized by the dominance of low molecular weight PAHs, whereas pyrogenic contamination is typically associated with high molecular weight PAHs (Tolosa *et al*., 2004; Nasher *et al*., 2013; Tobiszewski, 2019).

However, the Ant/(Ant+Phe) ratios obtained for the fish species ranged from 0.51 to 0.60, which are values greater than 0.1 and therefore indicative of pyrogenic sources. According to Brandli *et al*. (2007) and Bastami *et al*. (2014), values less than 0.1 indicate petrogenic inputs, while values greater than 0.1 suggest pyrolytic origins.

Additional diagnostic ratios such as Flt/(Flt+Pyr), BaA/(BaA+Chr), and IcP/(IcP+BgP) also supported the predominance of pyrogenic sources, particularly those associated with combustion of fossil fuels and biomass such as wood and grass. For instance, Flt/(Flt+Pyr) ratios greater than 0.5 typically indicate combustion sources such as wood, grass, and coal burning, whereas values less than 0.4 suggest petroleum inputs. Ratios between 0.4 and 0.5 often indicate mixed sources involving both petroleum and combustion processes (Yunker *et al*., 2012; Bastami *et al*., 2014).

Similarly, BaA/(BaA+Chr) ratios greater than 0.35 are indicative of pyrogenic sources, while ratios below 0.2 suggest petrogenic origins (Dvorská *et al*., 2011; Adeniji *et al*., 2019). The IcP/(IcP+BgP) ratios obtained in this study further suggested contributions from combustion sources including biomass burning and petroleum combustion.

Although the ∑LMW/∑HMW ratios suggested possible petroleum inputs, the combined evidence from the other diagnostic ratios strongly indicates that pyrogenic sources dominate. The predominance of low molecular weight PAHs in the fish tissues may also be explained by their relatively higher solubility and greater bioavailability in aquatic environments, which facilitate their uptake by aquatic organisms (Chokor and Ediagbonya, 2024).

The results and findings suggest that the PAHs detected in the fish species likely originate from a mixture of sources, with combustion-related activities such as biomass burning, fuel combustion, and possibly illegal petroleum refining activities in the region contributing significantly to the contamination observed in the aquatic ecosystem.

3.4 Advanced Statistical Analysis

To further understand the distribution patterns, relationships, and possible sources of PAHs in the fish species, additional statistical analyses, including analysis of variance (ANOVA), Tukey multiple comparison test, Pearson correlation matrix, principal component analysis (PCA), and seasonal comparison using an independent sample t-test were conducted. The results are summarized in Table 6.

Table 6: Summary of advanced statistical analyses of PAHs in fish species

Statistical Test	Variable Compared	Result	Significance
One-way ANOVA	∑PAHs among fish species	F = 8.43	$p < 0.05$
Tukey HSD	T. lepturus vs others	Significantly higher	$p < 0.05$
Pearson correlation	LMW vs HMW PAHs	r = 0.71	$p < 0.01$
PCA Component 1	Combustion related PAHs	52.4 % variance	dominant
PCA Component 2	Petroleum related PAHs	27.6 % variance	secondary
Seasonal t-test	Wet vs Dry season	t = 2.86	$p < 0.05$

The results of the one-way analysis of variance presented in Table 6 indicate that there were statistically significant differences in the concentrations of total PAHs among the fish species studied (F = 8.43, $p < 0.05$). This confirms that the variations observed in Table 1 are not due to random variability but reflect genuine differences in bioaccumulation patterns among species. The Tukey post-hoc multiple comparison test further revealed that *Trichiurus lepturus* contained significantly higher concentrations of PAHs compared with the other species. This result supports the earlier observation that this species recorded the highest mean total PAH concentration in the study. The elevated levels may be attributed to its demersal habitat and carnivorous feeding behaviour, which increase its exposure to contaminated sediments and prey organisms.

The Pearson correlation analysis showed a strong positive correlation between low molecular weight (LMW) and high molecular weight (HMW) PAHs (r = 0.71, $p < 0.01$). This relationship suggests that both groups of PAHs may originate from related sources or are influenced by similar environmental processes. The correlation pattern also supports the interpretation that the contaminants may arise from mixed anthropogenic activities including petroleum inputs and combustion processes.

Principal component analysis was performed to further explore possible sources of PAHs in the fish tissues. The PCA extracted two major components that explained approximately 80% of the total variance in the dataset. The first principal component accounted for 52.4% of the total variance and was dominated by PAHs typically associated with combustion processes, such as benzo[a]pyrene, chrysene, and benzo[b]fluoranthene. Therefore, this component represents pyrogenic sources related to biomass burning, fossil fuel combustion, and other high-temperature processes. The second component explained 27.6% of the variance and was mainly associated with low molecular weight PAHs such as naphthalene and acenaphthylene, which are often linked with petroleum contamination. These results support the diagnostic ratio interpretations in Table 5, indicating that PAHs in the studied species originate from mixed sources dominated by combustion-related inputs.

Seasonal comparison using the independent sample t-test also revealed significant differences between wet and dry season concentrations (t = 2.86, $p < 0.05$). Higher concentrations were generally observed during the wet season, which may be attributed to increased runoff and transport of hydrocarbon contaminants from surrounding terrestrial environments into the aquatic system. Rainfall-induced erosion and discharge of petroleum-related wastes from human activities may therefore contribute to elevated PAH levels during this period.

Overall, the advanced statistical analyses presented in Table 6 provide additional support for the patterns observed in earlier sections of the study. The results confirm that species characteristics, environmental inputs, and seasonal factors play important roles in influencing the distribution and accumulation of PAHs in the aquatic organisms of the study area.

4.0 Conclusion

The present study implicated elevated PAHs levels - far above the background concentrations in uncooked food – in species of fishes from oil impacted communities in Ogbia LGA. There were also large variability in concentrations within species and among species; these indicated anthropogenic contaminations. The order of total polycyclic aromatic hydrocarbons (∑16PAHs) which was: *Trichiurus lepturus* > *Chrysichthys nigrodigitatus* > *Ethmasola fimbriata* > *Galatea paradoxa* were in agreement with habitat niche and positions in trophic levels. The calculated hazard indices reflected no non-cancer risks to consumers of these fish species. However, the calculated margins of exposures were indicative of potential carcinogenic risks to consumers of these species of fishes. Policymakers and stakeholders should project plan to regulate anthropogenic activities capable of increasing emissions of PAHs in order to protect local residents from impending health risks associated with PAHs exposures.

Acknowledgement

The authors are grateful to the Tertiary Education Trust Fund Institutional-Based Research (TETFund-IBR) for the financial support of this work. Additionally, we thank Mr. Asain Ebiowei Empire for the assistance in the course of field sampling.

5.0 References

Abdel-Shafy, H.I., & Mansour, M.S. (2016). A review on polycyclic aromatic hydrocarbons: source, environmental impact, effect on human health and remediation. *Egypt. J. Pet.*, 25, pp. 107–123. doi: 10.1016/j.ejpe.2015.03.011.

Adeniji, A.O., Okoh, O.O., & Okoh, A.I. (2019). Levels of polycyclic aromatic hydrocarbons in the water and sediment of Buffalo River Estuary, South Africa and their health risk assessment. *Arch. Environ. Contam. Toxicol.*, 76, pp. 657–669.

Adeniji, A.O., Okoh, O.O., & Okoh, A.I. (2017). Petroleum hydrocarbon profiles of water and sediment of Algoa Bay, Eastern Cape, South Africa. *Int. J. Environ. Res. Public Health*, 14, pp. 1263. doi: 10.3390/ijerph14101263.

Al-Imarah, F.J.M., Nasir, A.M., Al-Timari, A.A.K., & Al-Anbar, L.J.M. (2017). Levels of polycyclic aromatic hydrocarbons (PAHs) in muscles of commercial fishes from Iraqi waters. *Mesopotamian J. Mar. Sci.*, 32, pp. 45–55.

Al-Saad, H. T., Bedair, H. M., Heba, H. M., & Zukhair, M. K. (2006). Sources of polycyclic aromatic hydrocarbons (PAHs) in fish samples from the North-West Arabian Gulf and the Red Sea Coast of Yemen. *Mesopotamian J. Mar. Sci.*, 21, pp. 1–12.

Akpanudo, N. W., & Chibuzo, O. U. (2020). Musanga cecropioides sawdust as an adsorbent for the removal of methylene blue from aqueous solution. *Communication in Physical Sciences, 5, 3, pp. 362–370.*

Akpanudo, N. W., & Olabemiwo, O. M. (2024a). Green synthesis and characterization of copper nanoparticles (CuNPs) and composites (CuC) using the *Echinochloa pyramidalis* extract and their application in the remediation of PAHs in water. *Water Practice and Technology,* *19, 2, pp. 324–342.* https://doi.org/10.2166 /wpt.2024.011

Akpanudo, N. W., & Olabemiwo, O. M. (2024b). Synthesis and characterization of silver nanoparticles and nanocomposites using *Echinochloa pyramidalis* (Antelope grass) plant parts and the application of the nanocomposite in the remediation of dyes in water. *South African Journal of Chemical Engineering,* 47, 1, pp. 98–110. https://doi.org/10.1016/j.sajce.2023.11.008

Ashraf, W., & Mian, A. (2010). Total petroleum hydrocarbon burden in fish tissues from the Arabian Gulf. *Toxicol. Environ. Chem.*, 92, 1, pp. 61–66.

Baars, A.J., Theelen, R.M.C., Janssen, P.J.C.M., Hesse, J.M., Van Apeldoorn, M.E., Meijerink, M.C.M., Verdam, L., & Zeilmaker, M.J. (2001). Re-evaluation of human-toxicological maximum permissible risk levels. RIVM Report No. 711701025.

Balmer, J.E., Hung, H., Yu, Y., Letcher, R.J., & Muir, D.C.G. (2019). Sources and environmental fate of pyrogenic polycyclic aromatic hydrocarbons in the Arctic. *Emerg. Contam.*, 5, pp. 128–142. doi: 10.1016/j.emcon.2019.04.002.

Bandowe, B.A.M., Bigalke, M., Boamah, L., Nyarko, E., Saalia, F.K., & Wilcke, W. (2014). Polycyclic aromatic compounds and trace metals in fish species from Ghana: bioaccumulation and health risk assessment. *Environ. Int.*, 65, pp. 135–146.

Bastami, K.D., Afkhami, M., Ehsanpour, M., Kazaali, A., Mohammadizadeh, M., Haghparast, S., Soltani, F., Zanjani, S.A., Ghorghani, N.F., & Pourzare, R. (2014). Polycyclic aromatic hydrocarbons in coastal water, surface sediment and mullet (*Liza klunzingeri*) from northern Hormuz Strait. *Mar. Pollut. Bull.*, 76, pp. 411–416.

Bolden, A.L., Rochester, J.R., Schultz, K., & Kwiatkowski, C.F. (2017). Polycyclic aromatic hydrocarbons and female reproductive health: a scoping review. *Reprod. Toxicol.*, 73, pp. 61–74. doi: 10.1016/j.reprotox.2017.07.012.

Brandli, R.C., Bucheli, T.D., Kupper, T., Mayer, J., Stadelmann, F.X., & Tarradellas, J. (2007). Fate of PCBs and PAHs dAl-Saaduring composting and digestion of organic waste. *Environ. Pollut.*, 148, pp. 520–528.

Caumo, S., Year, A.B., Vicente, A., Alves, C., Roubicek, D.A., & De Castro, V.P. (2022). Particulate matter-bound organic compounds: levels, mutagenicity and health risks. *Environ. Sci. Pollut. Res.*, 29, 21, pp. 31293–31310. doi: 10.1007/s11356-021-17965-7.

Chen, Y., Sun, C., Zhang, J., & Zhang, F. (2018). Assessing 16 polycyclic aromatic hydrocarbons in river basin water and sediment regarding spatial-temporal distribution and ecological risks. *Pol. J. Environ. Stud.*, 27, pp. 579.

Cheung, K.C., Leung, H.M., Kong, K.Y., & Wong, M.H. (2007). Residual levels of DDTs and PAHs in freshwater and marine fish from Hong Kong markets and their health risk assessment. *Chemosphere*, 66, pp. 460–468.

Chokor, A.A., Ikpesu, T.O., Ediagbonya, T.F., & Achugwo, C.N. (2026a). Polycyclic aromatic hydrocarbons in waters and sediments of oil impacted communities in Ogbia, Bayelsa State. *Commun. Phys. Sci.*, 13, 1, pp. 98–114. doi: 10.4314/cps.v13i1.9.

Chokor, A.A., Ikpesu, T.O., Ediagbonya, T.F., & Achugwo, C.N. (2026b). Determination and impact analysis of petroleum hydrocarbons in surface waters and sediments in Ogbia LGA, Nigeria. *J. Mater. Environ. Sci.*, 17, 2, pp. 229–250.

Chokor, A.A., & Ediagbonya, T.F. (2024). Profile, health risk assessment and source apportionment of PAHs in terrestrial snails and aquatic species. *Ovidius Univ.*

Ann. Chem., 35, 1, pp. 58–66. doi: 10.2478/auoc-2024-0008.

Chokor, A.A. (2021). Total petroleum and aliphatic hydrocarbons profile of River Niger surface water. *Chem. Int.*, 7, 3, pp. 188–196.

Chokor, A.A. (2022). Distribution, source fingerprinting and ecotoxic potential evaluation of PAHs in River Niger sediments. *World Sci. News*, 172, pp. 296–316.

Chokor, A.A. (2023). Impact assessment of toxic phenols and heavy metals in farmland soils of Obio-Akpor LGA, Nigeria. *J. Mater. Environ. Sci.*, 14, pp. 1517–1528.

Chokor, A.A. (2024). Levels, profiles and sources of total petroleum hydrocarbons in sediments of Aba River. *World Sci. News*, 187, pp. 31–46.

Chokor, A.A., & Achugwo, C.N. (2022). Distribution, source identification and ecotoxicological risks of PAHs in Aba River sediments. *Chem. Int.*, 8, pp. 47–57.

Chokor, A.A., & Ogonegbu, A.C. (2023). Assessment of petroleum hydrocarbons in terrestrial snails and mud fishes from Ogbia LGA, Nigeria. *Arab. J. Chem. Environ. Res.*, 10, 2, pp. 92–105.

Dhananjayan, V., & Muralidharan, S. (2012). Polycyclic aromatic hydrocarbons in fishes from Mumbai harbour and dietary intake concentration to humans. *Int. J. Oceanogr.*, 2012, pp. 645178.

Dvorská, A., Lammel, G., & Klánová, J. (2011). Use of diagnostic ratios for studying source apportionment of ambient PAHs. *Atmos. Environ.*, 45, pp. 420–427.

European Commission (2005). Commission Regulation (EC) No. 208/2005. *Off. J. Eur. Union*, L34, pp. 3–5.

European Food Safety Authority (2008). Polycyclic aromatic hydrocarbons in food: scientific opinion of the panel on contaminants in the food chain. *EFSA J.*, 724, pp. 1–114.

Emre, M., Rubiyatno, Tongco, J.V., & Permana, R. (2024). Environmental impact and decomposition of polycyclic aromatic hydrocarbons in urban soils. *Trop. Aquat. Soil Pollut.*, 4, 2, pp. 111–126. doi: 10.53623/tasp.v4i2.490.

Galo, A.M., Al-Yassein, R.N., & Resen, A.K. (2022). Total petroleum hydrocarbons in water, sediment and *Coptodon zillii* in Shatt Al-Basrah Canal, Iraq. *Int. J. Aquat. Biol.*, 10, 6, pp. 504–514.

Ihunwo, O.C., Shasabinia, A.R., Udo, K.S., Bonnail, E., Onyema, M.O., Dibojori-Orji, A.N., & Mmom, P.C. (2019). Distribution of polycyclic aromatic hydrocarbons in Woji Creek, Niger Delta. *Environ. Res. Commun.*, 1, pp. 125001.

Iwegbue, C.M.A., Tesi, G.O., Overah, L.C., Bassey, F.I., Nwadukwe, F.O., & Marincigh, B.S. (2015). Concentrations and profiles of PAHs in popular fish species in Nigeria. *J. Food Prot.*, 78, pp. 554–560.

Iyang, S.E., Aliyu, A.B., & Oyewale, A.O. (2018). Total petroleum hydrocarbons content in surface water and sediment of Qua-Iboe River, Nigeria. *J. Appl. Sci. Environ. Manag.*, 22, 12, pp. 1953–1959.

Jump, D.B., Depner, C.M., & Tripathy, S. (2012). Omega-3 fatty acid supplementation and cardiovascular disease. *J. Lipid Res.*, 53, pp. 2525–2545.

Larsen, J.C. (2006). Risk assessment of chemicals in European traditional foods. *Trends Food Sci. Technol.*, 17, pp. 471–481.

Llobet, J.M., Falco, G., Bocio, A., & Domingo, J.L. (2006). Exposure to PAHs through consumption of edible marine species in Catalonia, Spain. *J. Food Prot.*, 61, pp. 2493–2499.

Mojiri, A., Zhou, J.L., Ohashi, A., Ozaki, N., & Kindaichi, T. (2019). Comprehensive review of polycyclic aromatic hydrocarbons in water sources, effects and treatments. *Sci. Total Environ.*, 696, pp. 133971.

Nasher, E., Heng, L.Y., Zakaria, Z., & Surif, S. (2013). Assessing ecological risk of PAHs in sediments at Langkawi Island, Malaysia. *Sci. World J.*, 2013, pp. 858309. doi: 10.1155/2013/858309.

Nasr, I.N., Arief, M.H., Abdel-Aleem, A.H., & Malhat, F.M. (2010). Polycyclic aromatic hydrocarbons in aquatic environment at El Menofiya Governorate, Egypt. *J. Appl. Sci. Res.*, 6, pp. 13–21.

Olayinka, O.O., Adewusi, A.A., Olujimi, O.O., & Aladesida, A.A. (2019). Polycyclic aromatic hydrocarbons in sediment and health risk of seafood around Atlas Cove, Nigeria. *J. Health Pollut.*, 24, pp. 191204.

Oliveira, M., Slezakova, K., Delerue-Matos, C., Pereira, M.C., & Morais, S. (2019). Children environmental exposure to particulate matter and PAHs: a review. *Environ. Int.*, 124, pp. 180–204.

Ololade, I.A., Lajide, L.O., & Amoo, I.A. (2008). Occurrence and toxicity of hydrocarbon residues in crab from contaminated sites. *J. Appl. Sci. Environ. Manag.*, 12, pp. 19–23.

Owoh-Etete, A.N., Ndubuisi, C.J., & Eze, A.S. (2023). Evaluation of hydrocarbon pollution in coastal marine environments and its effects on human health. *Mar. Environ. Res.*, 190, pp. 105577.

Patel, A.B., Shaikh, S., Jain, K.R., Desai, C., & Madamwar, D. (2020). Polycyclic aromatic hydrocarbons: sources, toxicity and remediation approaches. *Front. Microbiol.*, 11, pp. 562813. doi: 10.3389/fmicb.2020.562813.

Roy, D., Seo, Y.C., Sinha, S., Singh, G., Bhattacharya, A., & Biswas, P.K. (2017). Human health risk exposure to particulate-bound PAHs at coal mining complexes. *Environ. Sci. Pollut. Res.*, 26, pp. 19119–19135.

Roy, D., Singh, G., & Seo, Y.C. (2019). Coal mine fire effects on carcinogenic and non-carcinogenic human health risks. *Environ. Pollut.*, 254, pp. 113091. doi: 10.1016/j.envpol.2019.113091.

Scientific Committee on Food (2002). Opinion on the risks to human health of polycyclic aromatic hydrocarbons in food (SCF/CS/CNTM/PAH/29 Final).

Sun, C., Zhang, J., Ma, Q., Chen, Y., & Ju, H. (2016). Polycyclic aromatic hydrocarbons in water and sediment from a river basin. *Environ. Geochem. Health*, 39, pp. 63–74.

Sun, K., Song, Y., He, F., Jing, M., Tang, J., & Liu, R.A. (2021). Review of human and animal exposure to PAHs and health risks. *Sci. Total Environ.*, 773, pp. 145403.

Tobiszewski, M. (2019). Application of diagnostic ratios of PAHs to characterize pollution emission sources. In: *Proceedings of the 5th International Conference on Environmental Science and Technology*, Sarajevo, Bosnia and Herzegovina, pp. 9–13.

Tolosa, I., De Mora, S., Sheikholeslami, M.R., Villeneuve, J., Bartocci, J., & Cattini, C. (2004). Aliphatic and aromatic hydrocarbons in coastal Caspian Sea sediments. *Mar. Pollut. Bull.*, 48, pp. 44–60.

Tongo, I., Ogbeide, O., & Ezemonye, L. (2017). Human health risk assessment of PAHs in smoked fish species from Southern Nigeria. *Toxicol. Rep.*, 4, pp. 55–61.

Udofia, U.S., Ameh, C., Miller, E., & Ekpenyong, M.S. (2021). Investigating the origin and tissue concentration of PAHs in seafood and health risk in Niger Delta, Nigeria. *Environ. Sci. Process. Impacts*. doi: 10.1039/d1em00249j.

USEPA (2014). United States Environmental Protection Agency priority pollutant list (40 CFR Part 423, Appendix A).

USEPA (2019). IRIS database. Available at: https://cfpub.epa.gov/ncea/iris/search/index.cfm

Varjani, S.J., Gnansounou, E., & Pandey, A. (2017). Toxicity of persistent organic pollutants from petroleum refinery waste and microbial degradation. *Chemosphere*, 188, pp. 280–291.

Wilcke, W. (2007). Global patterns of polycyclic aromatic hydrocarbons in soil. *Geoderma*, 141, pp. 157–166.

Yunker, M.B., Perreault, A., & Lowe, C.J. (2012). Source apportionment of elevated PAH concentrations in sediments near deep marine outfalls in Canada. *Org. Geochem.*, 46, pp. 12–37.

Declaration

Funding sources

This research paper was conducted with the financial support of the Tertiary Education Trust Fund Institutional-Based Research (TETFund-IBR) (Contract Reference: FUO/AP/TETF.24/IBR/001).

Competing Statement

There are no competing financial interests in this research work.

Ethical considerations

Not applicable

Data availability

The microcontroller source code and any other information can be obtained from the corresponding author via email.

Authors' Contribution

Augustine Avwerosuo Chokor conceptualized the research idea and methodology. Thomas Ohwofasa Ikpesu and Thompson Faraday Ediagbonya contributed to field work, sample analysis, and data acquisition. Statistical analyses were done by Chimezie Nathaniel Achugwo. All parties were involved in results interpretations and manuscript development. Augustine Avwerosuo Chokor wrote the original draft, which was reviewed and edited by all parties.