

## Concentration and associated risks of polycyclic aromatic hydrocarbons in soils around abandoned oil wellheads in Kolo Creek, Bayelsa State, Nigeria

Richard Alexis Ukpe\*, and Paschal Okiroro Iniaghe

Received: 11 November 2025/Accepted: 11 February 2026 /Published: 20 February 2026

**Abstract:** Polycyclic aromatic hydrocarbons (PAHs) are recalcitrant pollutants commonly associated with oil exploration activities. This study assessed the concentration and associated risks of PAHs in soils around abandoned oil wellheads in Kolo Creek, Bayelsa State, Nigeria. The total PAHs concentration varied between 226 - 228.2  $\mu\text{g kg}^{-1}$ , while that of the most carcinogenic PAH, benzo[a]pyrene (BaP), varied between 58 and 61  $\mu\text{g kg}^{-1}$ . The concentration of  $\Sigma 16$  PAHs and BaP did not vary significantly ( $p > 0.05$ ) across the four locations. High-molecular-weight PAHs predominated over low-molecular-weight PAHs. The PAHs' ring-size distribution followed the order: 5-ring > 3-ring > 2-ring > 4-ring. The calculated risk quotient values for individual PAHs were within their permissible limits. Non-cancer risk assessment suggested no immediate non-carcinogenic health risk, with values < 1. However, the estimated incremental lifetime cancer risk exceeded the US EPA acceptable limit for both children and adults exposure scenarios, indicating a health concern in the long-term. These results suggest the need for continuous monitoring and remediation to limit the risks associated with PAHs in the studied areas.

**Keywords:** benzo[a]pyrene, risk quotient, hazard index, incremental lifetime cancer risk

**Richard Alexis Ukpe\***

Department of Chemistry, Faculty of Science, Federal University Otuoke, Nigeria

Email: [ukpera@fuotuoke.edu.ng](mailto:ukpera@fuotuoke.edu.ng)

<https://orcid.org/0000-0002-1010-4933>

**Paschal Okiroro Iniaghe**

Department of Chemistry, Faculty of Science, Federal University Otuoke, Nigeria

Email: [iniaghepo@fuotuoke.edu.ng](mailto:iniaghepo@fuotuoke.edu.ng)

### 1.0 Introduction

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous compounds comprising at least two fused aromatic rings. They are natural components of crude oil, accounting for about 2 %wt (Ravindra *et al.*, 2008). They can enter the environment through partial combustion activities and crude oil leakage/spillage (Nikitha *et al.*, 2017). The slow degradation rates and continuous input of PAHs into soil from various anthropogenic activities make it a primary source of PAH exposure and risk to humans. The US EPA prioritized 16 out of the several existing PAHs as pollutants for routine monitoring and control (US EPA, 2011). The ability of PAHs to biomagnify in the food chain, alongside their carcinogenic, teratogenic and mutagenic properties, increases their overall risk of toxicity to humans (Zheng *et al.*, 2016). The composition of PAHs varies, depending on the source of generation and as such, the toxicity of PAHs from varying sources may not be only based on the sum-total of PAHs, but also on the toxicity of individualistic PAHs from the various sources (Yadav *et al.*, 2018). The acute health effects of PAHs depend on the PAHs' toxicity and exposure route (Kim *et al.*, 2013), while chronic exposures could lead to kidney and liver damage, lung abnormalities, and decreased immune function (Abdel-Shafy and Mansour, 2016).

One source of PAHs in soil emanates from the environs of abandoned oil wellheads. These sources are a significant

environmental concern, especially in regions like Nigeria's Niger Delta, where extensive oil exploration activities take place. The environmental impact of such wells may be worsened by prolonged neglect, leading to possible leakage of hydrocarbons, which can release toxic and environmental PAHs into the surrounding environment. It was reported that the PAH level in soil around new oil wellheads originated from oil sources (petrogenic) while PAHs in soils around older wellheads were related to combustion sources (Fu *et al.*, 2018). Also, residual PAH level in soil can surpass  $100 \mu\text{g kg}^{-1}$  with continuous years of oil exploration activities (Fu *et al.*, 2018). Local residents in such areas may thus be exposed to PAHs, as they often have limited personal protection due to a lack of awareness and understanding of the toxicity of PAHs. Therefore, understanding the distribution of PAHs in soils around abandoned oil wellheads is crucial for assessing the potential risks to human health and the ecosystems, and for developing effective remediation strategies (Babaniyi *et al.*, 2023).

Soils around abandoned oil wellheads in Kolo Creek, specifically in Imiringi area of Bayelsa State, Nigeria, was selected for this study to conduct risk assessment of soils contaminated by PAHs. This study became necessary due to the lack of existing data on the environmental impact of these abandoned oil wellheads to the surrounding ecosystem. This is in contrast to earlier studies within the region, which focused mainly on soil and water contamination from oil spill sites (Eucharia *et al.*, 2016; Ezekwe *et al.*, 2018; Itodo *et al.*, 2019; Ahiamadu *et al.*, 2021; Enuneku *et al.*, 2021; Iniaghe and Kpomah, 2023). The objectives of this study were to quantify the PAHs level in soils around abandoned oil wellheads in Imiringi area of Bayelsa State, and to assess the ecological and human health risks associated with PAHs in such soils.

## 2.0 Materials and Methods

### 2.1 Study area



The Kolo Creek includes all communities in Ogbia area of Bayelsa State in Nigeria's Niger Delta region, where oil exploration activities occur. The oil and gas field in Kolo Creek is located in Imiringi community. Imiringi community is historically known for its richness in oil deposits, with several oil exploration activities taking place. It is located on  $4.8519^{\circ}\text{N}$  and  $6.3745^{\circ}\text{E}$ . The inhabitants of the area are mainly fishermen, subsistence agricultural farmers, palm wine tapping and small-scale traders (Ezekwe *et al.*, 2018). Many of the abandoned oil wellheads in Imiringi have been left unmonitored after their abandonment. The proximity of these wellheads to the community and the natural ecosystem make the region a critical study area for understanding the broader implications of oil extraction on soil, as well as human health. The environs of the abandoned oil wellheads in this study are located between the Federal Government College Imiringi, and the Kolo Creek flow station. Fig. 1 is a map of Nigeria, indicating Bayelsa State and the study locations.

### 2.2 Sample collection and preparation

Four (4) composite top-soil samples (0-10 cm) were obtained from four identified locations within abandoned oil wellheads in Imiringi using a stainless steel soil auger. Collected samples were kept in aluminum foils, placed in ziplock bags. In the laboratory, they were air-dried at ambient temperature, ground and sieved using 2 mm mesh. Samples were kept in the refrigerator before extraction.

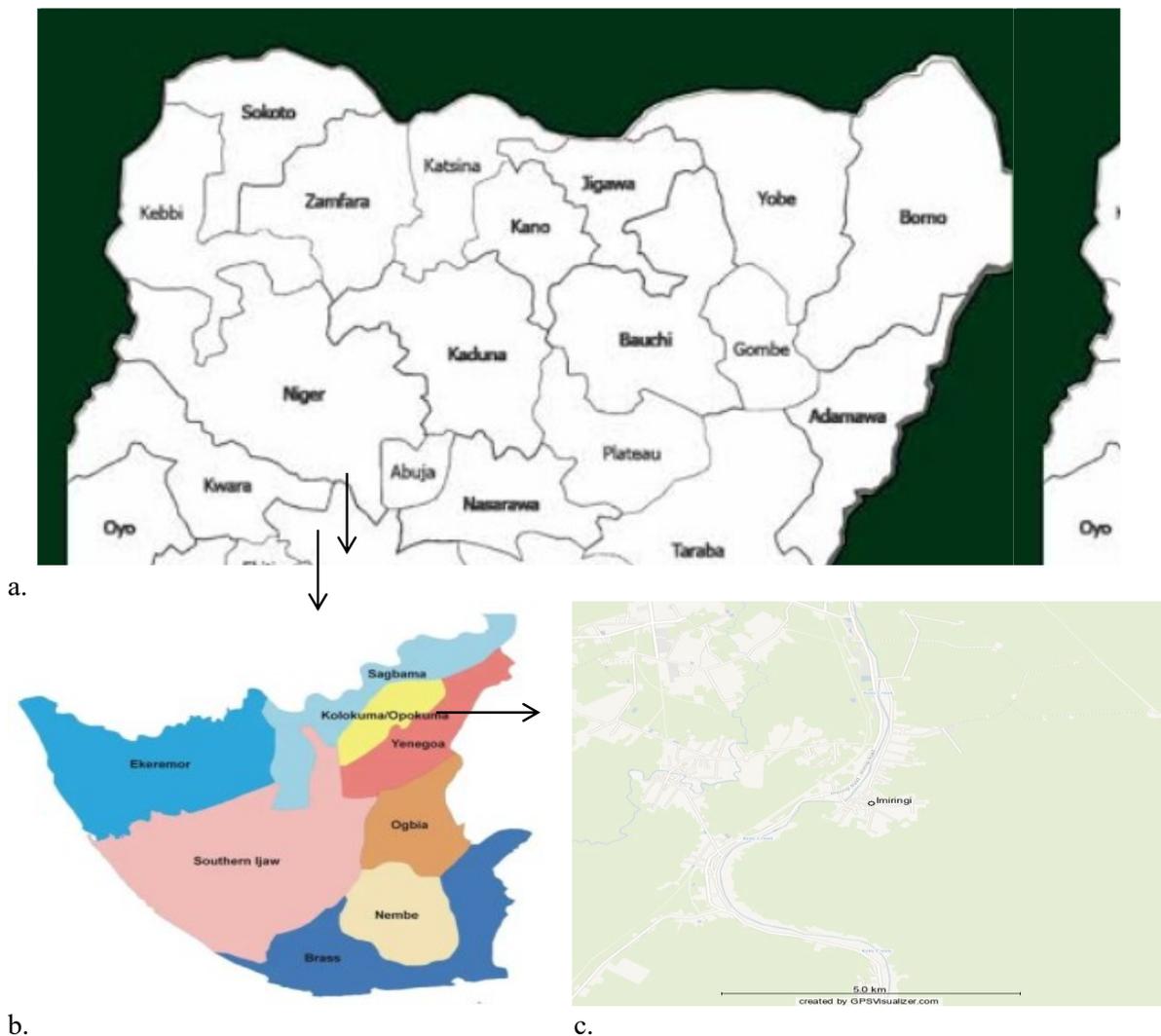
### 2.3 Extraction and quantification of PAHs from soil samples

The USEPA Method 3550C (US EPA, 2007) was used for this purpose. A 10.0 g of sieved soil was weighed into a beaker, followed by the addition of 50 mL of an *n*-hexane and methylene chloride mixture (3:1 v/v), and spiking with ortho-terphenyl. The mixture was shaken using a vortex mixer for approximately five minutes, then at  $70^{\circ}\text{C}$  for ten minutes. After sonication, the extract



was filtered through a glass funnel containing glass wool and anhydrous  $\text{Na}_2\text{SO}_4$ . The filtrate was then transferred to

a teflon-lined screw-cap vial and stored at  $4\text{ }^\circ\text{C}$  until analysis.



**Fig. 1: Map of (a) Nigeria showing Bayelsa State (b) Bayelsa State showing Ogbia LGA (c) Imiringi community within Kolo Creek**

Quantification of PAHs in the filtrate was accomplished using a gas chromatograph (Agilent 6890A) coupled to a mass selective detector (Agilent 5975B, Palo Alto, CA, USA). Further information on the equipment can be found in Iniaghe and Kpomah (2023).

**2.4 Quality control measures/ statistical analysis**

All glassware were first washed with detergent and rinsed with tap water and distilled water. Then, they were subsequently soaked in 5% nitric for 24 hours, rinsed with distilled water and finally with acetone. Procedural blanks were

prepared to monitor background contamination to prevent contamination.

One-way analysis of variance (ANOVA) was used to test for significant differences in PAH concentrations across the four locations. Statistical significance was set at  $p < 0.05$  for all analyses.

**2.5 Risk assessment of PAHs**

**2.5.1 Ecological risk assessment**

The risk quotient method (RQ) is a valuable tool for assessing the potential risk posed to organisms and ecosystems (Wu *et al.*, 2011). The



RQ of PAHs was evaluated using equation (1) (Cao *et al.*, 2010):

$$RQ = \frac{C_{PAH}}{C_{QV}} \quad (1)$$

where  $C_{PAH}$  is the individual PAH concentration in the soil, and  $C_{QV}$  is the associated guideline value (Kalf and Crommentuijn, 1997).

The RQ (NCs) represents the the environmental concentration threshold below which pollutants are not expected to cause adverse effects, while the RQ (MPCs) represents the maximum permissible concentration of pollutants, beyond which there will be unacceptable risk of adverse effects on the ecosystem (Crommentuijn *et al.*, 2000). These were computed using equations (2) and (3) below (Cao *et al.* 2010):

$$RQ (NCs) = \frac{C_{PAH}}{C_{QV(NCs)}} \quad (2)$$

$$RQ (MPCs) = \frac{C_{PAH}}{C_{QV(MPCs)}} \quad (3)$$

RQ (NCs) < 1.0 indicates very low/insignificant ecological risk; RQ (NCs) ≥ 1 and RQ (MPCs) < 1 indicates that the pollution of individual PAHs is at moderate risk; while RQ (MPCs) ≥ 1 suggests high ecological risks.

The RQΣPAHs (NCs) and RQΣPAHs (MPCs) reflect the overall pollution level posed by PAHs in soil. RQΣPAHs(NCs) ≥ 1 represents low risk; RQΣPAHs (NCs) ≥ 800 indicates moderate risk<sub>1</sub>; RQΣPAHs (NCs) < 800 and RQΣPAHs (MPCs) ≥ 1 indicates moderate risk<sub>2</sub>, while RQΣPAHs (NCs) ≥ 800 and RQΣPAHs (MPCs) ≥ 1 indicates high risk (Cao *et al.*, 2010). The following NCs values (μg kg<sup>-1</sup>) adapted from Cao *et al.* (2010) were used in this study: Nap - 1.4, Ace, Acy, Flo, Ant & Pyr - 1.2, Phe - 5.1, Flu - 26, BaA & BbF - 3.6, Chry - 107, BkF - 24, BaP & DahA - 27, IPyr - 59, BghiP - 75; while the MPCs values (μg kg<sup>-1</sup>) used in this study were: Nap - 104, Ace, Acy, Flo, Ant & Pyr - 120, Phe - 510, Flu - 2600, BaA & BbF - 360, Chry - 10700, BkF - 2400, BaP & DahA - 2700, IPyr - 5900, and BghiP - 7500.

### 2.5.2 Non-cancer risk assessment

The non-cancer risk is characterised by the Hazard quotient (HQ). It is a ratio of the average

daily intake (ADI) to the oral reference dose (RfD) of a given contaminant. Equation 4 gives the expression:

$$HQ = \frac{ADI}{RfD} \quad (4)$$

For  $n$  contaminants, the non-cancer risk is the sum of HQs of single contaminants (ie, the Hazard Index (HI)) (USEPA, 1989). It is given by the expression in Equation (5):

$$HI = \sum HQ \quad (5)$$

HI values > 1 suggest level of concern for potential non-cancer risk, while HI values < 1 suggest otherwise (Luo *et al.*, 2012).

The ADI was evaluated for ingestion pathway as follows:

$$ADI = \frac{C \times IngR \times EF \times ED \times CF}{BW \times AT} \quad (6)$$

where ADI = average daily intake of PAH (mg kg<sup>-1</sup> day), C = concentration of PAH in soil (mg kg<sup>-1</sup>), IngR = ingestion rate (mg day<sup>-1</sup>), EF = exposure frequency (days year<sup>-1</sup>), ED = exposure duration (years), BW = body weight of the exposed individual (kg), AT = time period over which the dose is averaged (days) and CF = conversion factor (10<sup>-6</sup>).

### 2.5.3 Cancer risk assessment

The incremental lifetime carcinogenic risk models (ILCRs) was used to estimate the likelihood of an individual to develop cancer when exposed to PAHs in soil over their lifetime. The BaP-toxic equivalent concentration (BaP-TEQ) was first calculated using the expression (Nisbet and Lagoy, 1992)

$$BaPTEQ = \sum_{i=1}^n C \times TEF \quad (7)$$

where C is the concentration of individual carcinogenic PAHs (mg kg<sup>-1</sup>), and TEF is the toxic equivalency factors for individual PAHs relative to BaP. The TEF values of PAHs used in this study were - 0.1 for BaA., 0.001 for Chry, 0.1 for BbF, 0.01 for BkF, 1.0 for BaP, 0.1 for IPyr, and 1.0 for DBahA (USEPA, 1993). The greater the TEF of individual PAHs, the greater the toxicity.

The ILCR assessment of ingested soil was evaluated using equation 8

$$ILCR = CSF \times \frac{BaPTEQ \times IngR \times EF \times ED \times CF}{BW \times AT} \quad (8)$$



where, CSF is the cancer slope factor for individualistic carcinogenic PAHs ( $\text{mg kg}^{-1} \text{ day}^{-1}$ ). The CSF values ( $\text{mg kg}^{-1} \text{ day}^{-1}$ ) used in this study were  $7.3 \times 10^{-1}$  for BaA,  $7.3 \times 10^{-3}$  for Chry,  $7.3 \times 10^{-1}$  for BbF,  $7.3 \times 10^{-2}$  for BkF,  $7.3$  for BaP,  $7.3 \times 10^{-1}$  for IPyr, and  $7.3$  for DBaH (USEPA, 2012)

#### 2.5.4 Source Identification of PAHs

Isomeric ratios are used for identification of PAHs origin in different environmental compartments. The isomeric ratios used in this study and their interpretations can be found in Lawal (2017).

### 3/0 Results and discussion

#### 3.1 Concentration, distribution and sources of PAHs in soil

The concentration of PAHs in soils around abandoned oil wellheads in Imiringi area of Bayelsa State is presented in Table 1. The concentration of  $\Sigma 16$  PAHs (average in parenthesis) in soil across the four locations ranged from  $226.00 - 228.20 \mu\text{g kg}^{-1}$  ( $227.25 \mu\text{g kg}^{-1}$ ). The highest PAHs concentrations were BbF, BaP, and BkF, with average concentrations of  $91.23$ ,  $58.88$  and  $42.13 \mu\text{g kg}^{-1}$ . The concentration of PAHs in the four locations were not significantly different ( $p > 0.05$ ), with similar

distributions of high- and low- molecular weight PAHs in each location. The lack of significant variation in PAHs concentration across the four location suggests a common source of contamination, which could be associated with historical crude oil spills during oil exploration, similar environmental conditions and approximate degradation rates.

According to Maliszewska-Kordybach (1996), soil classification with respect to contamination with 16 priority PAHs is described as follows: non-contaminated:  $< 200 \mu\text{g kg}^{-1}$ , weakly contaminated:  $200 - 600 \mu\text{g kg}^{-1}$ , strongly contaminated:  $600 - 1000 \mu\text{g kg}^{-1}$ , and heavily contaminated:  $> 1000 \mu\text{g kg}^{-1}$ . Based on the results of this study, the soils around abandoned oil wellheads in Imiringi are classified as weakly contaminated with PAHs, since the concentrations obtained were slightly greater than  $200 \mu\text{g kg}^{-1}$ .

The results of this study are significantly lower than those of Faboya *et al.* (2023) who reported an average concentration of  $29,953 \mu\text{g kg}^{-1}$  in soils around oil facilities in Nigeria's Niger Delta area, and those of Ahiamadu *et al.* (2021) Emohua oil spill sites in Rivers State, Nigeria. Table 2 compares the results of this study with similar studies from literature.

**Table 1: Concentration of PAHs in soils around abandoned oil wellheads in Imiringi area**

PAHs	Concentration of PAHs ( $\mu\text{g kg}^{-1}$ )				
	Location 1	Location 2	Location 3	Location 4	Average
Nap	2.50	3.00	2.00	2.00	2.38
Ace	6.20	5.20	5.80	6.00	5.80
Acy	8.00	7.50	8.10	8.00	7.90
Flu	2.30	2.10	1.80	2.00	2.05
Phen	2.20	2.20	2.10	2.00	2.13
Ant	1.80	2.00	2.20	2.00	2.00
$\Sigma$ LMW PAHs	23.00	22.00	22.00	22.00	22.25
Flo	2.10	1.80	1.60	2.00	1.88
Pyr	ND	0.20	0.10	ND	0.08
Chry	6.80	6.50	6.40	6.00	6.43
BaA	3.80	5.10	4.80	4.00	4.43
BbF	92.10	89.60	91.20	92.00	91.23
BkF	41.70	43.00	41.80	42.00	42.13
BaP	58.20	60.10	59.20	58.00	58.88



BghiP	ND	ND	ND	ND	ND
IPyr	ND	ND	ND	ND	ND
DBahA	ND	ND	ND	ND	ND
ΣHMW PAHs	204.70	206.20	205.10	204.00	205.00
ΣPAHs	227.70	228.20	227.10	226.00	227.25
Σ2-ring PAHs	2.50	3.00	2.00	2.00	2.38
Σ3-ring PAHs	20.50	19.00	20.00	20.00	19.88
Σ4-ring PAHs	12.70	13.60	12.90	12.00	12.80
Σ5-ring PAHs	192.00	192.70	192.20	192.00	192.23
Σ7 carcinogenic PAHs	202.60	204.30	203.40	202.00	203.08

**ND - below detection limit. Values represent means (n=3). No significant differences were observed among locations for any PAH congener**

**Table 2: Comparing the PAH level in soil in this study with the literature**

S/No.	Location	Concentration ( $\mu\text{g kg}^{-1}$ )	Reference
1	Oil exploration sites, Texas, USA	86,400	Peter and Heidi (2007)
2	Host oil communities	24-120	Sojinu <i>et al.</i> (2010)
3	Flow stations, Rivers State, Nigeria	7.40-78.3	Adedosu <i>et al.</i> (2013)
4	NNPC oil depot soils, Aba, Nigeria	7,400	Emeka (2014)
5	Oil polluted sites, Delta State, Nigeria	1,261 - 4,631	Eucharía <i>et al.</i> (2016)
6	Petroleum-contaminated areas of the Loess Plateau, China	5,220	Wang <i>et al.</i> (2018)
7	Oil-spill sites, Emohua, Rivers State, Nigeria	16,200 - 98,100	Ahiamadu <i>et al.</i> (2021)
8	Flow station, Warri, Delta State, Nigeria	1,230	Enuneku <i>et al.</i> (2021)
9	Oil facilities in Owaza, Abia State, Nigeria	29,953	Faboya <i>et al.</i> (2023)
10	Crude oil explosion site, Okpare, Delta State, Nigeria	110-4,842	Iniaghe and Kpomah, (2023)
11	Oil wells in the Yellow River Delta, China	1744.41 (in 2009) and 149.63 (in 2021)	Wu <i>et al.</i> (2023)
12	Oil wellheads, Imiringi, Bayelsa State, Nigeria	227.5	This study

Regulatory guideline values are used for controlling residential exposures to surface soil contamination (Jennings, 2012). The U.S. DHHS/PHS/NTP (2011) classifies six PAHs- BaP, BaA, BbF, BkF, DBahA and IPyr- as reasonably anticipated to be human carcinogens, while the WHO/IARC (1998) classifies BaA, BaP and DBahA as probable human carcinogens

(Class 2A), and BbF, BkF and IPyr as possible human carcinogens (Class 2B). The concentration of BaP in the studied soils did not differ significantly ( $p>0.05$ ), with a concentration range between 58.00 and 60.10  $\mu\text{g kg}^{-1}$ . The concentration of BaP exceeded its regulatory limit in residential soils based on the 15  $\mu\text{g kg}^{-1}$  US EPA guideline value (US EPA, 2012), but were within the 200  $\mu\text{g kg}^{-1}$  and 150  $\mu\text{g kg}^{-1}$  limits



set by the Canadian soil quality guideline (CCME, 2010) and the Chinese Ministry of Protection (PRCMEP, 2007). These values exceed those of Faboya *et al.* (2023) who reported an average BaP concentration of  $26 \mu\text{g kg}^{-1}$ , Sojinu *et al.* (2010) with a reported BaP concentration range of  $0.09\text{--}2.05 \mu\text{g kg}^{-1}$ , and Adedosu *et al.* with a concentration range of  $0.02\text{--}2.98 \mu\text{g kg}^{-1}$ . This demonstrates the environmental persistence of BaP. For BaA and BbF, their average concentrations of  $4.43$  and  $91.22 \mu\text{g kg}^{-1}$  were within the  $6,200 \mu\text{g kg}^{-1}$  set by CCME (2010),  $1,500 \mu\text{g kg}^{-1}$  set by PRCMEP (2007), and  $150 \mu\text{g kg}^{-1}$  set by US EPA (2011). For BkF, its average concentration of  $42.13$  was well within the  $1,500 \mu\text{g kg}^{-1}$  set by USEPA (2011) and PRCMEP (2007), and  $1,000 \mu\text{g kg}^{-1}$  set by CCME (2010). Chrysene is not classified as a human carcinogen according the WHO/IARC (1998) and USDHHS/PHS/NTP (2011). The concentration of the sum of 7 carcinogenic PAHs ranged from  $202.00$  to  $204.30 \mu\text{g kg}^{-1}$ , with an average concentration of  $203.08 \mu\text{g kg}^{-1}$ . These concentrations accounted for  $88.97\%$ ,  $89.52\%$ ,  $89.56\%$  and  $89.38\%$  of the total PAHs in the four locations.

Significantly lower concentration of LMW PAHs ( $p < 0.05$ ) compared to HMW PAHs were observed in all studied locations. This observance could be attributed to the activities of soil bacteria during biodegradation, which utilize mostly LMW PAHs (Akpanudo & Olabemiwo, 2024a-b). On the other hand, the increased levels of HMW PAHs, which are commonly associated with pyrogenic processes, could be attributed to the aging and weathering effects, since LMW PAHs degrade more rapidly due to their increased volatility (Enuneku *et al.*, 2021). However, ratios LMW/HMW and fluoranthene/pyrene were  $< 1$  in the former, and  $> 1$  in the latter in all locations, suggesting combustion/pyrolysis. This again could be associated with historical flaring of gas directly into soil in the Imiringi community, and this could have additionally led to destruction of LMW PAHs through evaporation, leaving a higher percentage of HMW PAHs.

As shown in Fig. 2, the ring size distribution of PAHs in all locations followed the general order: 5-ring  $>$  3-ring  $>$  2-ring  $>$  4-ring. 5-ring PAHs constituted  $84.32\%$ ,  $84.44\%$ ,  $84.85\%$  and  $84.95\%$  of the total PAHs in the studied soil samples, with BbF being the predominant 5-ring PAH compound in all locations.

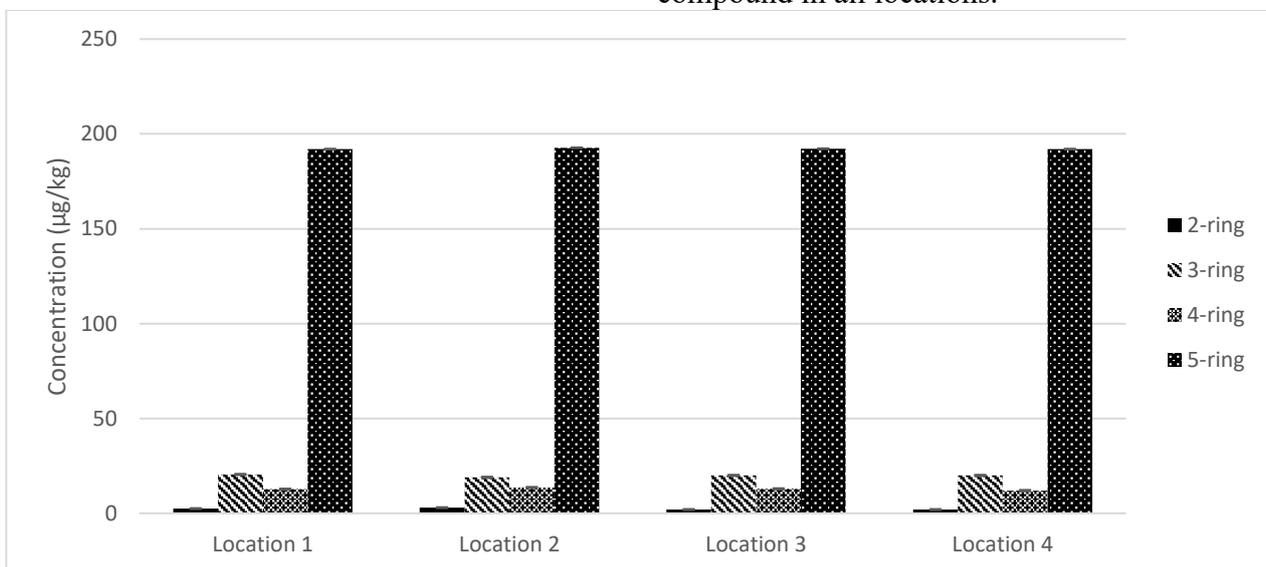


Fig. 2: Ring-size distribution of PAHs in oil-spill abandoned soils

### 3.2 Risk assessment of PAHs



3.2.1 Ecological risk assessment

The calculated values of RQ of PAHs in soils in this study are presented in Table 3. The RQ (NCs) ranged from 0.056 - 25.58  $\mu\text{g kg}^{-1}$  while the RQ (MPCs) ranged from 0.001 - 0.26  $\mu\text{g/kg}$  for the individual PAHs across the four locations. These values suggest low ecological risk was posed by Phen, Flo, Chry, and Pyr for biota and ecosystem in the study locations, with RQ (NCs) < 1, indicating that some PAH compounds of both low- and high- molecular weights do not pose any significant environmental risk. On the other hand,

Nap, Ace, Acy, Flu, Ant, BaA, BbF, BkF and BaP posed moderate of pollution by these PAHs, with RQ (NCs) > 1 and RQ (MPCs) < 1. The overall risk posed by the identified PAHs in the studied soils, expressed as RQ $\Sigma$ PAHs (NCs) and RQ $\Sigma$ PAHs (MPCs) indicate a low risk of  $\Sigma$ PAHs to surrounding organisms and the ecosystem. In a related study, Faboya *et al* (2023) reported high ecological risk of PAHs, with LMW PAHs posing a greater risk to biota and the ecosystem in crude oil impacted soils in Abia State, Nigeria.

Table 3: Values of RQ (NCs) and RQ (MPCs) of PAHs in soils around abandoned oil wellheads

	RQ (NCs) ( $\mu\text{g kg}^{-1}$ )				RQ (MPCs) ( $\mu\text{g kg}^{-1}$ )			
	Location 1	Location 2	Location 3	Location 4	Location 1	Location 2	Location 3	Location 4
Nap	1.79	2.14	1.43	1.43	0.018	0.021	0.014	0.014
Ace	5.17	4.33	4.83	5.00	0.052	0.043	0.048	0.050
Acy	6.67	6.25	6.75	6.67	0.067	0.063	0.068	0.067
Flu	1.92	1.75	1.50	1.67	0.019	0.018	0.015	0.017
Phen	0.43	0.43	0.41	0.39	0.004	0.004	0.004	0.004
Ant	1.50	1.67	1.83	1.67	0.015	0.017	0.018	0.017
Flo	0.08	0.07	0.062	0.08	0.001	0.001	0.001	0.001
Pyr	0	0.17	0.083	0.00	0.000	0.002	0.001	0.000
Chry	0.06	0.06	0.060	0.06	0.001	0.001	0.001	0.001
BaA	1.06	1.42	1.33	1.11	0.011	0.014	0.013	0.011
BbF	25.58	24.89	25.33	25.56	0.256	0.25	0.25	0.26
BkF	1.74	1.79	1.74	1.75	0.017	0.018	0.017	0.018
BaP	2.16	2.23	2.19	2.15	0.022	0.022	0.022	0.021
$\Sigma$ PAHs	48.14	47.19	47.56	47.52	0.48	0.47	0.48	0.48

3.2.2 Health risk assessments

Results for non-cancer risk assessment of PAHs, expressed as HQ and HI for adults and children exposure scenarios, are shown in Table 4. The calculated HI values varied between  $3.05 \times 10^{-4}$  and  $4.41 \times 10^{-4}$  for adult exposure scenario, and between  $2.83 \times 10^{-3}$  and  $3.18 \times 10^{-3}$  for children exposure scenario. The HQ and HI values for the exposure scenarios considered in this study were < 1, which implies that adults and children living around the abandoned oil wellheads can be exposed for elongated periods with negligible non-cancer risk effects. The BaP-TEQ and ILCR values were computed for carcinogenic PAHs, and these results are presented in Tables 5 and 6, respectively. The calculated BaPTEQ values

ranged from 55.20 to 60.10  $\mu\text{g kg}^{-1}$ , and were of the order: BaP > Bbf > Bkf > BaA > Chry. The PAH compound, BaP, contributed the most to the total BaPTEQ concentration, accounting for over 85%, followed by BbF, which accounted for at least 13% across the four locations. The BaP-TEQ values are greater than the Regional Screening Level of 15  $\mu\text{g kg}^{-1}$  for residential soil for BaP-TEQ (US EPA, 2012), but within the 300  $\mu\text{g kg}^{-1}$ , for agricultural and residential soils (300  $\mu\text{g kg}^{-1}$ ) based on the Canadian Environmental Quality Guidelines (CCME, 2010). The ILCR values varied between  $1.01 \times 10^{-1}$  and  $1.03 \times 10^{-1}$ . These values are at least 1000 times greater than the EPA’s acceptable limit of  $1 \times 10^{-4}$ . This implies



that continuous exposure to PAHs poses a significant cancer risk to adults.

**Table 4: Non-cancer risk of PAHs in soil**

PAHs -Adult ( $\times 10^{-4}$ )	Location 1	Location 2	Location 3	Location 4
Nap	1.79	2.14	1.43	1.43
Ace	1.48	1.24	1.38	1.43
Acy	1.90	1.79	1.93	1.90
Flu ( $\times 10^{-5}$ )	8.21	7.50	6.40	7.10
Ant ( $\times 10^{-5}$ )	0.86	1.00	1.00	1.00
Flo*	0.75	64.00†	0.57	0.71
Pyr ( $\times 10^{-5}$ )	–	2.00	0.50	–
<b>Hazard Index (<math>\times 10^{-4}</math>)</b>	<b>6.82</b>	<b>6.70</b>	<b>6.10</b>	<b>6.30</b>
PAHs- Child ( $\times 10^{-3}$ )	Location 1	Location 2	Location 3	Location 4
Nap	0.83	1.00	0.67	0.67
Ace	0.69	0.58	0.64	0.67
Acy	0.89	0.83	0.90	0.89
Flu ( $\times 10^{-4}$ )	3.83	3.50	0.30	3.33
Ant ( $\times 10^{-5}$ )	4.00	4.40	4.99	4.40
Flo ( $\times 10^{-4}$ )	3.50	3.00	2.67	0.33
Pyr ( $\times 10^{-5}$ )	–	4.40	2.20	–
<b>Hazard Index (<math>\times 10^{-3}</math>)</b>	<b>3.18</b>	<b>3.15</b>	<b>2.85</b>	<b>2.93</b>

The ILCR values for children exposures are greater than those of adult exposures, implying that the former are at a significantly greater risk of exposure to carcinogenic PAHs, due to their characteristic hand-to-mouth activities, smaller body weight and higher absorption rates. Two PAH compounds, DBahA and IPyr were not detected, while BaP, the most carcinogenic PAH, contributed the greatest percentage to the total carcinogenicity of the studied soils. It accounted for over 90% of the total cancer risk in all

studied soils. On the other hand, Chry constituted the least contributor to the total carcinogenicity. A similar report was earlier reported by Enuneku *et al.* (2021). BaP is a known human carcinogen which can bind to DNA and cellular protein, forming DNA adduct, which have the potential to interfere with normal cellular processes, causing mutation and initiating cancer development (Dybing *et al.*, 2016; Bjelić *et al.*, 2022). The results thus suggests urgent intervention in the form of remediation of the studied soils.

**Table 5: BaPTEQ values of PAHs in soil**

PAHs	BaPTEQ values ( $\mu\text{g kg}^{-1}$ )			
	Location 1	Location 2	Location 3	Location 4
Chry	$6.80 \times 10^{-3}$	$6.50 \times 10^{-3}$	$6.40 \times 10^{-3}$	$6.00 \times 10^{-3}$
BaA	$3.80 \times 10^{-1}$	$5.10 \times 10^{-1}$	$4.80 \times 10^{-1}$	$4.00 \times 10^{-1}$
BbF	9.21	8.96	9.11	9.20
BkF	$4.17 \times 10^{-1}$	$4.31 \times 10^{-1}$	$4.10 \times 10^{-1}$	$4.20 \times 10^{-1}$
BaP	58.20	60.10	55.20	58.21
<b><math>\Sigma</math>BaPTEQ</b>	<b>68.21</b>	<b>70.01</b>	<b>69.22</b>	<b>68.01</b>



Table 6: Incremental lifetime carcinogenic risk of PAHs in soil

PAHs-Adult	Location 1	Location 2	Location 3	Location 4
Chry ( $\times 10^{-8}$ )	3.50	3.40	3.30	3.10
BaA ( $\times 10^{-4}$ )	1.98	2.65	2.50	2.08
BbF ( $\times 10^{-3}$ )	4.80	4.67	4.75	4.79
BkF ( $\times 10^{-5}$ )	2.17	2.24	2.17	2.19
BaP ( $\times 10^{-2}$ )	9.56	9.87	9.72	9.53
<b>ILCR (<math>\times 10^{-1}</math>)</b>	<b>1.01</b>	<b>1.03</b>	<b>1.02</b>	<b>1.01</b>
PAHs-Child	Location 1	Location 2	Location 3	Location 4
Chry ( $\times 10^{-7}$ )	3.31	3.16	3.11	2.92
BaA ( $\times 10^{-3}$ )	1.89	2.48	2.33	1.96
BbF ( $\times 10^{-2}$ )	4.48	4.36	4.43	4.47
BkF ( $\times 10^{-4}$ )	2.02	2.09	2.03	2.04
BaP ( $\times 10^{-1}$ )	8.92	9.20	9.07	8.89
<b>ILCR (<math>\times 10^{-1}</math>)</b>	<b>9.39</b>	<b>9.67</b>	<b>9.04</b>	<b>9.36</b>

#### 4.0 Conclusion

This study assessed the concentration and associated risks of PAHs in soils around abandoned oil wellheads in Imiringi area of Kolo creek, Bayelsa State, Nigeria. The findings revealed that the PAHs level in soil within the vicinity of abandoned oil wellheads were not significantly different, and the soils were weakly contaminated with PAHs. Among the carcinogenic PAHs, benzo[b]fluoranthene had the greatest concentration, followed by benzo[a]pyrene. High molecular weight PAHs were predominant in all locations, with 5-ring PAHs being dominant. Although, risk quotient values and non-cancer risk values were within regulatory limits, the ILCR values exceeded acceptable limits for both children and adults exposure scenarios, suggesting potential long-term health concerns. These results highlight the need for continuous monitoring and appropriate remediation strategies to combat the long-term risks associated with PAH contamination of soils within the vicinity of abandoned oil wellheads.

#### 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. *Egyptian Journal of Petroleum*, 25(1), 107–123.

Adedosu, T. A., Adedosu, H. O., Sojinu, O. S., & Olajire, A. A. (2013). N-alkanes and polycyclic aromatic hydrocarbons (PAHs) profile of soil from some polluted sites in Niger Delta, Nigeria. *Environmental Earth Sciences*, 68(8), 2139–2144.

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), 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), 98–110. <https://doi.org/10.1016/j.sajce.2023.11.008>



- Ahiamadu, N. M., Nwaogazie, I. L., & Momoh, Y. O. L. (2021). Assessment of polycyclic aromatic hydrocarbons in crude oil spill sites in Emohua Local Government Area of Rivers State, Nigeria. *American Journal of Engineering Research*, 10(6), 175–187.
- Babaniyi, B. R., Ogundele, O. D., Bisi-Omotosho, A., Babaniyi, E. E., & Aransiola, S. A. (2023). Remediation approaches in environmental sustainability. In *Microbiology for Cleaner Production and Environmental Sustainability* (pp. 321–346). CRC Press.
- Bjelić, L. S., Markić, D. N., Ilić, P., & Farooq, Z. U. (2022). Polycyclic aromatic hydrocarbons in soils in industrial areas: Concentration and risks to human health. *Polish Journal of Environmental Studies*, 31(1), 595–608.
- Cao, Z., Liu, J., Luan, Y., Li, Y., Ma, M., Xu, J., & Han, S. (2010). Distribution and ecosystem risk assessment of polycyclic aromatic hydrocarbons in the Luan River. *Ecotoxicology*, 19(5), 827–837.
- Canadian Council of Ministers of the Environment (CCME). (2010). *Polycyclic aromatic hydrocarbons: Canadian soil quality guidelines for the protection of environmental and human health*. Winnipeg, Canada.
- Crommentuijn, T., Sijm, D., de Bruij, J., van den Hoop, M., van Leeuwen, K., & van de Plassche, E. (2000). Maximum permissible and negligible concentrations for metals and metalloids in the Netherlands, taking into account background concentrations. *Journal of Environmental Management*, 60(2), 121–143.
- Dybing, E., Schwarze, P. E., Nafstad, P., Victorin, K., & Penning, T. M. (2016). Polycyclic aromatic hydrocarbons in ambient air and cancer. *IARC Scientific Publications*, 161, 75–78.
- Emeka, O. (2014). Evaluation of polycyclic aromatic hydrocarbons, total petroleum hydrocarbons and some heavy metals in soils of NNPC oil depot Aba metropolis, Abia State, Nigeria. *IOSR Journal of Environmental Science, Toxicology and Food Technology*, 8(5), 21–27.
- Enuneku, A., Ogbeide, O., Okpara, B., Kubeyinje, B. F., Job, O., Asemota, C. O., Imoobe, T., & Ezemonye, L. I. (2021). Ingestion and dermal cancer risk via exposure to polycyclic aromatic hydrocarbon-contaminated soils in an oil-producing community, Niger Delta, Nigeria. *Environmental Toxicology and Chemistry*, 40(1), 261–271.
- Eucharia, O. N., Chuku, L., & Igboavwogan, E. (2016). Polycyclic aromatic hydrocarbons and selected heavy metals in some oil polluted sites in Delta State, Nigeria. *Journal of Environmental Protection*, 7, 1389–1410.
- Ezekwe, I. C., Oshionya, E. O., & Demua, L. D. (2018). Ecological and potential health effects of hydrocarbons and heavy metal concentrations in the Kolo Creek wetlands, South-south Nigeria. *International Journal of Environmental Science and Natural Resources*, 11(1), Article 555801.
- Faboya, O. L., Sojину, O. S., & Otugboyega, J. O. (2023). Preliminary investigation of polycyclic aromatic hydrocarbons (PAHs) concentration, compositional pattern, and ecological risk in crude oil-impacted soil from Niger Delta, Nigeria. *Heliyon*, 9(4), Article e215508. <https://doi.org/10.1016/j.heliyon.2023.e215508>
- Fu, X. W., Li, T. Y., Ji, L., Wang, L. L., Zheng, L. W., Wang, J. N., & Zhang, Q. (2018). Occurrence, sources and risk of polycyclic aromatic hydrocarbons in soils around oil wells in the border regions between oil fields and suburbs. *Ecotoxicology and Environmental Safety*, 157, 276–284.
- Iniaghe, P. O., & Kpomah, E. D. (2023). A comparative analysis on the concentration and potential risk of polycyclic aromatic hydrocarbons in surface water, sediment and soil from a non-crude oil and a crude oil explosion site in the Niger Delta, Nigeria.



*Chemistry Africa*. <https://doi.org/10.1007/s42250-023-00596-5>

- Itodo, A. U., Akeju, T. T., & Itodo, H. U. (2019). Polycyclic aromatic hydrocarbons (PAHs) in crude oil contaminated water from Ese-Odo offshore, Nigeria. *Annals of Ecology and Environmental Science*, 3(1), 12–19.
- Jennings, A. A. (2012). Worldwide regulatory guidance values for surface soil exposure to carcinogenic or mutagenic polycyclic aromatic hydrocarbons. *Journal of Environmental Management*, 110, 82–102.
- Kalf, D. F., & Crommentuijn, E. J. (1997). Environmental quality objectives for polycyclic aromatic hydrocarbons (PAHs). *Ecotoxicology and Environmental Safety*, 36(1), 89–97.
- Kim, K. H., Jahan, S. A., Kabir, E., & Brown, R. J. C. (2013). A review of airborne polycyclic aromatic hydrocarbons (PAHs) and their human health effects. *Environment International*, 60, 71–80.
- Lawal, A. T. (2017). Polycyclic aromatic hydrocarbons: A review. *Cogent Environmental Science*, 3(1), Article 1339841. <https://doi.org/10.1080/23311843.2017.1339841>
- Liu, F., Liu, J., Chen, Q., Wang, B., & Cao, Z. (2012). Pollution characteristics, ecological risk and sources of polycyclic aromatic hydrocarbons (PAHs) in surface sediment from Tuhai-Majia River system, China. *Procedia Environmental Sciences*, 12, 1301–1314.
- Ma, L. L., Chu, S. G., Wang, X. T., Cheng, H. X., Liu, X. F., & Xu, X. B. (2005). Polycyclic aromatic hydrocarbons in the surface soils from outskirts of Beijing, China. *Chemosphere*, 58(10), 1355–1363.
- Maliszewska-Kordybach, B. (1996). Polycyclic aromatic hydrocarbons in agricultural soils in Poland: Preliminary proposals for criteria to evaluate the level of soil contamination. *Applied Geochemistry*, 11(1–2), 121–127. [https://doi.org/10.1016/0883-2927\(95\)00076-3](https://doi.org/10.1016/0883-2927(95)00076-3)
- Nikitha, T., Satyaprakash, M., Satya Vani, S., Sadhana, B., & Padal, S. B. (2017). A review on polycyclic aromatic hydrocarbons: Their transport, fate and biodegradation in the environment. *International Journal of Current Microbiology and Applied Sciences*, 6(4), 1627–1639. <https://doi.org/10.20546/ijcmas.2017.604.199>
- Nisbet, I. C., & LaGoy, P. K. (1992). Toxic equivalency factors (TEFs) for polycyclic aromatic hydrocarbons (PAHs). *Regulatory Toxicology and Pharmacology*, 16(3), 290–300.
- Peter, P. G., & Heidi, B. K. (2007). Characterization of EPA's 16 priority pollutant polycyclic aromatic hydrocarbons (PAHs) in tank bottom solids and associated soils at oil exploration and production sites in Texas. *Regulatory Toxicology and Pharmacology*, 47(3), 288–295. <https://doi.org/10.1016/j.yrtph.2006.11.007>
- Ravindra, K., Sokhi, R., & Van Grieken, R. (2008). Atmospheric polycyclic aromatic hydrocarbons: Source attribution, emission factors and regulation. *Atmospheric Environment*, 42(13), 2895–2921.
- Sojini, O. S., Wang, J. Z., Sonibare, O. O., & Zeng, E. Y. (2010). Polycyclic aromatic hydrocarbons in soils and sediments from oil exploration areas, Niger Delta, Nigeria. *Journal of Hazardous Materials*, 174(1–3), 641–647.
- Wang, D., Ma, J., Li, H., & Zhang, X. (2018). Concentration and potential ecological risk of PAHs in different layers of soil in the petroleum-contaminated areas of the Loess Plateau, China. *International Journal of Environmental Research and Public Health*, 15(8), Article 1785. <https://doi.org/10.3390/ijerph15081785>
- Wang, X. T., Miao, Y., Zhang, Y., Li, Y. C., Wu, M. H., & Yu, G. (2013). Polycyclic aromatic hydrocarbons (PAHs) in urban soils of the megacity Shanghai: Occurrence, source apportionment and potential human health risk. *Science of the Total Environment*, 447, 80–89.



Wu, B., Zhang, R., Chen, S. P., Timothy, F., Aimin, L., & Xuxuang, Z. (2011). Risk assessment of polycyclic aromatic hydrocarbons in aquatic ecosystems. *Ecotoxicology*, 20(5), 1124–1130.

Wu, Y., Zhao, Y., Qi, Y., Li, J., Hou, Y., Hao, H., Xiao, N., & Zhi, Q. (2023). Characteristics, source and risk assessment of polycyclic aromatic hydrocarbons around oil wells in the Yellow River Delta, China. *Water*, 15(8), Article 3324. <https://doi.org/10.3390/w15183324>

Zheng, B., Wang, L., Lei, K., & Nan, B. (2016). Distribution and ecological risk assessment of polycyclic aromatic hydrocarbons in water, suspended particulate matter and sediment from Daliao River estuary and the adjacent area, China. *Chemosphere*, 149, 91–100.

#### **Data availability**

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

#### **Funding**

The entire work was funded by the Tertiary Education Trust Fund of Nigeria (TERTFund) as a consequence of Institutional Based Research (IBR) with the Federal University, Otuoke.

#### **Authors' Contribution**

Richard Alexis Ukpe designed the study, conducted sampling and laboratory analyses, performed data and risk assessments, and drafted the manuscript. Paschal Okiroro Iniaghe supervised the research, supported statistical analysis and interpretation, and critically reviewed and edited the manuscript. Both authors approved the final version for publication.

#### **Declaration**

##### **Competing Financial Interests Statement:**

There are no competing financial interests in this research work.

##### **Ethical considerations**

Not applicable

