



Distribution patterns and associated health risks of polycyclic aromatic hydrocarbons in some surface water within Ekeremor Local Government Area, Bayelsa State, Nigeria.

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ABSTRACT

This study examined the distribution patterns and associated health risks of polycyclic aromatic hydrocarbons (PAHs) in surface water (some tributaries of Bomadi and Gbotebo rivers) within Ekeremor Local Government Area, Bayelsa State. Twelve sampling points with 5 replicates were analyzed. The PAHs were analyzed with gas chromatography with mass spectrometry. Results revealed that PAHs were detected only at SW1, SW3, and SW7, where concentrations ranged between 4.22 and 19.80 µg/L. The detected compounds included both low and high-molecular-weight PAHs, with notable carcinogenic species such as benzo[a]anthracene and benzo[ghi]perylene. Correlation analysis revealed complex associations among PAH groups, with strong links between high molecular weight and carcinogenic fractions. Health risk assessments indicated that both non-carcinogenic and carcinogenic risks for adults and children were below critical thresholds, suggesting minimal immediate health concerns. However, the presence of carcinogenic PAHs, coupled with the area's proximity to oil and gas operations, highlights the potential for future contamination risks. The study recommends continuous monitoring, stricter pollution control measures, provision of alternative potable water sources, and further research on seasonal variations, sediment deposition, and bioaccumulation to safeguard ecological integrity and public health.

INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) are a major environmental concern, mainly produced through the incomplete combustion of organic material, petroleum extraction, and various industrial processes (Nabebe et al., 2024). Their hydrophobic nature and long-lasting presence in ecosystems add to their mutagenic and carcinogenic effects, posing risks to both the environment and human health (Honda & Suzuki, 2020; Cao et al., 2022). In areas such as the Niger Delta in Nigeria, where oil extraction is common, surface waters are especially susceptible to PAH contamination. These regions are vital for local communities because they provide sources for fishing, farming, and household use, increasing the importance of assessing PAH levels to evaluate exposure risks and guide environmental management efforts.

Research demonstrates that PAHs in aquatic environments can originate from oil spills and urban runoff from industrial sources (Wang et al., 2024; Zhang et al., 2020). The proximity of human settlements to these pollution sources increases the potential for exposure through the consumption of contaminated water and food (Sankar et al., 2023). The ecological impacts of PAH pollution are profound, affecting biodiversity and altering ecosystem functionality, necessitating routine monitoring and assessment of PAH concentrations in surface waters (He et al., 2023; Cheng et al., 2023). Investigations into the origins and distribution of these compounds reveal a complex interplay of local and upstream sources of pollution, underscoring the need for targeted strategies in pollution management (Wang et al., 2021; Zhang et al., 2022).

Studies assessing the health risks linked to PAHs highlight the presence of carcinogenic PAHs in environmental samples, which can significantly elevate cancer risk among exposed populations (Saleem et al.,

2022; Cao et al., 2019). Elevated concentrations of specific PAH compounds, especially those resulting from fossil fuel combustion, are associated with increased toxicity and adverse health outcomes (Zhang et al., 2024; Xu et al., 2023). This highlights the importance of health risk assessments for communities living in PAH-affected areas and suggests that more comprehensive ecological risk frameworks are needed to better understand these pollutants' implications (Yu et al., 2023; Cao et al., 2022).

Strengthening regulatory frameworks that emphasize monitoring and controlling PAH emissions, particularly in oil-producing regions, is vital for mitigating health impacts and preserving local ecosystems (Cao et al., 2022; Wang et al., 2021). This includes collaborating with governmental and non-governmental organizations to develop localized strategies to minimize PAH emissions and bolster community resilience against contamination (Cheng et al., 2023; Zhang et al., 2022).

In Bayelsa State, several studies have examined surface water resources, with the majority focusing on heavy metals, bacteriological properties, and physicochemical characteristics rather than organic pollutants such as PAHs. For instance, Izah et al. (2021) assessed fungi density and diversity in Epie Creek, while Ben-Eledo et al. (2017a, 2017b) conducted water quality and bacteriological assessments in the same creek. Seiyaboh et al. (2017a) reported on Sagbama Creek water quality, whereas Ogamba et al. (2021) and Charles et al. (2019) evaluated heavy metals and hydrocarbons in Taylor Creek. Similar studies have investigated bacteriological quality (Seiyaboh et al., 2020), physicochemical parameters of the Nun River (Aghoghovwia et al., 2018a), and the impacts of anthropogenic activities on heavy metals in the same river (Aghoghovwia et al., 2018b). Further, Ogamba et al. (2015) assessed water quality and proximate composition of *Eichhornia crassipes* from the River Nun,

while Seiyaboh and Izah (2017) and Seiyaboh et al. (2017b) examined bacteriological quality in different creeks and nun river respectively in Bayelsa State.

While these studies provide valuable insights into the ecological and health implications of heavy metal and microbial pollution in surface waters, there remains limited research on the occurrence and risks associated with PAHs in the region. Given the heavy reliance of local communities on rivers and creeks for fishing, domestic use, and transportation, alongside the proximity of these waters to oil and gas activities, assessing PAH distribution and associated health risks is crucial. This study therefore, investigates the distribution patterns of PAHs in surface water within Ekeremor Local Government Area, Bayelsa State, and evaluates the non-carcinogenic and carcinogenic health risks associated with human exposure.

2.0 MATERIALS AND METHODS

Study Area

This study was conducted in the Ekeremor Local Government Area of Bayelsa State, focusing on the Bomadi and Gboto rivers and their adjoining regions (latitude 4°58'29"N–5°03'25"N; longitude 5°39'50"E–5°41'25"E), which drain into the Forcados. The investigation covered communities near the Birigbene and Gboto creeks, including settlements such as Ozobobenisede and Ogboto, located close to oil and gas facilities. The rivers serve as vital sources of livelihood, providing fishing grounds, supporting agriculture along river ridges, and facilitating trade and wood transportation. Vegetation is dominated by oil palm, *Raphia* palm, elephant grass, plantain, and other species.

2.2 Study Design

A cross-sectional study was selected as the most appropriate research design for this investigation.

2.3 Sample Technique

Mixed sampling approach, incorporating cluster sampling focused on the numerous entry points of the Forcados River into Bayelsa State from the Ekeremor Local Government Area was utilized in this study. This method enabled us to achieve a more precise representation of the population, resulting in an ecologically representative river sample. The deliberate choice of clusters, represented by the rivers, was driven by the substantial human activity in these locations. Nevertheless, the actual sample collection was carried out at random points across the study area.

2.4 Water sample collection

The collection of water samples involved obtaining five replicate samples of water from each of the twelve sampling stations, resulting in a total of sixty water samples. Water samples were obtained from the middle of the river and placed in clean glass containers, each labeled with a unique code. Subsequently, these samples were stored in a refrigerator for later laboratory examination.

2.5 laboratory analysis

The PAHs was analyzed using HP 6890 gas chromatograph connected to a 5973 mass selective detector as previously described by Aigberua and Seiyaboh (2021).

3.6 Health risk assessment

The human health risk assessment of PAHs was conducted by evaluating exposure levels, assessing toxicity, and estimating the risks associated with these compounds. In this study, the standard framework developed by the USEPA was applied, incorporating the calculation of chronic daily intake (CDI), hazard quotients (HQ), hazard index (HI), and carcinogenic risk. This approach, as outlined by Aigberua *et al.* (2023), provided a structured basis for quantifying both non-carcinogenic and carcinogenic risks linked to PAH exposure.

Chronic Daily Intake

$$\text{CDI (ingestion)} = \frac{C_i \times \text{InR} \times \text{ExF} \times \text{ExD}}{\text{BoW} \times \text{AT}} \times 0.001 \quad \text{Equation 4}$$

Where, CDd (mg/kg day) is the exposure dose via dermal absorption; C_i ($\mu\text{g/L}$) is the concentration of pollutants in water; ExF is the exposure frequency and 350 days/year for dermal absorption was used in the calculation; ExD is the exposure duration (70 years); BoW (kg) is the average body weight for adults (70 kg) and children (15 kg); and AT is the average time for carcinogens ($\text{ExD} \times 365$ days) i.e. $70 \times 365 = 25,550$ days, and CF is the conversion factor 10^{-3} (Olayinka *et al.*, 2018).

Hazard quotients and Hazard Index for

$$\text{Hazard quotients (HQ)} = \frac{\text{CDI}}{\text{RFD}}$$

Where the RFD for BaP = 0.003 (Ekere *et al.* 2019), BgP = 0.04, Phe = 0.04 (Adeniji *et al.* 2019), NaP, Ace, Flu, Ant, Flt, and Pyr is 0.02, 0.06, 0.04, 0.30, 0.04, and 0.03 respectively (Tongo *et al.* 2017)

$$\text{Hazard index (HI)} = \sum \text{HQ}$$

If the HQ and HI values are less than one, the exposed population (consumers of the water) is regarded as safe. However, if the HQ value is equal to or more than one,

human health is compromised. On the other hand, the HQ does not assess the hazard level; it simply indicates the degree of risk associated with pollutant exposure (Ekere *et al.* 2019).

Cancer Risk

The probability of cancer development was assessed following the methods outlined in Adeniji *et al.* (2019). Carcinogenic risks were calculated by multiplying the average daily intake by the carcinogenic slope factor.

$$\text{Cancer risk} = CDI \times SF$$

The term "Chronic daily intake" is represented as "CDI," and the "slope factor" is denoted as "SF" (specifically for BbF, BaA, InP, DaA = 0.73, BkF, Chr = 0.073, BaP = 7.3) (Adeniji *et al.* 2019). According to Aigberua *et al.* (2023), when the calculated carcinogenic risk value falls below 10^{-6} – 10^{-4} , it signifies that there is no likelihood of carcinogenic tendencies.

2.7 Statistical Analysis

Statistical analyses were carried out using SPSS version 20. The concentrations of PAHs were expressed as mean values accompanied by their standard errors. Pearson correlation analysis was performed to identify potential sources and explore the relationships among the PAHs.

3.0 RESULTS AND DISCUSSION

3.1 Results

Table 1 displays the concentrations of priority PAHs ($\mu\text{g/L}$) in water samples collected from various tributaries of the Bomadi and Gbotebo rivers within the Ekeremor local government area of Bayelsa state, Nigeria. Among the 12 sampling points investigated, PAHs were only detected at three locations, namely SW1, SW3, and SW7.

Overall, the total PAH concentrations ranged from 10 to 19.80 (with a mean of 15.30 ± 1.68) for SW1, 4.22 to 9.45 (with a mean of 5.90 ± 0.96) for SW3, and 8.38 to 11.04 (with a mean of 9.81 ± 0.55) for SW7. The individual PAH congeners across locations are: In SW1, the following PAHs were identified: Acy, Phen, Flt, Pry, BaA, BbF, BkF, and BghiP, with mean concentrations of 4.64 ± 0.27 , 0.33 ± 0.09 , 0.46 ± 0.01 , 0.66 ± 0.04 , 5.88 ± 1.47 , 0.07 ± 0.01 , 0.05 ± 0.00 , and 3.21 ± 0.22 $\mu\text{g/L}$, respectively. At SW3, BkF, BbF, BaA, Ace, Naph, and 2-Mn were detected with mean concentrations of 0.06 ± 0.01 , 0.32 ± 0.08 , 0.70 ± 0.12 , 1.33 ± 0.30 , and 2.67 ± 1.10 , respectively. In SW7, the PAHs Flt, Ace, 2-Mn, Naph, Chry, and BghiP exhibited mean concentrations of 0.09 ± 0.00 , 0.16 ± 0.01 , 0.47 ± 0.01 , 0.49 ± 0.07 , 0.93 ± 0.04 , and 7.67 ± 0.47 , respectively.

Table 1: Concentration of the priority PAHs ($\mu\text{g/L}$) in water samples from some tributaries of Bomadi and Gbotebo rivers in Bayelsa state, Nigeria

PAHs variable	SW1			SW3			SW7		
	mean $\pm$ SE (n=5)	Min	Max	mean $\pm$ SE (n=5)	Min	Max	mean $\pm$ SE (n=5)	Min	Max
Naph	0.00 ± 0.00	0.00	0.00	1.33 ± 0.30	0.53	2.04	0.49 ± 0.07	0.21	0.57
2-Mn	0.00 ± 0.00	0.00	0.00	2.67 ± 1.10	1.32	6.98	0.47 ± 0.01	0.45	0.50
Acy	4.64 ± 0.27	3.88	5.10	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00
Ace	0.00 ± 0.00	0.00	0.00	0.81 ± 0.03	0.74	0.90	0.16 ± 0.01	0.13	0.18
Flu	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00
Phen	0.33 ± 0.09	0.15	0.67	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00
Ant	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00
Flt	0.46 ± 0.01	0.45	0.49	0.00 ± 0.00	0.00	0.00	0.09 ± 0.00	0.09	0.09
Pry	0.66 ± 0.04	0.57	0.81	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00
BaA	5.88 ± 1.47	1.03	9.76	0.70 ± 0.12	0.39	0.94	0.00 ± 0.00	0.00	0.00
Chry	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.93 ± 0.04	0.83	0.99
BbF	0.07 ± 0.01	0.05	0.09	0.32 ± 0.08	0.15	0.57	0.00 ± 0.00	0.00	0.00
BkF	0.05 ± 0.00	0.03	0.05	0.06 ± 0.01	0.04	0.08	0.00 ± 0.00	0.00	0.00
BaP	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00
DahA	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00
IndP	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00
BghiP	3.21 ± 0.22	2.35	3.46	0.00 ± 0.00	0.00	0.00	7.67 ± 0.47	6.60	8.74
Total	15.30 ± 1.68	10.00	19.80	5.90 ± 0.96	4.22	9.45	9.81 ± 0.55	8.38	11.04

Note that PAHs were not detected in SW2, SW4 – SW6, SW8 – SW12

Table 2 presents an analysis of various rings of PAHs found in water samples collected from tributaries of Bomadi and Gbotebo rivers in the Ekeremor local government area of Bayelsa state, Nigeria. These PAHs

were categorized into carcinogenic PAHs and Low Molecular Weight (LMW) and High Molecular Weight (HMW) PAHs.

Table 2: Different rings of PAHs, carcinogenic PAHs, Low and high molecular weight PAHs in the water sample from in water sample from some tributaries of Bomadi and Gbotebo rivers in Bayelsa state, Nigeria

PAHs variable	SW1	SW3			SW7				
	mean± SE	Min	Max	mean± SE	Min	Max	mean± SE	Min	Max
2-ring	0.00±0.00	0.00	0.00	4.00±0.96	2.35	7.51	0.96±0.01	0.68	1.07
3- ring	4.97±0.24	4.25	5.35	0.81±0.03	0.74	0.90	0.16±0.01	0.13	0.18
4 -ring	7.00±1.43	2.30	10.86	0.70±0.12	0.39	0.94	1.02±0.04	0.92	1.08
5 -ring	0.12±0.01	0.10	0.14	0.39±0.09	0.19	0.65	0.00±0.00	0.00	0.00
6 -ring	3.21±0.22	2.35	3.46	0.00±0.00	0.00	0.00	7.67±0.47	6.60	8.74
PAHc	6.00±1.47	1.13	9.90	1.08±0.06	0.86	1.19	0.93±0.04	0.83	0.99
LMW	4.97±0.24	4.25	5.35	4.82±0.98	3.09	8.36	1.12±0.06	0.86	1.22
HMW	10.34±1.51	5.75	14.46	1.08±0.06	0.86	1.19	8.69±0.51	7.52	9.82

In the case of SW1, no 2-ring PAHs were detected. However, for SW3 and SW7, 2-ring PAHs were found in concentrations of 4.00 ± 0.96 and 0.96 ± 0.01 , with concentration ranges of 2.35-7.51 and 0.68-1.07, respectively. Moving to 3-ring PAHs, SW1, SW3, and SW7 exhibited concentration ranges of 4.25-5.35 (4.97 ± 0.24), 2.35-7.51 (0.81 ± 0.03), and 0.13-0.18 (0.16 ± 0.01), respectively. The 4-ring PAHs ranged from 2.30-10.86 (7.00 ± 1.43), 0.39-0.94 (0.70 ± 0.12), and 0.92-1.08 (1.02 ± 0.04) for SW1, SW3, and SW7, respectively. SW1 and SW7 contained 5-ring PAHs with concentration ranges of 0.10-0.14 (0.12 ± 0.01) and 0.19-0.65 (0.39 ± 0.09), respectively. For 6-ring PAHs, SW1 and SW7 showed concentrations of 3.21 ± 0.22 and 7.67 ± 0.47 , respectively.

In addition, the total concentration of PAHs (PAHc) ranged from 1.13 to 9.90 (6.00 ± 1.47) for SW1, 0.86 to 1.19 (1.08 ± 0.06) for SW3, and 0.83 to 0.99 (0.93 ± 0.04) for SW7. These PAHs were further divided into

LMW and HMW categories, with concentration ranges for LMW being 4.25 to 5.35 (4.97 ± 0.24), 3.09 to 8.36 (4.82 ± 0.98), and 0.86 to 1.22 (1.12 ± 0.06) for SW1, SW3, and SW7, respectively. For HMW, the concentrations ranged from 75 to 14.46 (10.34 ± 1.51) for SW1, 0.86 to 1.19 (1.08 ± 0.06) for SW3, and 7.52 to 9.82 (8.69 ± 0.51) for SW7. In terms of proportions, LMW made up 32.48% in SW1, 81.69% in SW3, and 11.42% in SW7, while HMW accounted for 67.58% in SW1, 18.31% in SW3, and 88.58% in SW7 (as shown in Figure 1).

An overall trend analysis revealed that HMW PAHs dominated in SW1 and SW7, whereas LMW PAHs were more prevalent in SW3 (Figure 1). The order of prevalence of the different PAH ring types was 4-ring > 3-ring > 6-ring > 5-ring for SW1, 2-ring > 3-ring > 4-ring > 5-ring for SW3, and 6-ring > 4-ring > 2-ring > 3-ring (as illustrated in Figure 2).

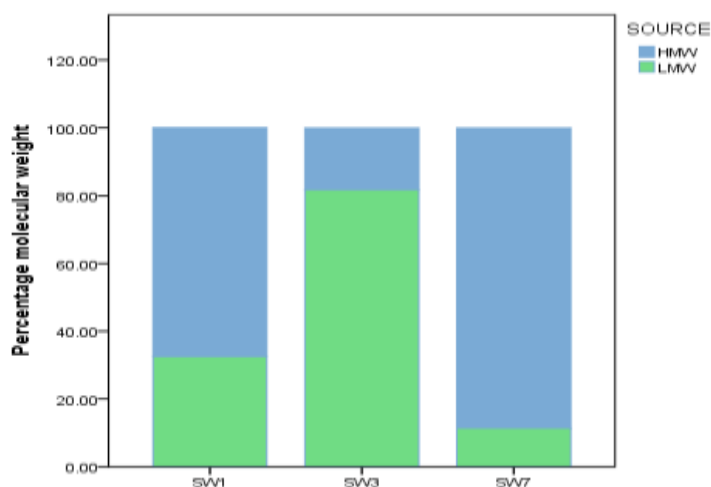


Figure 1: Percentage composition of molecular weight of the PAHs in water from the various locations (SW1, SW3 and SW7) of Bomadi and Gbotoebo rivers in Bayelsa state, Nigeria

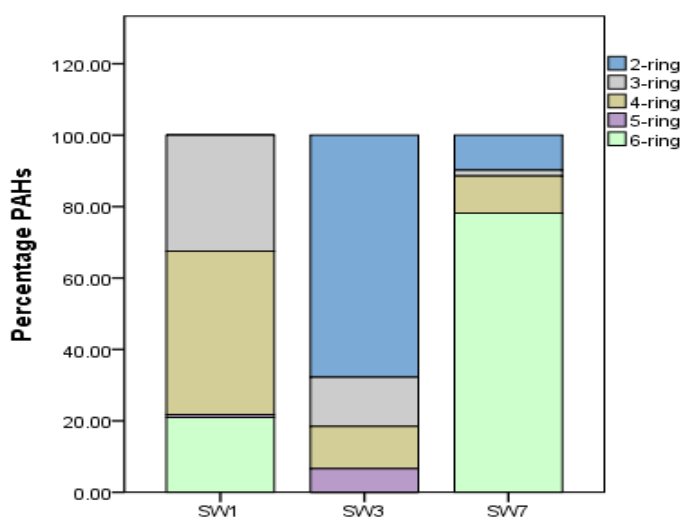


Figure 2: Percentage composition of PAHs in water from the various locations (SW1, SW3 and SW7) in water sample from some tributaries of Bomadi and Gbotoebo rivers in Bayelsa state, Nigeria

The correlation analysis conducted in this study aimed to reveal the relationships among individual PAHs and their sources. Table 3 presents the Pearson correlation coefficients of the priority PAHs detected in water samples, specifically SW1, SW3, and SW7, taken from tributaries of the Bomadi and Gbotoebo rivers within the Ekeremor local government area of Bayelsa state, Nigeria.

Table 4 provides the Pearson correlation matrix for the sum of various ring-sized PAHs categories, including carcinogenic PAHs and both low and high molecular weight PAHs, within water samples collected from communities near the Birigbene and Gbotoebo creeks, including settlements such as Ozobobenisede and Ogbotobo in Bayelsa State, Nigeria. The analysis reveals several interesting findings in the relationships among these PAH categories.

Firstly, the 2-ring PAHs exhibit both strong and weak statistical relationships with the 5-ring PAHs and LMW PAHs. This implies that there is a mix of robust and weaker associations between these compounds. Next, the 3-ring PAHs display a strong and significant relationship with the 4-ring PAHs and the category of PAHc, while showing a weaker relationship with LMW and HMW PAHs. These findings suggest that the 3-ring PAHs are particularly linked to the 4-ring PAHs and carcinogenic PAHs. Moving on to the 4-ring PAHs, they exhibit a strong correlation with PAHc and HMW PAHs but display a weaker relationship with LMW PAHs. This implies a pronounced connection between 4-ring PAHs and carcinogenic PAHs and the high molecular weight category.

Table 3: Pearson correlation of the detected priority PAHs in water sample (SW1, SW3 and SW7 only) from some tributaries of Bomadi and Gbotebo rivers in Bayelsa state, Nigeria.

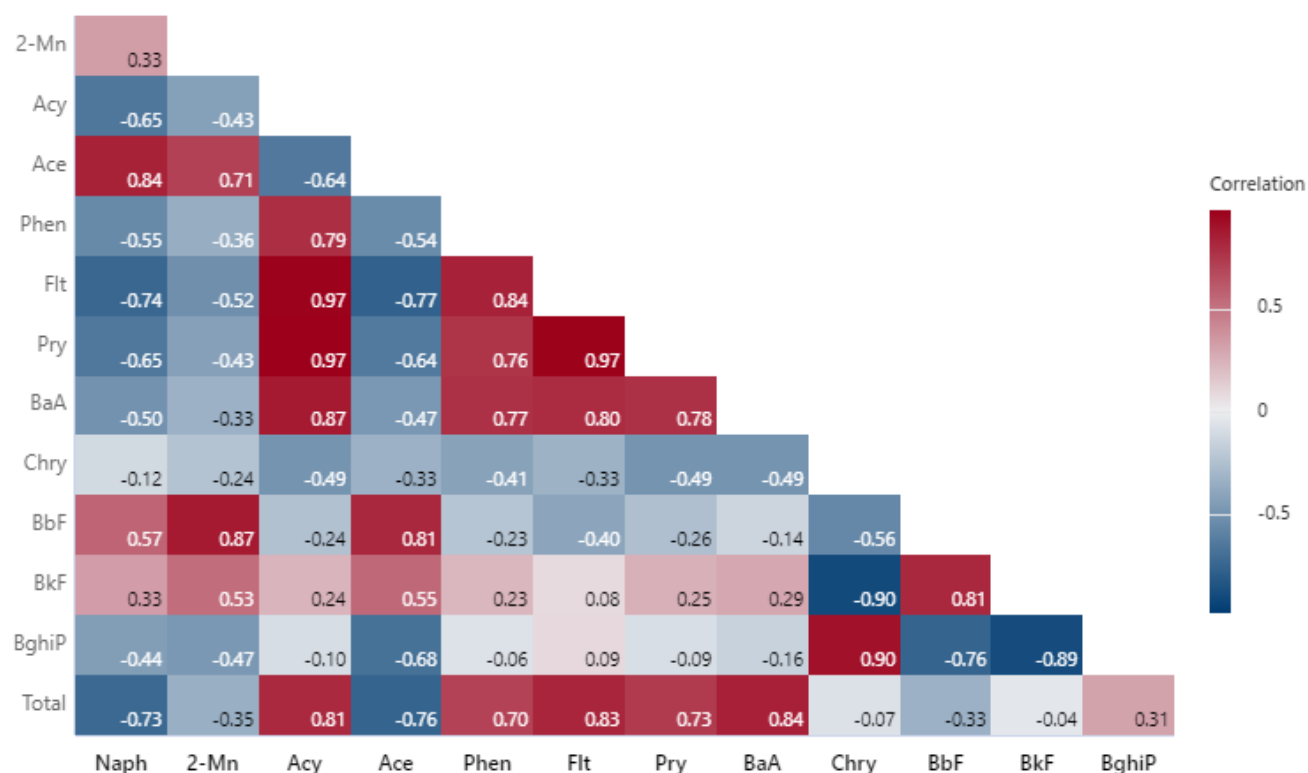
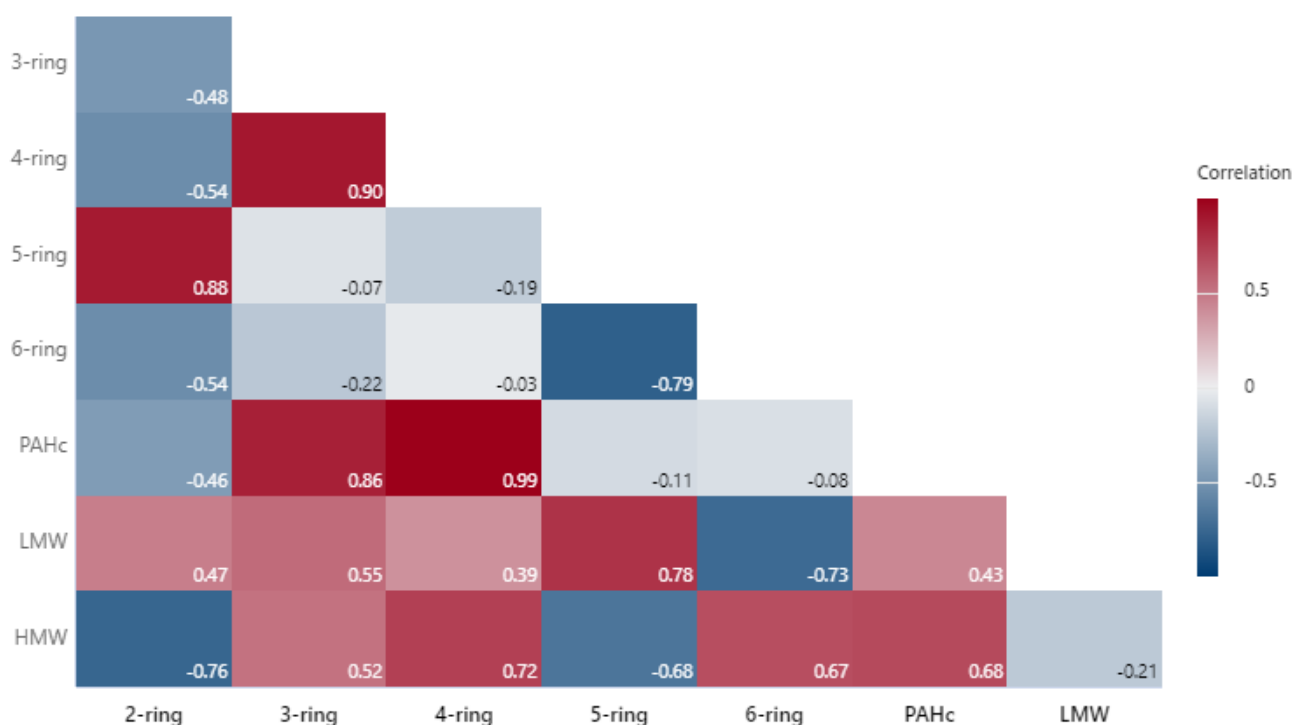


Table 4: Pearson correlation matrix of sum of different rings of PAHs, carcinogenic PAHs, Low and high molecular weight PAHs in the water sample from some tributaries of Bomadi and Gbotebo rivers in Bayelsa state, Nigeria.



Furthermore, the 5-ring PAHs demonstrate a strong correlation with LMW PAHs, suggesting a significant association between them. Likewise, the 6-ring PAHs exhibit a strong statistical relationship with HMW PAHs, highlighting a substantial connection between these two groups of compounds. Notably, PAHc, the carcinogenic PAH category, demonstrates a strong relationship with HMW PAHs but a weaker relationship with LMW PAH.

The results presented in Figure 3, show the percentage composition of carcinogenic PAHs in water samples from different locations (SW1, SW3, and SW7) in Bomadi and Gboto Rivers in Bayelsa State, Nigeria, have significant implications for environmental and public health.

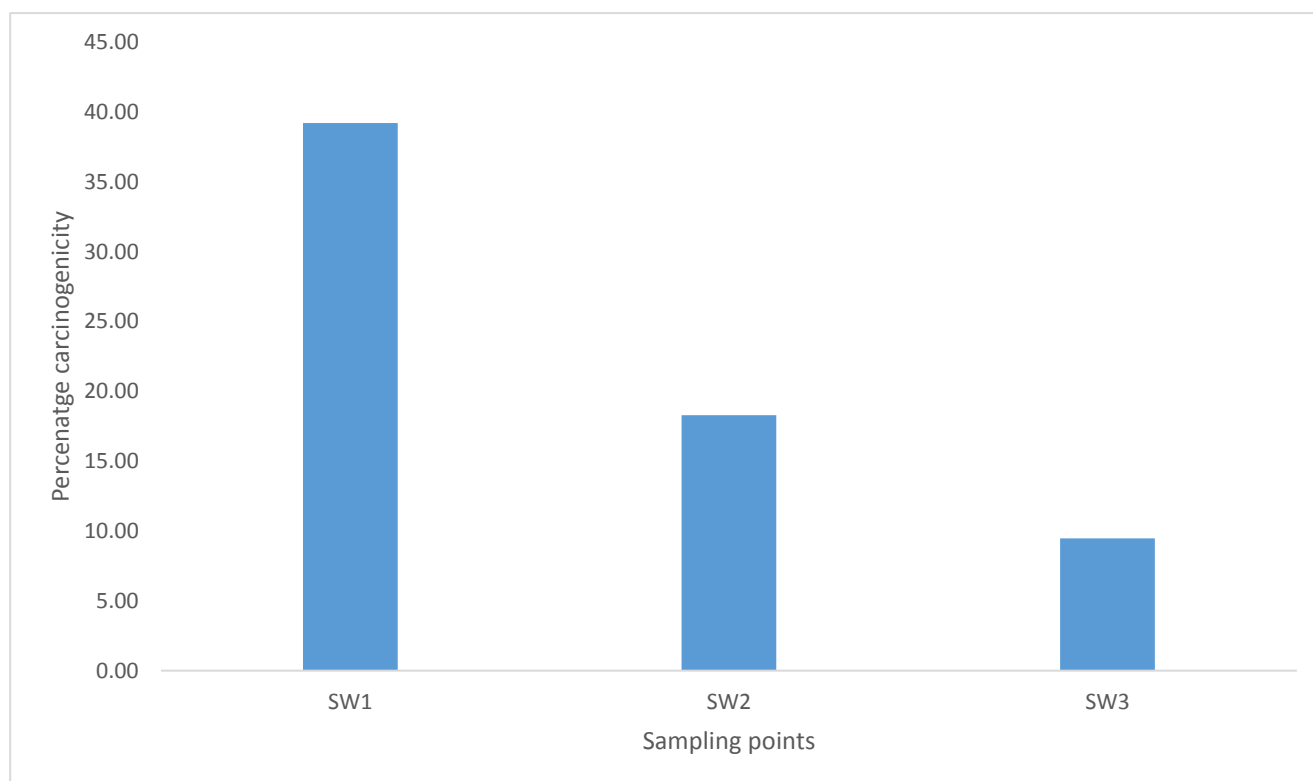


Figure 3: Percentage composition of the carcinogenic PAHs in water from the various locations (SW1, SW3 and SW7) in some tributaries of Bomadi and Gboto rivers in Bayelsa state, Nigeria

Health risk assessment is a valuable approach for assessing the potential toxicity of environmental pollutants. In this context, the human health risk associated with water samples was evaluated using four key indices: chronic daily intake (as presented in Table 5), Hazard Quotients, Hazard Index (as detailed in Table 6), and carcinogenic hazards (as shown in Table 7) (for the ingestion).

Table 5: Chronic daily intake of PAH due to ingestion of the water sample from some tributaries of Bomadi and Gboto rivers in Bayelsa state, Nigeria

PAH Variable	Locations	Adult Mean	Minimum	Maximum	Child Mean	Minimum	Maximum
Naph	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	5.44E-07	2.16E-07	8.33E-07	1.27E-06	5.05E-07	1.94E-06
	SW7	2.01E-07	8.57E-08	2.33E-07	4.69E-07	2.00E-07	5.43E-07
2-Mn	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	1.09E-06	5.39E-07	2.85E-06	2.54E-06	1.26E-06	6.65E-06
	SW7	1.91E-07	1.84E-07	2.04E-07	4.46E-07	4.29E-07	4.76E-07
Acy	SW1	1.89E-06	1.58E-06	2.08E-06	4.42E-06	3.70E-06	4.86E-06
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
Ace	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	3.31E-07	3.02E-07	3.67E-07	7.73E-07	7.05E-07	8.57E-07
	SW7	6.37E-08	5.31E-08	7.35E-08	1.49E-07	1.24E-07	1.71E-07
Flu	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
Phen	SW1	1.34E-07	6.12E-08	2.73E-07	3.12E-07	1.43E-07	6.38E-07
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
Ant	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
Flt	SW1	1.89E-07	1.84E-07	2.00E-07	4.40E-07	4.29E-07	4.67E-07
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	3.67E-08	3.67E-08	3.67E-08	8.57E-08	8.57E-08	8.57E-08
Pry	SW1	2.69E-07	2.33E-07	3.31E-07	6.27E-07	5.43E-07	7.71E-07
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
BaA	SW1	2.40E-06	4.20E-07	3.98E-06	5.60E-06	9.81E-07	9.30E-06
	SW3	2.85E-07	1.59E-07	3.84E-07	6.65E-07	3.71E-07	8.95E-07
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
Chry	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	3.79E-07	3.39E-07	4.04E-07	8.84E-07	7.90E-07	9.43E-07
BbF	SW1	2.94E-08	2.04E-08	3.67E-08	6.86E-08	4.76E-08	8.57E-08
	SW3	1.32E-07	6.12E-08	2.33E-07	3.09E-07	1.43E-07	5.43E-07
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
BkF	SW1	1.88E-08	1.22E-08	2.04E-08	4.38E-08	2.86E-08	4.76E-08
	SW3	2.53E-08	1.63E-08	3.27E-08	5.90E-08	3.81E-08	7.62E-08
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
BaP	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
DahA	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
IndP	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
BgHiP	SW1	1.31E-06	9.59E-07	1.41E-06	3.06E-06	2.24E-06	3.30E-06
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	3.13E-06	2.69E-06	3.57E-06	7.31E-06	6.29E-06	8.32E-06
Total	SW1	6.24E-06	4.08E-06	8.08E-06	1.46E-05	9.52E-06	1.89E-05
	SW3	2.41E-06	1.72E-06	3.86E-06	5.62E-06	4.02E-06	9.00E-06
	SW7	4.00E-06	3.42E-06	4.51E-06	9.34E-06	7.98E-06	1.05E-05

The laboratory analysis did not detect these values, as denoted by "VNDD."

The CDI of PAHs in water samples from tributaries of the Bomadi and Gbotebo rivers showed variations across locations and age groups. In adults, the highest mean CDI was observed for BghiP at SW7 ($3.13\text{E-}06$ mg/kg/day), followed by total PAHs at SW1 ($6.24\text{E-}06$ mg/kg/day), while lower values were recorded for BkF at SW1 ($1.88\text{E-}08$ mg/kg/day). For children, higher mean values were consistently observed compared to adults, with BghiP at SW7 ($7.31\text{E-}06$ mg/kg/day) and total PAHs at SW1 ($1.46\text{E-}05$ mg/kg/day) representing the most significant exposures. Compounds such as Naph, Flu, Ant, BaP, DahA, and IndP were not detected in several sites (VNDD). Overall, children showed approximately two to three times higher CDI values than adults, indicating greater susceptibility to PAH exposure through water ingestion in the study area.

From Table 6, the assessment of non-carcinogenic risks revealed varying hazard quotients (HQs) and hazard index (HI) values across the sampled tributaries of Bomadi and Gbotebo rivers. For

naphthalene (Naph), HQ values were detected only in SW3 and SW7, with adult mean values ranging from $1.00\text{E-}05$ to $2.72\text{E-}05$, while corresponding child values ranged from $2.34\text{E-}05$ to $6.34\text{E-}05$. Phenanthrene (Phen) was detected only in SW1, with a mean HQ of $3.35\text{E-}06$ for adults and $7.81\text{E-}06$ for children. Fluoranthene (Flt) showed low mean HQs at SW1 ($4.71\text{E-}06$ in adults, $1.10\text{E-}05$ in children) and SW7 ($9.18\text{E-}07$ in adults, $2.14\text{E-}06$ in children). Benzo(ghi)perylene (BghiP) was more prominent, with mean HQ values of $3.28\text{E-}05$ (adults) and $7.65\text{E-}05$ (children) in SW1, and higher levels in SW7 with $7.83\text{E-}05$ (adults) and $1.83\text{E-}04$ (children). The hazard index (HI) values indicated the cumulative risk, ranging from $2.72\text{E-}05$ to $8.92\text{E-}05$ in adults and $6.34\text{E-}05$ to $2.09\text{E-}04$ in children. Notably, all HQ and HI values were below 1, suggesting no immediate non-carcinogenic risk, although children exhibited consistently higher values compared to adults.

Table 6: Hazard Quotients (HQ) and Hazard index (HI) of PAHs in the water sample from some tributaries of Bomadi and Gbotebo rivers in Bayelsa state, Nigeria

PAH Variable	Locations	Adult			Child		
		Mean	Minimum	Maximum	Mean	Minimum	Maximum
Naph	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	$2.72\text{E-}05$	$1.08\text{E-}05$	$4.16\text{E-}05$	$6.34\text{E-}05$	$2.52\text{E-}05$	$9.71\text{E-}05$
	SW7	$1.00\text{E-}05$	$4.29\text{E-}06$	$1.16\text{E-}05$	$2.34\text{E-}05$	$1.00\text{E-}05$	$2.71\text{E-}05$
Flu	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
Phen	SW1	$3.35\text{E-}06$	$1.53\text{E-}06$	$6.84\text{E-}06$	$7.81\text{E-}06$	$3.57\text{E-}06$	$1.60\text{E-}05$
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
Ant	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
Flt	SW1	$4.71\text{E-}06$	$4.59\text{E-}06$	$5.00\text{E-}06$	$1.10\text{E-}05$	$1.07\text{E-}05$	$1.17\text{E-}05$
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	$9.18\text{E-}07$	$9.18\text{E-}07$	$9.18\text{E-}07$	$2.14\text{E-}06$	$2.14\text{E-}06$	$2.14\text{E-}06$
BghiP	SW1	$3.28\text{E-}05$	$2.40\text{E-}05$	$3.53\text{E-}05$	$7.65\text{E-}05$	$5.60\text{E-}05$	$8.24\text{E-}05$
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	$7.83\text{E-}05$	$6.73\text{E-}05$	$8.92\text{E-}05$	$1.83\text{E-}04$	$1.57\text{E-}04$	$2.08\text{E-}04$
HI	SW1	$4.09\text{E-}05$	$3.01\text{E-}05$	$4.71\text{E-}05$	$9.53\text{E-}05$	$7.03\text{E-}05$	$1.10\text{E-}04$
HI	SW3	$2.72\text{E-}05$	$1.08\text{E-}05$	$4.16\text{E-}05$	$6.34\text{E-}05$	$2.52\text{E-}05$	$9.71\text{E-}05$
HI	SW7	$8.92\text{E-}05$	$7.25\text{E-}05$	$1.02\text{E-}04$	$2.09\text{E-}04$	$1.69\text{E-}04$	$2.37\text{E-}04$

The laboratory analysis did not detect these values, as denoted by "VNDD."

From Table 7, the carcinogenic risk estimates varied depending on the PAH compound and location. Benzo(a)anthracene (BaA) presented measurable risks at SW1 and SW3, with adult mean values of $1.75\text{E-}06$ and $2.08\text{E-}07$, respectively, while children recorded higher risks at $4.09\text{E-}06$ (SW1) and $4.85\text{E-}07$ (SW3). Chrysene (Chry) was detected only in SW7, where adult and child means were $2.77\text{E-}08$ and $6.45\text{E-}08$, respectively. Benzo(b)fluoranthene (BbF) displayed low risks at SW1 ($2.15\text{E-}08$ for adults; $5.01\text{E-}08$ for children), but relatively higher risks at SW3 with adult and child

means of $9.65\text{E-}08$ and $2.25\text{E-}07$, respectively. Similarly, Benzo(k)fluoranthene (BkF) was found in SW1 and SW3, with adult mean risks of $1.37\text{E-}08$ and $1.85\text{E-}08$, and child mean risks of $3.20\text{E-}08$ and $4.31\text{E-}08$, respectively. The life carcinogenic hazard risk index (LCHRI) ranged from $2.77\text{E-}08$ at SW7 to $1.79\text{E-}06$ at SW1 for adults, and from $6.45\text{E-}08$ at SW7 to $4.17\text{E-}06$ at SW1 for children. Overall, while most risk values remained below the threshold of $1.0\text{E-}04$, suggesting limited carcinogenic concern, children consistently demonstrated higher susceptibility compared to adults.

Table 7: Carcinogenic risks (Life carcinogenic risk and life carcinogenic hazard risk index) of PAHs through ingestion route in water sample from some tributaries of Bomadi and Gbotebo rivers in Bayelsa state, Nigeria

PAH variables	Locations	Adult			Child		
		Mean	Minimum	Maximum	Mean	Minimum	Maximum
BaA	SW1	$1.75\text{E-}06$	$3.07\text{E-}07$	$2.91\text{E-}06$	$4.09\text{E-}06$	$7.16\text{E-}07$	$6.79\text{E-}06$
	SW3	$2.08\text{E-}07$	$1.16\text{E-}07$	$2.80\text{E-}07$	$4.85\text{E-}07$	$2.71\text{E-}07$	$6.54\text{E-}07$
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
Chry	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	$2.77\text{E-}08$	$2.47\text{E-}08$	$2.95\text{E-}08$	$6.45\text{E-}08$	$5.77\text{E-}08$	$6.88\text{E-}08$
BbF	SW1	$2.15\text{E-}08$	$1.49\text{E-}08$	$2.68\text{E-}08$	$5.01\text{E-}08$	$3.48\text{E-}08$	$6.26\text{E-}08$
	SW3	$9.65\text{E-}08$	$4.47\text{E-}08$	$1.70\text{E-}07$	$2.25\text{E-}07$	$1.04\text{E-}07$	$3.96\text{E-}07$
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
BkF	SW1	$1.37\text{E-}08$	$8.94\text{E-}09$	$1.49\text{E-}08$	$3.20\text{E-}08$	$2.09\text{E-}08$	$3.48\text{E-}08$
	SW3	$1.85\text{E-}08$	$1.19\text{E-}08$	$2.38\text{E-}08$	$4.31\text{E-}08$	$2.78\text{E-}08$	$5.56\text{E-}08$
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
BaP	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
DahA	SW1	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW3	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
	SW7	VNDD	VNDD	VNDD	VNDD	VNDD	VNDD
LCHRI	SW1	$1.79\text{E-}06$	$3.31\text{E-}07$	$2.95\text{E-}06$	$4.17\text{E-}06$	$7.72\text{E-}07$	$6.89\text{E-}06$
LCHRI	SW3	$3.23\text{E-}07$	$1.73\text{E-}07$	$4.74\text{E-}07$	$7.53\text{E-}07$	$4.03\text{E-}07$	$1.11\text{E-}06$
LCHRI	SW7	$2.77\text{E-}08$	$2.47\text{E-}08$	$2.95\text{E-}08$	$6.45\text{E-}08$	$5.77\text{E-}08$	$6.88\text{E-}08$

The laboratory analysis did not detect these values, as denoted by "VNDD."

3.2 DISCUSSION

The observed variations in the concentrations of individual polycyclic aromatic hydrocarbons (PAHs) and their spatial distribution can be attributed to various hydrogeological factors, including degradation, adsorption, precipitation, and dissolution processes. Such findings align with prior research; for instance, Ekere et al. (2019) reported PAH concentrations in water

samples from the Lokoja axes of the River Niger and River Benue, revealing a range for Naphthalene (Naph) from not detected to 0.543 mg/L , and for Phenanthrene (Ph) from not detected to 0.083 mg/L , with an order of concentrations as $\text{Naph} > \text{BaP} > \text{BbF} = \text{BkF} = \text{Ant} = \text{Ph}$.

Similarly, Adekunle et al. (2020) studied PAH levels in River Sasa, Osun State, Nigeria, finding Phenanthrene and Fluoranthene exhibiting the highest concentrations,

with total PAH levels ranging from 100.68 ng/L to 521.16 ng/L across dry and wet seasons. Asagbra et al. (2015) observed an average concentration of 34 ng/ml for 11 priority PAHs in the Warri River, while Ambade et al. (2021) reported concentrations in the Damodar River Basin, India, varying from not detected to as high as 36 units, indicating a significant diversity of contamination.

Wu et al. (2011) identified PAH concentrations in drinking water sources in China ranging from 7.62 to 9662 ng/L, highlighting regional discrepancies in contamination. Further, Zhu et al. (2015) reported variations in PAH concentrations within the Three Gorges Reservoir, noting Phe as the most abundant.

These studies illustrate the complex and varied distribution of PAHs across different regions and water sources, emphasizing the influence of environmental conditions and human activities. In contrast, the findings from this study suggest different trends in PAH occurrence. For example, Asagbra et al. (2015) reported low molecular weight (LMW) PAHs in their samples, while Ambade et al. (2021) found a significant presence of 3-ring (67%) and 4-ring (28%) PAHs in water from the Damodar River. This difference indicates the influence of local anthropogenic activities and hydrological conditions during sampling.

In terms of correlations among PAHs, the analysis indicates that Naph exhibited strong positive relationships with Acenaphthene (Ace) and BbF, while showing weaker correlations with 2-Methylnaphthalene (2-Mn) and Benzo[k]fluoranthene (BkF). On the other hand, 2-Mn displayed strong correlations with Ace, BbF, and BkF, alongside a negative correlation with Fluoranthene (Flt). The relationships among other PAHs also reveal complex interactions, with different compounds exhibiting both positive and negative correlations.

Significantly, these relationships suggest various potential sources and transformation pathways for the compounds, indicating the ecological impacts present in the studied environment. Furthermore, the presence of both strong and weak correlations among different PAH classes points to the heterogeneous interactions in these compounds, which could be influenced by their chemical structures, sources, and toxicological properties. Overall, this analysis emphasizes the need for a focused examination of individual PAH compounds, particularly regarding their associations and implications for environmental health.

This may be of concern because it indicates potential toxicity associated with 3-ring PAHs due to their close association with carcinogenic compounds. Also, the strong correlation of 4-ring PAHs with PAHc and high molecular weight (HMW) PAHs indicates a pronounced connection between these 4-ring compounds and carcinogenic PAHs and the high molecular weight category. This finding could be of regulatory significance,

as it implies that monitoring and controlling 4-ring PAHs may help reduce the risk associated with carcinogenic PAH exposure. Furthermore, the strong correlation between 5-ring PAHs and LMW PAHs, as well as between 6-ring PAHs and HMW PAHs, suggests distinct associations between these compounds. Therefore, understanding these associations is essential for assessing the environmental fate and potential health impacts of PAHs. Lastly, the strong relationship between carcinogenic PAHs (PAHc) and HMW PAHs is significant, indicating that carcinogenic PAHs are primarily associated with high molecular weight compounds. This insight can inform risk assessments and environmental policies aimed at reducing exposure to carcinogenic PAHs.

These results suggest that the relationships between different classes of PAHs are not uniform and vary in strength and significance. These findings have implications for environmental monitoring, risk assessment, and regulatory actions related to PAH exposure, especially concerning the carcinogenic potential of certain PAH compounds and their association with specific categories. Further research and analysis may be needed to better understand the underlying factors driving these statistical relationships.

Based on the information presented in Tables 3 and 4, it is evident that various PAHs and their corresponding ring structures exhibit co-contamination in some instances, while in others, they share common anthropogenic sources or are influenced by similar hydrogeological conditions. This observation aligns with the findings of previous researchers, such as Singh *et al.* (2021) and Shukla *et al.* (2022), who have noted that a higher relationship coefficient between the PAHs (as shown in Table 3) and their respective ring structures (as presented in Table 4) suggests a shared origin, interdependence, and similar behavior during transport.

Conversely, when the connections between PAHs and their corresponding ring structures are weak, it implies that the composition of these compounds is influenced by a range of hydrogeological factors, highlighting a more complex and diverse set of environmental influences.

Based on Figure 3, the differences in the percentage composition of carcinogenic PAHs at the three locations (SW1, SW3, and SW7) indicate that the level of environmental contamination varies. SW1 has the highest percentage at 39.22%, suggesting a potentially higher risk of exposure to carcinogens in this area, while SW3 and SW7 have lower percentages, indicating a comparatively lower risk. High levels of carcinogenic PAHs in the water can harm the aquatic ecosystem, harming aquatic life, such as fish and other organisms. Additionally, the presence of carcinogens in water bodies can eventually impact human health if people consume contaminated water or consume fish and other seafood from these waters. The presence of carcinogenic PAHs in water sources raises concerns about the potential health risks to the communities living in proximity to these rivers. Prolonged exposure to

carcinogens can increase the risk of various health issues, including cancer. Therefore, it is crucial to understand the extent of contamination and take appropriate measures to protect public health.

In the specific study, assessing the hazard quotients and hazard indices for both adults and children exposed to PAHs in water samples from various locations (SW1, SW3, and SW7), the findings revealed that the hazard quotients for adults ranged from 10^{-7} to 10^{-5} , while for children, the values ranged from 10^{-6} to 10^{-4} . These hazard quotients reflect the risk associated with PAH exposure in the sampled water. The presence of both adult and child HQ values within the range of 10^{-7} to 10^{-4} indicates a level of risk associated with exposure to these compounds; however, these figures alone do not provide a definitive measure of risk severity.

The hazard index for adults at the sampling points SW1, SW3, and SW7 was found to be approximately 10^{-5} . In contrast, the hazard index for children varied across these points, with values of 10^{-5} , 10^{-4} , and 10^{-5} , respectively. The HI serves as a cumulative measure, summing the hazard quotients for multiple PAHs. Generally, an HI value below 1 suggests that there is no significant non-carcinogenic hazard associated with exposure to the assessed substances. The observation that both adults and children exhibited HI values less than 1 implies that, according to the data available, there is no known non-carcinogenic hazard from PAH exposure in the water samples collected from SW1, SW3, and SW7. This finding is encouraging, as it indicates that exposure to PAHs at these sites is unlikely to pose a significant non-carcinogenic health risk to either demographic group. Previous research supports this conclusion, indicating that an HI value below 1 typically signifies a lack of known non-carcinogenic hazards.

Furthermore, the investigation revealed that the calculated carcinogenic risks of the detected PAHs fell within the range of 10^{-8} to 10^{-6} . This range represents the estimated probability of developing cancer due to exposure to these PAHs. The 10^{-8} to 10^{-6} range implies that the risk is relatively low (Aigberua et al., 2023; Ogamba et al., 2023). This implies that the estimated risk of developing cancer due to the consumption of water contaminated with PAHs is very low for both adults and children in the study area.

4.0 CONCLUSION

The study established that PAHs were detected only at three out of twelve sampling locations (SW1, SW3, and SW7), with concentrations ranging between 4.22 and 19.80 $\mu\text{g/L}$. The distribution revealed complex relationships among low, medium, and high molecular weight PAHs, with carcinogenic fractions showing strong associations with HMW PAHs. Although the non-carcinogenic and carcinogenic health risk indices for both adults and children were below critical thresholds,

the detection of carcinogenic compounds such as benzo[a]anthracene and benzo[ghi]perylene highlights the possibility of future risks, particularly in light of the area's proximity to oil and gas operations. These findings highlight the need for proactive measures to prevent escalation of contamination and safeguard community health. To address these concerns, continuous monitoring of PAHs in surface water is essential, particularly in areas near industrial activities. Strengthened pollution control measures should be enforced to limit hydrocarbon discharges into rivers and creeks, while communities should be sensitized on potential long-term risks and encouraged to adopt safe water practices. The provision of alternative potable water sources will further reduce dependence on potentially contaminated rivers. In addition, further research should investigate seasonal variations, sediment accumulation, and bioaccumulation in aquatic organisms to provide a comprehensive understanding of ecological and human health risks in the region.

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