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Health Risk Assessment and Source Apportionment of PAHs in Rainwater Obtained in an Urban Area in Southern Nigeria

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ABSTRACT

This study investigates the presence and composition of potential health risks from the sources of Polycyclic Aromatic Hydrocarbons (PAHs) in rainwater collected from urban rooftops in Asaba, Delta State, Nigeria. Ten rainwater samples were analyzed for their PAH composition using Gas Chromatography Flame Ionization Detection (GC-FID), HP5890 Series II model. Average Daily Dose (ADD), benzo(a)pyrene toxic equivalence (B(A)Pteq), and carcinogenic toxic equivalence (TEQs) were utilized to evaluate the potential health risks associated with the consumption of the rainwater. Also, molecular diagnostic ratios were employed to identify the sources of PAHs in the water. The results indicated the presence of PAHs in all the samples, with average concentrations ranging from 0.21 to 6.4 µg/L. The evaluated ADD values ranged from 0.006286 to 0.201143 µg/L, while B(A)Pteq ranged from 0.0013 to 2.5, with a TEQ value of 5.1. The study established that most PAH levels were below critical thresholds for non-carcinogenic effects. The potential cancer risk assessment (B(A)Pteq and TEQs) revealed values exceeding the USEPA's negligible risk threshold for cancer risk (CR), indicating significant public health concerns. Furthermore, it was observed that lower molecular weight PAHs accounted for 63.73% of the total composition. Inferences from the molecular diagnostic ratio plots suggest that the pyrogenic processes, particularly fuel combustion from industrial and vehicular emissions were dominant sources of PAHs in the rainwater.

1. INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) comprise a category of more than 100 distinct chemical substances that are commonly produced during the incomplete combustion of organic materials at elevated temperatures. These compounds are characterized by multiple interconnected benzene rings, which are primarily composed of carbon and hydrogen atoms (Abdel-Shafy and Mansour, 2016). PAHs are released into the atmosphere from numerous primary sources. The major source is the incomplete combustion of organic materials, primarily by organic materials such as the burning of biomass and the combustion of fossil fuels like coal, oil, and natural gas, happening in industrial

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DIO

processes, power generation, and domestic heating. Due to engine combustion, motor vehicle emissions also considerably raise the quantities of PAHs in the atmosphere. PAH emissions are also a result of a variety of industrial processes, including the manufacturing of coal tar and the thermal cracking of petroleum products, as well as the deliberate and inadvertent burning of biomass from local bakeries and other domestic activities.

PAHs are common environmental contaminants that pose various health risks (Odesa, and Olannye, 2025). Due to their mutagenic and carcinogenic effects, a selection of 16 PAHs has been classified as priority pollutants because of their toxicity and persistence in the environment WHO,2003). Exposure to these PAHs has been linked to serious health issues, including an elevated risk of cancer and genetic mutations, particularly among vulnerable groups such as children living near heavily trafficked roads (Odesa et al., 2024[a]). Studies show that PAH exposure can cause oxidative stress and DNA damage, leading to potential long-term health effects and other severe health implications.

Benzo[a]pyrene (BaP) serves as a representative marker for the broader group of PAHs for setting air quality limits due to its well-documented carcinogenic properties and its prevalence in the environment. Its ability to bind to particulate matter allows it to persist in the atmosphere, making it a reliable indicator of overall PAH contamination in ambient air Agency for Toxic Substances and Disease Registry (ATSDR, 2023)

As semi volatile organic compounds, PAHs can exist as gases or adsorb onto particles, with their distribution and partitioning highly influenced by factors such as temperature, atmospheric pressure, organic carbon content, and aerosol composition (Rao, and Vejerano, 2018). Factors such as Seasonal variations also play a significant role, as increased combustion activities during the dry seasons also affect the PAH concentrations on substrates.

PAHs are also known hydrophobic compounds with low solubility, which leads them to associate predominantly with solid particles, particularly larger particulate matter (PM) in the atmosphere. Their physical and chemical properties favor's adsorption onto these particles rather than remaining in the gaseous phase. Once PAHs are attached to PM, they can be transported over long distances by wind currents. Wind plays a crucial role in resuspending particles from surfaces such as roofs and vegetation, with factors like wind speed and turbulence significantly influencing the efficiency of this resuspension During transport, smaller particles can aggregate, resulting in larger particle sizes that deposit and settle on various surfaces (Zhang, et al 2020). As PM settles, it accumulates and subsequently contributes to an increase in levels of contaminants on roofs, leaves, and other substrates. This accumulateded PM constitutes diverse forms of contaminants including PAHs. This poses risks of environmental pollution and its attendant potential health hazards through direct contact with rainwater. (Souza, et al.,2021).

Rainwater harvesting has been identified as a major and critical practice for augmenting freshwater supplies in various regions globally. It involves the systematic collection and storage of rainwater, primarily from rooftop runoff, for subsequent domestic use. This method not only provides a sustainable source of fresh water but also mitigates the reliance on conventional water supply systems. In some regions, the first rain of the year is superstitiously believed to be medicinal, these practices have been held for ages.

Sometimes, the first rain of the year coincides with the first rain over a long dry season. In the Southern part of Nigeria, the dry season spans from November to March. This marks a period of accumulation of particulate matter and PAHs in the roofs of buildings. As rainwater flows over rooftops, it collects this particulate matter laden with PAHs, which is harvested for domestic use. Therefore, the need to investigate the inherent risk associated with the consumption of the first rainwater harvested from roof runoff has become inevitable.

The use of health index metrics such as Average daily dose (ADD) and Carcinogenic toxic equivalence (TEQs) have been successfully used to evaluate the effects of PAH contamination in potable water across the globe (ATSDR, 2023; Adeniji et al., 2019; Onyegeme-Okerenta et al., 2022;)

The application of molecular diagnostic ratios for pinpointing the sources of PAHs has been widely acknowledged as an essential method for evaluating environmental contamination (Tobiszewski, 2014; Wang, et al., 2007;). As industrialization and urban growth continue to proliferate globally, it is crucial to comprehend the dynamics of PAH emissions to develop effective regulatory measures aimed at reducing pollution and safeguarding public health (Iwegbue et al., 2022). By identifying the primary sources of PAHs, policymakers can introduce targeted strategies to lower emissions from specific activities, such as fossil fuel combustion and biomass burning (Ambade et al., 2007; Wu et al.,2011). This strategy is especially pertinent in areas where air quality regulations are not rigorously enforced or where there is a significant dependence on traditional energy sources.

Previous study conducted by Okoye et al., (2023), on the presence of PAHs in soil and vegetation in the Niger Delta observed significant levels of soil contamination from PAHs. The research indicates that some soils in the region require remediation due to high concentrations of PAHs, which pose risks to ecological health. similar findings have been reported on the concentration of PAH in soil by (Okoye, et al., 2023, Faboya et al., 2023), In surface water (Davies, et al., 2016; Nwineewii et al., 2015; Ibezue et al., 2018; Odesa, et al., 2024; Ogbonna et al., 2021; Saunders, 2022) in groundwater (Anyakora, and Coker, 2009; Ite, et al., 2018; Nwaozuzu, et al., 2024;).Despite the extensive body of research on PAHs within this region, there remains a significant knowledge gap regarding the probabilistic health implications associated with the consumption of PAH-contaminated rainwater harvested in urban areas and the dominant sources of PAHs in the environment. This study aims to address this deficiency by investigating the potential health risks linked to the ingestion of the water using some health metrics such as the average daily dose (ADD), carcinogenic toxic equivalence (TEQs) and molecular diagnostic ratios of PAHs.

2. METHODOLOGY

2.1. Study location

The study area, shown in Fig. 1 (Asaba), is an urban city located in Delta State, Nigeria. It is bounded by longitude 6°27'10.3"E and latitude 5°08'57.5"N. The city has a population of fifty thousand inhabitants (NPC, 2006) and serves as a central hub for industrial and commercial activities.

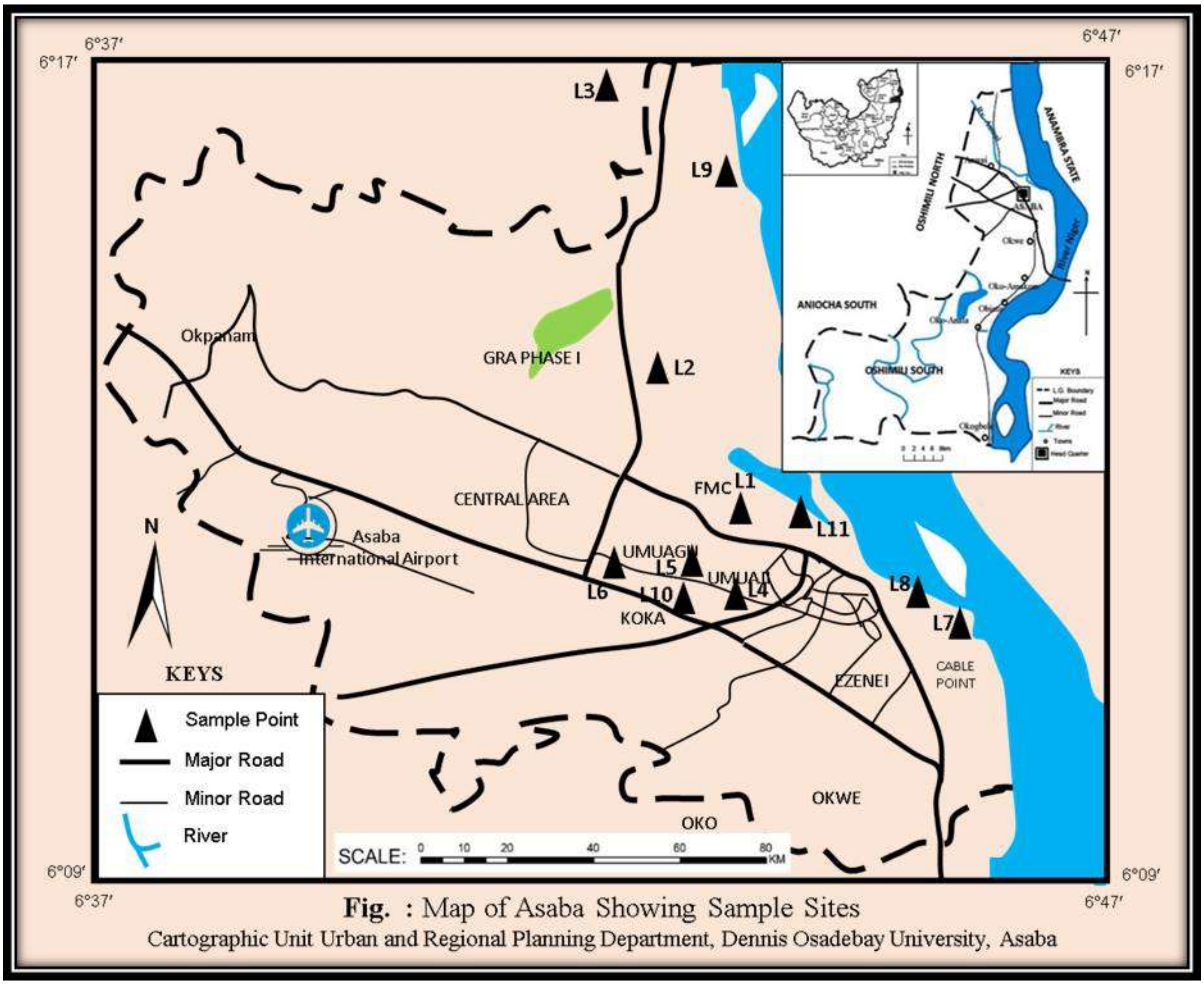

Fig 1: Map of the study area

2.2 Sample Collection and Analysis

A total of ten (10) rainwater samples were collected directly from the runoff associated with buildings, while an additional five (5) rainwater samples were obtained directly from designated control sites within the study areas during the month of February after the four (4) month period of no rain fall. All samples were collected using Amber glass containers with Teflon-lined caps. Following collection, these samples were promptly transported to the laboratory for subsequent analysis, where they were examined for concentrations of polycyclic aromatic hydrocarbons (PAHs)

The PAHs included all 16 priority PAHs identified by the U.S. Environmental Protection Agency (EPA). The study employed a liquid-liquid extraction method for the extraction of PAHs from water samples. The water samples were subjected to a serial extraction process using 25 mL of dichloromethane in three stages: 125 mL, followed by two additional 50 mL extractions. Subsequently, the extracts were dehydrated with anhydrous sodium sulphate. Detection of the PAH congeners was performed using Gas Chromatography with a Flame Ionization Detector (GC-FID), specifically utilizing the HP5890 Series II model.

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DIO

2.3 Quality assurance and control.

The extraction of samples was conducted within 24 hours of collection to guarantee the accuracy and dependability of the results. The laboratory adhered to stringent quality assurance protocols in compliance with the ISO/IEC 17025:2018 guidelines for testing and calibration in laboratory settings. To evaluate the quality assurance and quality control (QA/QC) of the analytical procedure, procedural blanks, replicate samples, and reference standards were utilized. The reference standards for the analytes were derived from certified stock solutions corresponding to the 16 priority PAHs designated by the USEPA: Naphthalene, Acenaphthylene, Acenaphthene, Fluorene, Phenanthrene, Anthracene, Fluoranthene, Pyrene, Benz[a]anthracene, Chrysene, Benzo[b]fluoranthene, Benzo[k]fluoranthene, Benzo[a]pyrene, Indeno[1,2,3-cd]pyrene, Dibenz[a,h]anthracene and Benzo[ghi]perylene. Concentrations for each set of samples were determined using the high-range calibration curve. Duplicate samples, representing 10% of the total, were analyzed to evaluate the reliability and reproducibility of the results. The calculated recovery rates for spiked samples varied between 80% and 120%

2.4 Health risk assessment for PAHs

Health risk assessment for the adult population was conducted utilizing the average Dietary Daily Intake (DDI). Concurrently, the potential for cancer risk was evaluated based on the carcinogenic potencies of individual polycyclic aromatic hydrocarbons (PAHs), specifically Benzo[a]pyrene equivalents (B(A)Pteq), along with the individual toxicity equivalency factors (TEFs) and a comprehensive cancer risk assessment.

2.4.1 Average Daily Dose (ADD)

The Average Daily Dose (ADD) of PAHs from water consumption was estimated by multiplying the average daily water consumption rate, known as the ingestion rate (IR), by the concentration of PAHs in the water. This calculation for DI of PAHs via water was performed following the recommendations from the Agency for Toxic Substances and Disease Registry (ATSDR, 2023)

However, the likelihood of negative health impacts from one-off exposure to both carcinogenic and non-carcinogenic substances was assessed for adult population. It was observed within the study area that the rainwater source is primarily utilized for domestic purposes. However, since the volume of the first rain after the long dry season period is limited and often used within a limited time, the risk associated via the ingestion route is of prime importance and one-off evaluation for carcinogenic and non-carcinogenic effects was ultilised as shown in equations 1 and 3 as recommended by ATSDR, (2023).

$$average\ \text{Daily dose (ADD)} = \text{Ci} \times \frac{\text{IR}}{BW} \quad (1)$$

Ci is the concentration of PAHs in water samples, IR is the ingestion rate of water (2Litres), and Bw is the average body weight of an adult, which is 70 kg (ATSDR, 2023), *2.4.2 Cancer Risk Characterization*

The potential cancer risk for PAHs associated with the ingestion of the water was assessed by evaluating the carcinogenic strengths of specific PAHs through the use of carcinogenic toxic equivalents (TEQs).

2.4.3 Carcinogenic toxic equivalence (TEQs)

TEQs serve as a technique for evaluating the cumulative carcinogenic strength of a blend of PAHs (Tango et al., 2017). The assessment of TEQs begins with determining the B(A)Pteq for each compound being studied. B(A)Pteq denotes the toxic equivalent of benzo(a)pyrene, serving as a metric for gauging the carcinogenic strength of PAHs (Moslena et al., 2019). The calculation of B(A)Pteq involves multiplying the concentration of each carcinogenic PAH by its corresponding toxicity equivalency factor (TEF), which is compared to benzo(a)pyrene (BaP). This approach is taken because BaP is regarded as the most potent carcinogenic PAH and is allocated a TEF value of 1. Other PAHs are assigned TEF values that range from 0 to 1, reflecting their carcinogenic potential in relative to BaP. This research employed TEF as utilized in studies by Tango et al. (2017) and Odesa and Olannye (2025) and presented in table 1. The evaluation of B(A)Pteq and TEQs was carried out using Equation (2) with the results are displayed in Table 1.

$$\mathrm{T}EQs = \Sigma(\mathrm{Ci} \times \mathrm{TEF}) \qquad (2)$$

2.4.4. Statistical analysis

One-way ANOVA was used to test the concentrations of PAHs. in water samples collected from rooftops and those from control sites. This analysis was performed using SPSS version 20.0 software for Windows. A statistical significance threshold was established at $p \leq 0.05$, corresponding to a 95% confidence level

3. RESULTS AND DISCUSSION

Health risk assessment for PAHs

Health risk assessment for the adult population was conducted utilizing the Average Daily Dose (ADD). Concurrently, the potential for cancer risk was evaluated based on the carcinogenic potencies equivalence of benzo (a) pyrene (B(A)Pteq) of individual polycyclic aromatic hydrocarbons (PAHs), and toxic equivalence (TEQ) for carcinogen.

The statistical analysis of potential health indices related to PAHs in drinking water from the roof and the control stations were assessed for B(a)Pteq. The results yielded p-values of 0.1139 and F-values of 1.445, respectively, all evaluated at a common alpha level of 0.05. This suggests that a significant difference and moderate variability exist in the rainwater data sets obtained from the roofs of buildings and the control sites. The laboratory results are presented in Table 1.

Table 1. Concentrations of the 16 priority PAHs in the Rainwater

PAHs	Symbols	Range in Rainwater (µg/L)	Control (µg/L)	TEF	(Mean ±SD) (µg/L)	ADD	B(a)P teq
Naphthalene	Nap	2.45-9.16	ND-1.2x10^{-7}	0.001	4.41 ±0.96	0.1386	0.00441
Acenaphthylene	Acy	1.19-12.41	ND	0.001	6.12 ±1.75	0.192343	0.00612
Acenaphthene	Ace	0.19-13.61	ND	0.001	6.4 ±1.21	0.201143	0.0064
Fluorene	Flu	1.85-9.44	1.0x10^{-5}	0.001	5.41 ±0.25	0.170029	0.00541
Phenanthrene	Phe	0.13-5.21		0.001	2.39 ±0.87	0.075114	0.00239
Anthracene	Ant	2.24-12.19	ND	0.01	6.33 ±0.14	0.198943	0.0633
Fluoranthene	Flt	0.23-7.41	ND	0.001	3.13 ±0.51	0.098371	0.00313
Pyrene	Pyr	0.09-4.11	ND	0.001	1.39 ±0.09	0.043686	0.00139
Benz[a]anthracene	BaA	0.19-5.87	ND	0.1	1.1 ±0.003	0.034571	0.11
Chrysene	Chr	0.07-7.21	ND	0.01	2.11 ±0.04	0.066314	0.0211
Benzo[b]fluoranthene	BbF	0.21-5.19	ND	0.1	1.42 ±0.35	0.044629	0.142
Benzo[k]fluoranthene	BkF	0.11-6.83	ND	0.1	3.15 ±0.47	0.099	0.315
Benzo[a]pyrene	BaP	0.12-4.19	ND	1	1.91 ±0.29	0.060029	1.91
Dibenz[a,h]anthracene	DahA	0.28-5.89	ND	1	2.54 ±0.91	0.079829	2.54
Indeno[1,2,3-cd]pyrene	IcdP	0.01-2.98	ND	0.1	0.21 ±0.51	0.0066	0.021
Benzo[ghi]perylene	ghiP	0.11-6.12	ND	0.01	0.71 ±0.22	0.022314	0.0071
Mean					**3.045625**	**0.178588**	**0.6**
Min					**0.21**	**0.006286**	**0.0013**
Max					**6.4**	**0.201143**	**2.54**
Sum (TEQs)							**5.15875**

3.1. Average Daily Dose (DD)

The study detected PAHs in all 10 rainwater samples, with an average concentration ranging from 0.21 to 6.4 µg/L.

The evaluated ADD values ranged from 0.006286 to 0.201143 µg/L, with an average value of 0.178588 µg/L (Table 1). Although most PAHs detected in this study were below critical thresholds for toxicological reference doses for non-carcinogenic effects, Acenaphthene's concentration (0.201143 µg/L) exceeded the WHO guideline of 0.2 µg/L, posing potential health risks if consumed over extended periods without treatment. The low but significant concentration of the PAHs across the study area is believed to be influenced by factors such as roofing materials. The dominant roofing material within the study area is aluminium roofs thus, this is believed to be the factor responsible for the low PAH observed. This observation aligned with the findings of Mendez et al. (2011), whose study reported the impact of roofing materials in determining the quality of harvested rainwater. The study opined that materials such as metal with smooth surfaces tend to accumulate fewer contaminants than rougher surfaces like asbestos or tar-based materials, which can retain more pollutants over time. similarly, Kennedy, et al., (2022) found that roofing materials such as aluminium, which have smooth surfaces, tend to accumulate fewer contaminants than rougher surfaces like asbestos. Specifically, the study indicated that aluminium roofs had a total PAH concentration of 0.036±0.012 ppm, while asbestos roofs showed a higher concentration of 0.045±0.018 ppm due to their rough surfaces that retain more pollutants over time. Also, in Poland, Tobiszewski (2010) showed that roofing materials could act as both sources and sinks for PAHs depending on weather patterns.

3.2 Cancer Risk Assessment

Individual PAH carcinogenic potencies (B(A)Pteq)

The harmful effects of PAHs, particularly their potential to cause cancer and genetic damage, raise serious concerns about consuming water contaminated with these substances. Benzo(a)pyrene (BaP) is a key indicator of the presence of carcinogenic PAHs. In 2012, the International Agency for Research on Cancer (IARC) classified BaP as a human carcinogen. Individuals exposed to levels of BaP that exceed recommended limits face a higher risk of developing cancer.

The evaluated B(A)Pteq for carcinogenic potentials ranged from 0.0013 to 2.5, with an average value of 0.6. Benzo[k]fluoranthene, Benzo[a]pyrene, and Dibenz[a,h]anthracene display a considerable value above the 0.2 µg/L recommended B(A)Pteq. The study reveals a TEQs value of 5.1. This value raises significant concerns about public health and environmental safety and indicates the noteworthy presence of PAHs in the rainwater. The value is concerning as it surpasses the United States Environmental Protection Agency's (USEPA) negligible risk threshold of 10^{-6} for cancer risk (CR). This aligns with findings from post-typhoon studies in China, where PAH levels also indicated substantial risks, with phenanthrene (PHE) contributing to carcinogenic potentials at levels ranging from 10^{-3} to 10^{-4} (Liu, et al., 2024). This underscores a global trend where environmental contaminants in rainwater are becoming a pressing public health issue. The implications of these findings are further compounded by the presence of other harmful substances in rainwater globally. Heavy metals such as lead (Pb) and cadmium (Cd) have been identified in Nigerian rainwater with health risk indices greater than one, suggesting unsafe consumption levels (Taiwo and Ogunbode, 2025). These findings illustrate a broader pattern of contamination that affects not only rainwater quality but also poses significant risks to human health and ecosystems.

3.3 Composition of PAHs

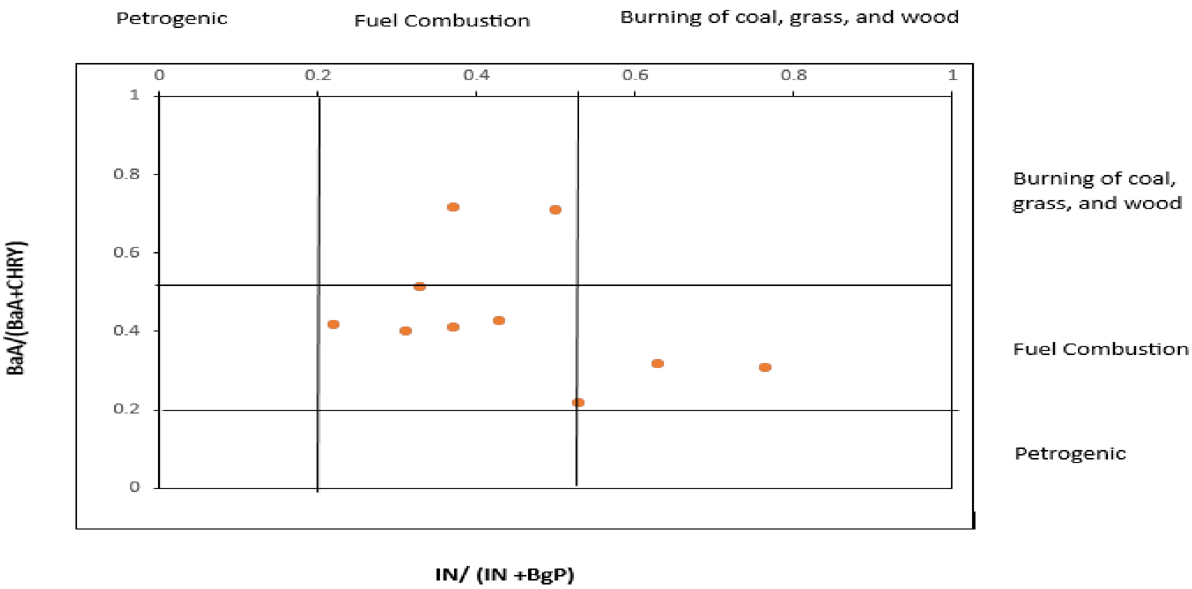

Figure 2: PAHs cross plot for ratios of BaA/(BaA + CHRY) and IN/(IN+ BgP).

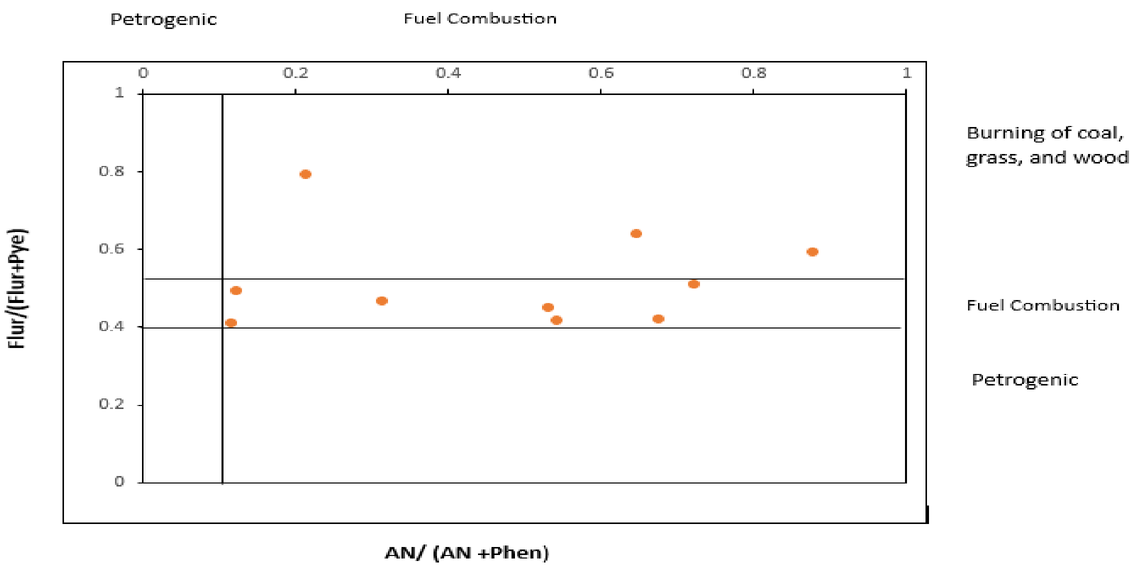

Figure 3: PAHs cross plot for ratios of Flur/(Flur + Pye) and AN/(AN+ Phen).

The identification of PAH emission sources in environmental matrices relies on diagnostic molecular ratios, particularly fluoranthene/pyrene (Flu/Pyr) and phenanthrene/anthracene (Phe/Ant). These isomer pairs are preferentially utilized in source apportionment studies due to their shared physicochemical properties, including vapor pressure, octanol-air partitioning coefficients (KOA), and thermodynamic stability under environmental conditions (Yunker et al., 2022). The similarity in their environmental behavior ensures that variations in these ratios predominantly reflect source-specific formation mechanisms rather than differential transport or degradation processes (Wang et al. 2007).

The robustness of these ratios stems from thermodynamic stability differences: anthracene (Ant) and pyrene (Pyr) are more stable than their isomers phenanthrene (Phe) and fluoranthene (Flu) under combustion conditions, leading to the enrichment of Ant and Pyr in pyrogenic emissions (Yogaswara et al., 2020). Field studies demonstrate the utility of these ratios in distinguishing mixed sources, such as vehicular emissions, biomass burning, and petroleum spills, though complex environmental interactions can create intermediate ratio values requiring multi-criteria analysis (Yogaswara et al., 2020).

Pyrogenic sources (combustion-derived PAHs) and petrogenic sources (petroleum-derived PAHs) exhibit distinct Flu/Pyr and Phe/Ant signatures: Flu/Pyr ratios > 1 indicate high-temperature combustion processes (pyrogenic), while ratios < 1 suggest petroleum contamination (Szewczyńska et al., 2017). Phe/Ant ratios < 10 and Ant/(Ant+Phe) > 0.1 are characteristic of combustion, whereas Phe/Ant > 10 and Ant/(Ant+Phe) < 0.1 denote petrogenic origins (Tobiszewski and Namieśnik, 2012).Flur/ (Flur + Pye) less than 0.2 indicates petrogenic origin, the range of 0.2 to 0.35 indicates PAHs derived from fuel combustion, and 0.35 and above it indicates PAHs derived from the burning of biomass (Adeniji et al., 2019).

The evaluated ratio of Flu/Pyr indicates a pyrogenic origin, and the ratios of Phe/Ant and Ant/(Ant+Phe) further show characteristics of combustion. Furthermore, the bivariate plot of AN/ (AN +Phen) versus Flur/(Flur+Pye) shown in (Fig 3) reveals that 60% of the samples are derived from fuel combustion and 40% indicate PAHs derived from burning biomass. The bivariate plot of BaA/(BaA + CHRY) versus IN/ (IN BgP) in (Fig 2) further shows that 70% and 30% of the samples indicate fuel combustion and burning of biomass as the sources of the PAHS, respectively.

The diagnostic ratios are complemented by molecular weight distributions. Pyrogenic sources predominantly release high molecular weight (HMW) PAHs (4–6 aromatic rings) from incomplete combustion, while petrogenic sources contain low molecular weight (LMW) PAHs (2–3 rings) from fossil fuel derivatives (Patel et al., 2020). The ∑LMW/∑HMW ratio further corroborates source identification, with values < 1 indicating pyrogenic inputs and > 1 reflecting petrogenic contamination (Yogaswara et al., 2020). In this study, the ratio of the molecular weight distributions reveals a pyrogenic source of origin.

This finding is synonymous with the observation of Szramowiat-Sala et al. (2025). The study examines the chemical makeup and sources of PAHs in Kraków, a city facing various air quality issues using chemical of PM10 and PM2.5-bound PAHs/ the study identified biomass combustion as the dominant source (60–65% contribution), with fossil fuel combustion (vehicular/industrial) accounting for 30–35%.

4. CONCLUSION

This study investigated the potential health risks, presence, composition, and sources of

PAH in rainwater collected from urban rooftops in Asaba, Delta State, Nigeria, after a four-month dry period. The findings revealed that the concentrations of PAHs in the rainwater samples were below critical thresholds for non-carcinogenic effects based on the evaluated Average Daily Dose (ADD). However, the Toxic Equivalency Quotients (TEQs) for potential cancer risk exceeded the USEPA's negligible risk threshold, signaling significant public health concerns. This highlights the need for urgent attention to mitigate the risks associated with PAH exposure through rainwater consumption. Further analysis showed that lower molecular weight PAHs accounted for 63.73% of the total PAH composition in the rainwater samples. This suggests that lighter PAHs are more prevalent in urban rainwater, possibly due to their higher volatility and ability to be transported over long distances. Molecular diagnostic ratio analysis revealed that pyrogenic processes, particularly fuel combustion from industrial and vehicular emissions, were the dominant sources of PAHs in the rainwater. These findings underscore the impact of urbanization and industrial activities on environmental contamination.

The study demonstrated the efficacy of health risk indices in probabilistic health risk assessments and molecular diagnostic ratios in identifying PAH sources. These tools are globally relevant for addressing environmental contamination challenges associated with rapid urbanization and industrialization. By applying these methodologies, this research contributes to a better understanding of how anthropogenic activities influence environmental pollution and public health.

Based on these findings, it is recommended

1. The rainwater should be adequately treated before consumption to reduce potential health risks.
2. Additionally, future research should focus on integrating these results into broader environmental management strategies aimed at mitigating PAH pollution and its associated risks. Such strategies could include stricter regulations on industrial emissions, improved urban planning to reduce pollutant accumulation, and public awareness campaigns on the safe use of rainwater.

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