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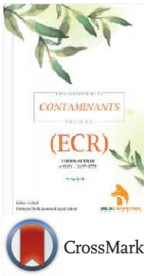

RESEARCH ARTICLE

SOURCE APPORTIONMENT OF $PM_{2.5}$-BOUND PAHS IN INDOOR MICRO-ENVIRONMENT OF URBAN SCHOOLS: A MULTIVARIATE STATISTICAL APPROACH

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ABSTRACT

Air pollution exposure in school environments poses significant health risks to children, yet source-specific contributions to $PM_{2.5}$-bound PAHs in indoor settings remain poorly characterized in Sub-Saharan Africa. This study aims to identify and quantify emission sources of $PM_{2.5}$-bound polycyclic aromatic hydrocarbons in the indoor micro-environment of urban schools using integrated multivariate statistical techniques. Sixteen priority PAHs were measured in $PM_{2.5}$ samples collected from 15 schools in four local government areas, Benin City, Nigeria. Principal component analysis (PCA) with varimax rotation and hierarchical cluster analysis (HCA) were used for source apportionment. PCA extracted three principal components, which explained 89.5–97.6% of the total variance. The source contribution of $PM_{2.5}$-bound PAHs was mainly anthropogenic, with vehicular emissions and industrial combustion accounting for 60 – 70% and 15 -25% of the total PAH, respectively. The significant seasonal variations reflect meteorological conditions and source activity patterns.

KEYWORDS

Source apportionment, PAHs, $PM_{2.5}$, Emission sources, Seasonal variation

1. INTRODUCTION

Air pollution is a growing global health regardless, which unfairly affects the urban population, and children are one of the most vulnerable groups (Archibong et al., 2025; World Health Organisation, 2023). Polycyclic aromatic hydrocarbons (PAHs) are a group of semi-volatile, carcinogenic organic substances that are mostly generated during the incomplete combustion of organic substances and fossil fuels (Cachon et al., 2023; Ravindra et al., 2008). These toxicants usually adsorb onto fine particulate matter ($PM_{2.5}$) which helps them to deep enter the respiratory system and the result is treatable with adverse health effects. Globally, developments in PM surveillance and the characterization of outdoor PAH exposures have contributed to improved knowledge concerning the issue of the urban air quality (Lovric et al., 2024; Onaiwu and Okuo, 2023).

Nonetheless, considerable gaps in the literature still exist on indoor exposures, especially in the school setting in Sub-Saharan Africa, where the data are still limited (Cachon et al., 2023; Archibong and Okuo, 2024). Children spend an average of six or more hours a day in classes, where both outdoor sources of $PM_{2.5}$ and indoor sources including building materials and human activities have a unique effect (Archibong and Michael, 2026; Zhang et al., 2020). Precise source apportionment of $PM_{2.5}$-bound PAHs in these micro environments is important to both develop interventions to reduce the exposure and inform evidence-based policies on health. The conventional source detection techniques, including the diagnostic molecular ratios, provide initial information but are not as specific and strong enough to de-mix the multiple-source indoor pollution mixtures (Lovric et al., 2024; Ravindra et al., 2008). Conversely, multivariate statistical methods, with the most notable one being principal component analysis (PCA), have become the strong weapons to simplify data and determine latent factors of emissions that portray the real world sources (Ravindra et al., 2008; Cachon et al., 2023). PAHs also have an adverse effect on children, with bound $PM_{2.5}$ being the cause of inflammation, asthma exacerbation, poor lung performance, and infection (Sram et al., 2013; Hsu et al., 2020). They also lead to cardiovascular dysfunction, neurodevelopmental losses (such as cognitive impairment and increased risk of Attention-Deficit/Hyperactivity Disorder (ADHD) and Autism Spectrum Disorder (ASD), adverse birth outcomes, and long-term cancer risk because of DNA damage (Holme et al., 2024; Sopian et al., 2021). The immature organs, increased intake rates, and lack of defences, and children are particularly vulnerable, which is why it is extremely important to reduce exposure to $PM_{2.5}$-bound PAH (Kalisa et al., 2023; Ouyang et al., 2020; Oliveira et al., 2019). Benin City, Nigeria, has limited air quality regulations and diverse emission profiles. This present study undertakes a comprehensive source apportionment of $PM_{2.5}$-bound PAHs in the indoor micro-environment of schools in four Local Government Areas of Benin City and its environs. The study, therefore, provides seasonal residual emission source characterization relevant to the pediatric population, public health institutions, and the government for policy formulation and guidelines.

2. MATERIALS AND METHODS

2.1 Study Area and Sampling Strategy

Fifteen government-owned primary and secondary schools representing urban and peri-urban settings in four LGAs (Oredo, Egor, Ikpoba-Okha, Ovia North-East) were selected using stratified random sampling (Table 1). $PM_{2.5}$ samples (n = 180) were collected in triplicate for 8-hour school periods, during dry and wet seasons with pre-calibrated APEX2IS Casella pumps (3.5 L min^{-1}) fitted with quartz-fibre filters. Field blanks (10%) and duplicates (10%) ensured quality control (Archibong and Okuo, 2024).

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The map of the study area is presented in Figure 1.

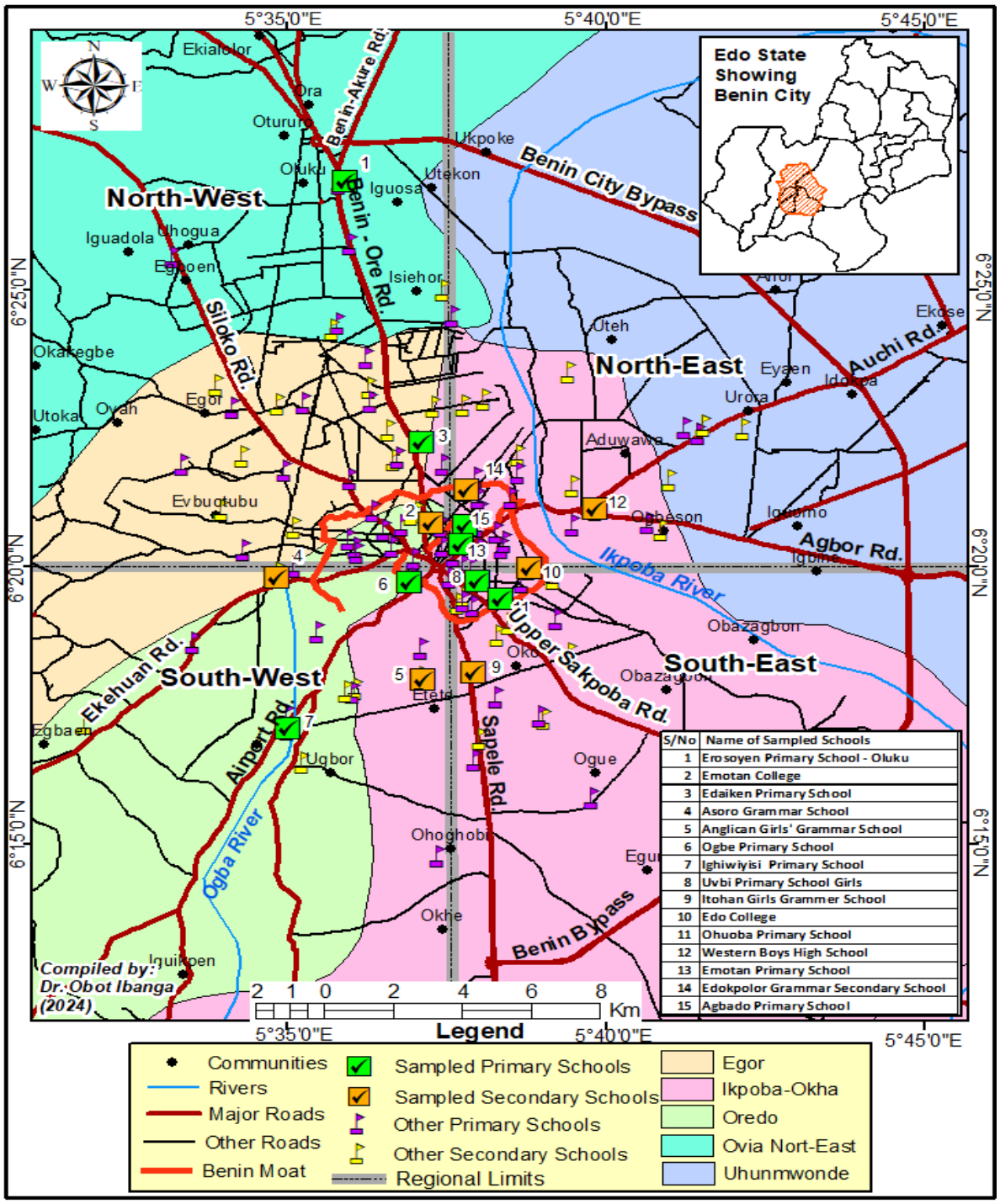

Figure 1: Map of Sampled Public Primary and Secondary Schools (Source: Fieldwork using Global Positioning Systems (GPS, 2024)

Table 1: Geographic Coordinates of Sampled Public Primary and Secondary Schools in Benin City

S/N	School Name	Address	Latitudes	Longitudes	LGA	Level	Ownership
1	Erosoyen Primary School – Oluku	Uselu - Lagos Road, Oluku	6.449202	5.598503	Ovia North East	Primary	Government
2	Emotan College	Wire Road	6.346583	5.621168	Oredo	Secondary	Government
3	Edaiken Primary School	Uselu - Lagos Road, Uselu	6.370854	5.618670	Egor	Primary	Government
4	Asoro Grammar School	Ekenhuan Road	6.330164	5.580835	Egor	Secondary	Government
5	Anglican Girls' Grammar School	Aigbekaen Aiyanyor, Upper Adesuwa Road	6.299467	5.618848	Oredo	Secondary	Government
6	Ogbe Primary School	Ogbe Road	6.328914	5.615458	Oredo	Primary	Government

Table 1 (Cont): Geographic Coordinates of Sampled Public Primary and Secondary Schools in Benin City

S/N	School Name	Address	Latitudes	Longitudes	LGA	Level	Ownership
7	Ighiwiyisi Primary School	Ogba	6.284833	5.583690	Oredo	Primary	Government
8	Uvbi Primary School Girls	First East Circular Road	6.329093	5.633304	Oredo	Primary	Government
9	Itohan Girls Grammer School	Benin-Sapele Road	6.301609	5.632233	Ikpoba-Okha	Secondary	Government
10	Edo College	Murtala Muhammed Way	6.332841	5.646868	Oredo	Secondary	Government
11	Ohuoba Primary School	Murtala Muhammed Way	6.323917	5.639372	Oredo	Primary	Government
12	Western Boys High School	Benin Agbor Road, Ikpoba Hill	6.350866	5.664001	Ikpoba-Okha	Secondary	Government
13	Emotan Primary School	Dawson Street	6.345869	5.630092	Oredo	Primary	Government
14	Edokpolor Grammar Secondary School	No 1, Federal Rd, New Benin	6.356577	5.630449	Oredo	Secondary	Government
15	Agbado Primary School	Cooker Road	6.340158	5.628843	Oredo	Primary	Government

2.2 Chemical Analysis

Filters were weighed with a precision of ±1 µg before and after sampling. Polycyclic aromatic hydrocarbons (PAHs) were extracted using ultrasonic agitation in a 1:1 mixture of acetone and dichloromethane for 30 minutes. The extracts were then concentrated and analyzed using an Agilent 6890 gas chromatographic instrument equipped with a flame ionization detector (GC-FID) and a DB-5 MS capillary column. Quantification of PAHs was performed using five-point calibration curves, all with correlation coefficients (R^2) greater than 0.995, and 16 priority PAHs were identified (Onaiwu and Okuo, 2023). The method detection limits ranged from 0.002 to 0.010 µg m^{-3}, with compound recoveries between 89% and 106%.

2.3 Statistical Analysis

Before multivariate analysis, the data were log-normalized and processed using SPSS version 25. Sampling adequacy was established as Kaiser-Meyer-Olkin (KMO) ≥ 0.70 and Bartlett test of sphericity was statistically significant ($p < 0.001$). Principal components the eigenvalues of which exceeded 1 were rotated by varimax, whereas the scree plot and parallel analysis were applied to prove the necessity of keeping the factors. Factor loadings ≥ 0.60 were deemed to be statistically significant (Kumar and Goyal, 2011). Ensuring the dendrograms, hierarchical cluster analysis (HCA) based on Ward method and squared Euclidean distance generated the dendrograms, and cophenetic correlation coefficients were used to determine the reliability of the clusters (Singh et al., 2023). The estimation of uncertainty was done through a Monte Carlo simulation of 10,000 steps.

2.4 Source Attribution

The categories of sources used in this research were determined according to the latest developments in the framework of the emission fingerprinting procedures (Lovric et al., 2024; Cachon et al., 2023). High loadings of Benzo(a)pyrene (B[a]P), Indeno(1,2,3 –cd) (InP), Benzo (g,h,i) perylene (BghiP), Benzo(a)anthracene (BaA), and Pyrene (Pyr) which are known to be indicators of gasoline and diesel engine emissions represented vehicular emissions. Benzo(b)fluoranthene (BbF), Benzo(k)fluoranthene (BkF), Anthracene (Ant), and Chrysene (Chry) were typical of industrial and other high-temperature sources of combustion.

Biomass burning signatures were associated with Ant, Phenanthrene (Phen), Fluoranthene (Flu), and Pyr, reflecting open or domestic burning activities common in urban environments.

Finally, petrogenic or volatilization sources were identified through elevated levels of Naphthylene (Nap), Acenaphthene (Acp), Acenaphthylene (Ace), as well as Flu and Flourene (Flo), which are typically linked to petroleum products and evaporative processes

3. Results and Discussion

3.1 PAH Concentrations and Seasonal Variation

Table 2 presents the average concentrations of PAHs. During the dry season, the mean ∑PAH concentration was 1.491 ± 0.098 µg m^{-3}, against 1.234 ± 0.095 µg m^{-3} in the wet season. High-molecular-weight PAHs (comprising 4–6 rings) were predominant, accounting for 73–76% of the Combustion PAHs (COMPAHs).

Carcinogenic PAHs (CANPAHs) contributed between 45.9% (wet season) and 64.1% (dry season) of the total PAH concentration. Notably, the concentration of benzo[a]pyrene exceeded the World Health Organization (WHO) guideline value of 0.001µg m^{-3} (1 ng m^{-3}) by an order of magnitude (Onaiwu and Okuo, 2023).

Table 2: Mean PAH Concentrations Grouped by Aromatic Ring count for Dry and Wet seasons.

PAHs components	Abbreviation	No. of rings	Overall Mean	
			Dry season	Wet season
Naphthylene	Nap	2	0.054±0.012	0.049±0.007
Acenaphthylene	Ace	3	0.060±0.015	0.055±0.010
Acenaphthene	Acp	3	0.052±0.019	0.051±0.015
Flourene	Flo	3	0.062±0.019	0.052±0.007

Table 2 (Cont): Mean PAH Concentrations Grouped by Aromatic Ring count for Dry and Wet seasons.				
Phenanthrene	Phen	3	0.063±0.010	0.061±0.011
Anthracene	Ant	3	0.069±0.007	0.063±0.015
Fluoranthene	Flu	4	0.061±0.011	0.060±0.009
Pyrene	Pyr	4	0.060±0.012	0.052±0.012
Benzo(a)anthracene	BaA	4	0.068±0.010	0.061±0.012
Chrysene	Chry	4	0.069±0.017	0.059±0.010
Benzo(b)fluoranthene	BbF	5	0.063±0.009	0.057±0.008
Benzo(k)fluoranthene	BkF	5	0.064±0.011	0.055±0.017
Benzo(a)pyrene	B[a]P	5	0.083±0.015	0.060±0.011
Dibenzo(a,h)anthracene	DbA	5	0.107±0.009	0.077±0.015
Indeno(1,2,3 –cd)	In.P	6	0.204±0.007	0.163±0.011
Benzo (g,h,i) perylene	BghiP	6	0.284±0.012	0.259±0.019
∑PAH (μg/m^3)			**1.491±0.098**	**1.234±0.095**
% CANPAHs of ∑PAH			64.10	45.90
%COMPAHs of ∑PAH			75.86	73.18
%BaP of CANPAHs			12.61	7.59

3.2 Source Apportionment by PCA and HCA

Principal Component Analysis (PCA) with varimax rotation identified three key factors that collectively accounted for 89.5 - 97.6% of the total variance, indicating that a limited number of sources predominantly influence indoor PAH profiles (Table 3). Factor 1, attributed to vehicular emissions, explained between 61.2 and 74.5% of the variance. It showed high loadings for compounds such as B[a]P), InP, BghiP, and BaA—all characteristic markers of gasoline and diesel engine combustion.

This was especially dominant in the wet season and it contributed a total of 69.8 % of the overall variance. This rise in season is probably because the reduced photochemical degradation of PAHs in the higher humidity and low solar radiation conditions results in the increased persistence of the combustion-generated pollutants inside the buildings. Factor 2 explained 14.8 - 26.7% of the variance and had high loadings of BbF, BkF, Ant, and Chry, which are indicative of industrial combustion and high-temperature mixed sources. This aspect was comparatively stable during both seasons, indicating that there are no significant changes in the background caused by minor industrial operations and the burning of wastes in the area. Factor 3, which describes sources of petrogenic or volatilization, had an explanation of 8.3 to 19.2%. Lighter PAHs like Nap, Ace, and Acp dominated it indicating evaporative emissions of petroleum products. Probably, the sources can be fuel storage, the use of generators, and oil-handling activities in or around the school surroundings (Singh et al., 2023). The discussion indicated that $PM_{2.5}$-bound PAHs in schools were primarily found to be caused by vehicular emissions, in the study area, particularly when it was humid. There is also seasonal variation in industrial and petrogenic sources (Cachon et al., 2023; Okuo and Onaiwu, 2022). The given observations indicate that special, season-related air quality control should be introduced to ensure schoolchildren are not exposed to threats.

Table 3: PCA Loading obtained from $PM_{2.5}$-bound PAHs Samples in the Study Area							
Dry season				**Wet season**			
Variables	**Factor 1**	**Factor 2**	**Factor 3**	**Variables**	**Factor 1**	**Factor 2**	**Factor 3**
In.P	0.893			Pyr	0.779		
BghiP	0.813			BbF	0.734		
Phen	0.762			BkF	0.725		
BaA	0.721			DbA	0.717		
B[a]P	0.702			BaA	0.702		

Table 3 (Cont): PCA Loading obtained from $PM_{2.5}$-bound PAHs Samples in the Study Area							
Nap	0.654			In.P	0.689		
BkF	0.618			BghiP	0.660		
Ace		0.769		B[a]P	0.652		
Flo		0.769		Phen		0.779	
Acp		0.683		Ant		0.718	
Ant		0.634		Flo		0.703	
Pyr		0.620		Chry		0.612	
DbA			-0.849	Nap			0.944
Flu			0.617	Acp			0.916
				Ace			0.677
Total variance (%)	61.15	16.90	11.47	Total variance (%)	69.80	16.28	9.74
Cumulative (%)	61.15	78.05	89.52	Cumulative (%)	69.80	86.08	93.82
Factor loading > 0.60							
Extraction Method: Principal Component Analysis.							
Rotation Method: Varimax with Kaiser Normalization.							

Figure 2 shows the PAH loadings on the first two major components, which are source specific, and colour coded. The biplots are able to provide visual affirmation of the source groupings and multiple critical spatial relationships across the PAH compounds between seasons. This analysis shows a clear clustering of the source-related compounds: the vehicular emission compounds like the BaP, In.P, BghiP, BaA, and Pyr consistently cluster along the major PC1 axis, whereas the industrial compounds are dispersed in the analysis as they have mixed sources (Kumar and Goyal, 2011).As the seasonal comparisons show, there is a more evident factor structure in the wet season, with a better establishment of separation between combustion-related and volatile PAHs. The dry season biplot, in contrast, shows more complicated source mixing, especially in the positioning of intermediate molecular weight PAHs which are both affected by a number of different sources of emission and due to the increased atmospheric stability of the dry season (Adegunwa et al., 2025).

Factor 1 seasonal variations also support the impact of school distance to major roads and traffic density, particularly in LGAs of Oredo and Ikpoba-Okha (Whaley et al., 2020). The cumulative variance increase by 6.30 % in the wet season suggests a better model performance, which means greater differentiation in source apportionment in the wet season (Areguamen et al., 2023). Further monitoring showed that there was an increment of vehicular $PM_{2.5}$-bound PAHs contribution during wet season (65% to 70%). This extreme variation indicates that under wet season atmospheric conditions, the persistence and transporting ability of combustion-produced PAHs is strengthened. Once again, it is true that vehicular emission can be more intense during wet seasons as there is less mixing of the atmosphere, low photolysis rate and high stability that enables these pollutants to be produced. Although the primary sources do not change with a variation in meteorology, their relative contributions change (Archibong and Okuo, 2024).

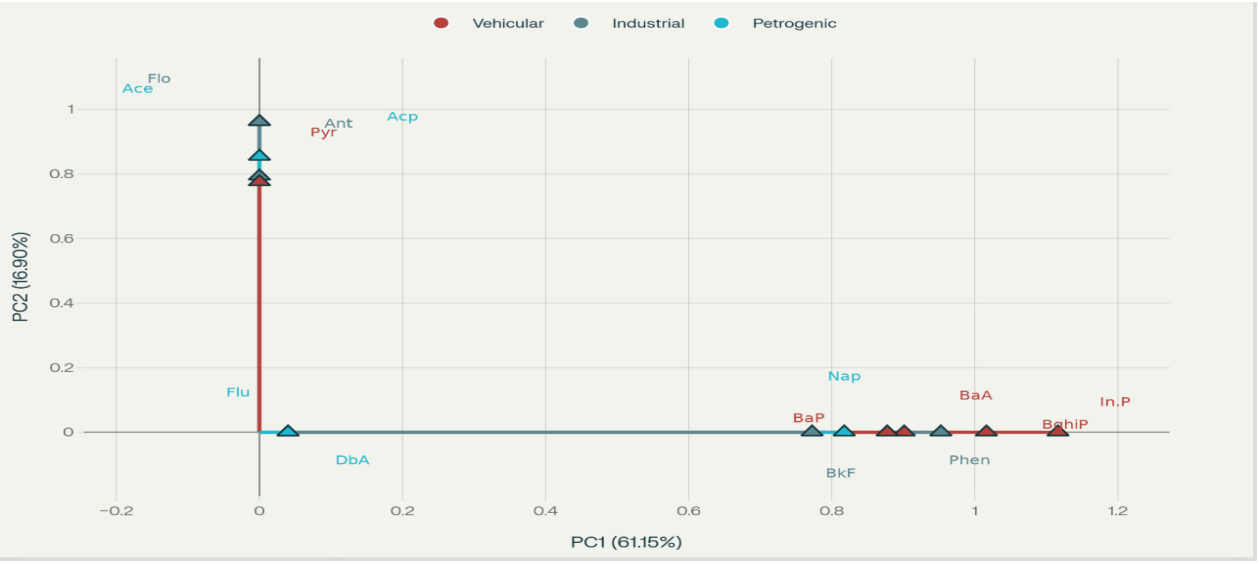

Figure 2: PCA Biplots for both Seasons

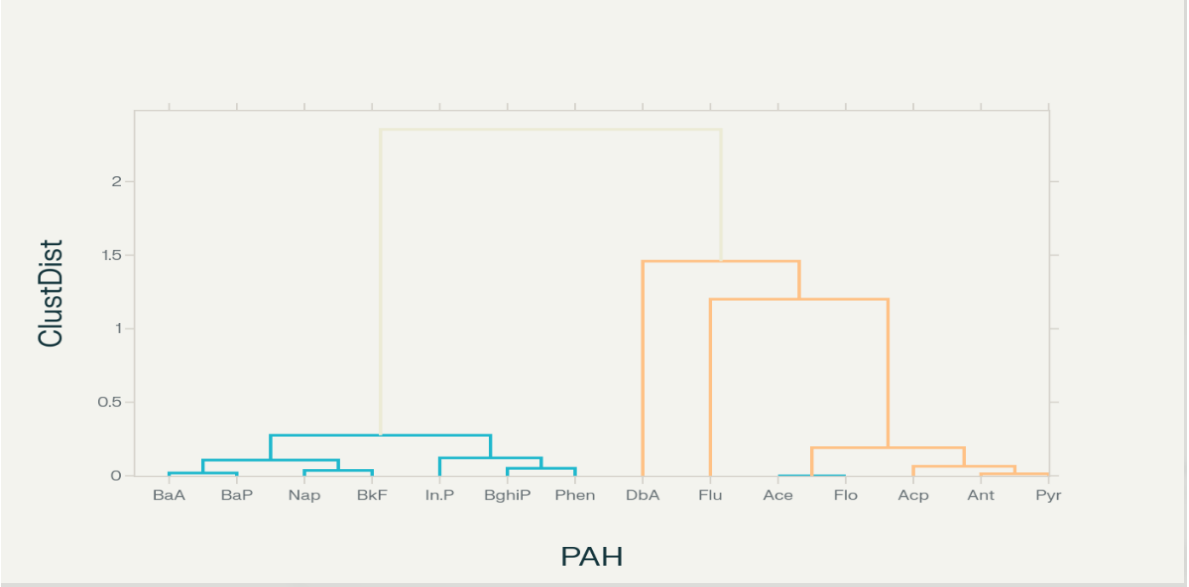

Figure 3: HCA Dendrograms for both Seasons

Figure 3 shows that Hierarchical Cluster Analysis (HCA) also came up with three main factors or clusters which include; vehiclular emissions, industrial combustion and petrogenic sources. This, also, lent added support to the identified groupings and highly supported the factor classifications with a cophenetic correlation coefficient of r = 0.92. PCA/HCA improved the strength and explanation of the source apportionment, which is consistent with the recent methodological advice in the analysis of complex urban exposure data (Ravindra et al., 2008; Lovric et al., 2024). Figure 4 shows the results of the loading strength distribution, which indicated that there were significant seasonal variations in the quality and discriminative ability of the factor structure. During the wet season, the loading was easier with 80 % of the factor loading as "High" (0.65-0.80) in comparison to 50 % during the dry season. This improvement depicts more explicit source signatures and less factor overlap when in wet-season atmospheric conditions.

Conversely, the dry season was more variable in loading strength with the higher percent of "Very High" loading (≥ 0.80) of 21.4 %, compared to 13.3 % in the wet season. Nonetheless, it is equally revealing more mixed and complex source loadings as there is a higher proportion of loadings between 0.50-0.65 (28.6) with the value of 0.65.

The total lack of Low (less than 0.50) loadings in the two seasons is evidence of the statistical significance of all of the factors extracted and provides support to the stability of the three-factor solution.

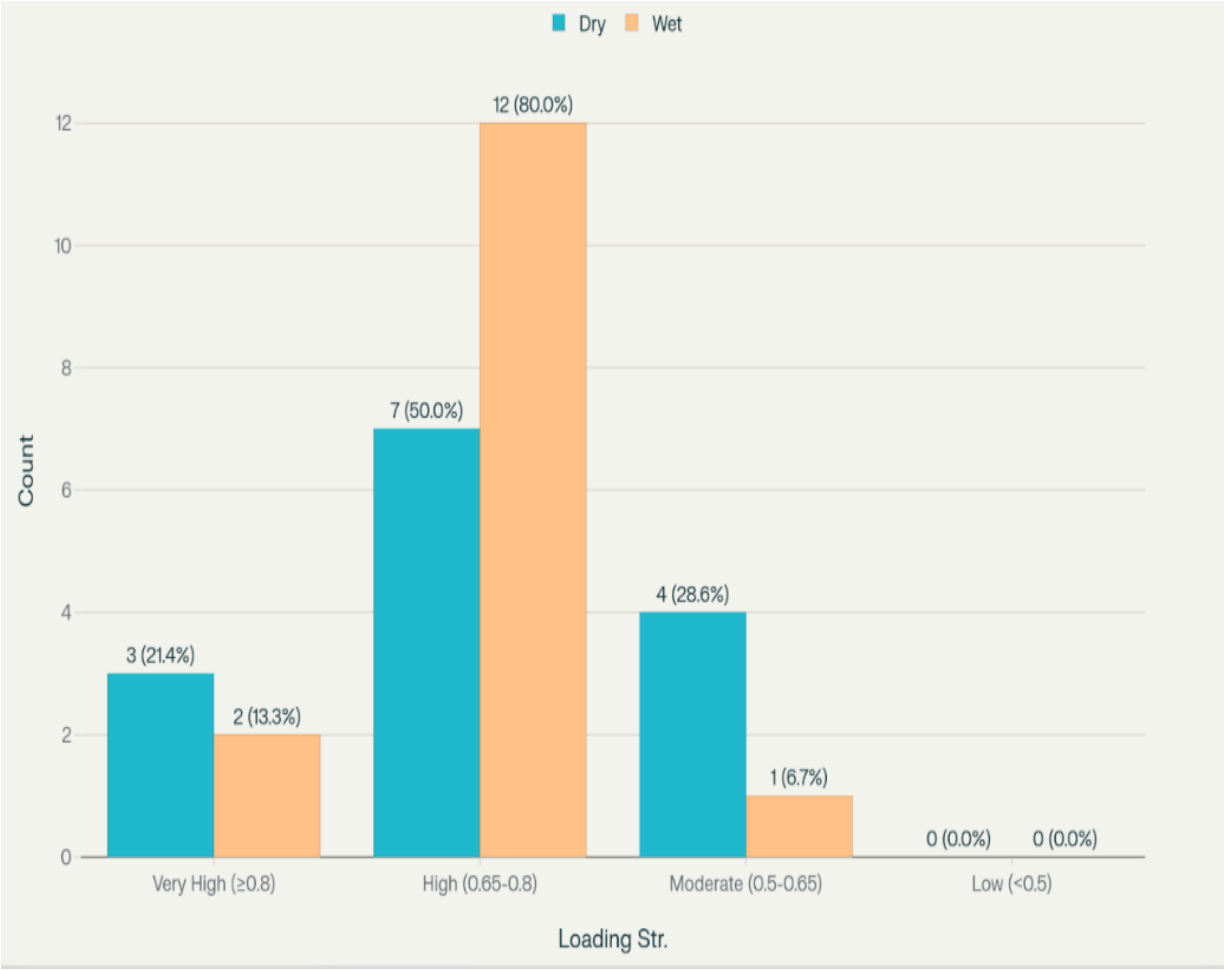

Figure 4: Distribution of PCA Loading Strength Categories by Seasons

3.3 Comparative Source Contributions and International Context

This study presents remarkably low total PAH concentrations in indoor school environments when compared globally, with values of approximately 1.491 μg/m^3 (dry season) and 1.234 μg/m^3 (wet season). The predominance of traffic-related emissions consistently emerges as a principal source across locations. This aligns with global patterns linking traffic emissions to elevated indoor pollutant loadings (Zhang et al., 2020; Parasin et al., 2023). These levels of $PM_{2.5}$-bound PAHs in the indoor air of school micro-environments in this study area were 41.1% lower than the dataset's overall mean and ranked Benin City 6th out of 7 regions among the international studies reported.

Table 3: Selected Global Benchmarks for Total PAH Concentrations (in μg/m^3)

Region	Mean indoor ∑PAH (μg/m^3)	Location/ Settings	Key pollution source(s)	References
Benin City, Nigeria	1.23 – 1.49	Urban Schools Indoor air (present study)	Vehicular emissions, biomass burning	Archibong and Okuo, 2024; Olstrip et al., 2025
Guangzhou, China	~2.50	Urban residential	Vehicular exhaust, industrial combustion	Zhang et al., 2020
Beijing, China	3.00	Urban indoor environments	Coal combustion, traffic emissions	Sun et al., 2022; Parasin et al., 2023
Sao Paulo, Brazil	1.80 – 2.20	Schools and homes	Traffic emission, residential cooking	Sram et al., 2013
Lahore, Pakistan	4.10	Urban residential indoor	traffic, biomass burning	Onaiwu and Okuo, 2023; Liu et al., 2018
New York City, USA	1.20	Urban school buildings	Traffic emission, heating systems	Holme et al., 2024; Nascimento et al., 2017
European Cities	1.00 - 3.00	Various (schools/residences)	Traffic, industrial air pollution	WHO, 2023

Despite the lower total PAH mass concentrations in indoor air of schools in Benin City, the benzo[a]pyrene levels (0.060–0.083 μg/m^3) as indicated in Table 4, notably exceed WHO health guidelines by 60 – 83 times (which recommends annual limits close to 0.001 μg/m^3). This elevated B[a]P concentration indicates a significant health risk with complex source profiles and potential toxicity (Cheepsattayakorn and Cheepsattayakorn, 2019; Olstrip et al., 2025).

Table 4: Benin City vs. International PAH Levels in Indoor School Settings

Region	B[a]P Concentration (μg/m^3)	Comparative Notes	References
Benin City, Nigeria	0.060 – 0.083	Exceeds WHO annual guideline (~0.001 μg/m^3) by 60–83 times; indicates severe carcinogenic risk despite low total PAHs.	Archibong and Okuo, 2024; Onaiwu and Okuo, 2023
Guangzhou, China	~0.020 – 0.030	Lower than Benin City; reflects industrial and traffic influence; moderate risk due to urban pollution	Zhang et al., 2020
Beijing, China	0.006 – 0.024	Lower B[a]P than Benin City despite higher total PAHs; extensive coal combustion and traffic emissions.	Sun et al., 2022; Parasin et al., 2023
Sao Paulo, Brazil	0.010 – 0.020	Somewhat comparable to Chinese cities; influenced by traffic and residential biomass burning.	Sram et al., 2013
Lahore, Pakistan	0.040 – 0.060	Close to Benin levels; reflects intense traffic and biomass burning contributing to carcinogenic PAHs	Onaiwu and Okuo, 2023; Liu et al., 2018
New York City, USA	0.005 – 0.010	Lower B[a]P; impacts mainly from traffic and heating systems	Holme et al., 2024; Nascimento et al., 2017
European Cities	0.001 – 0.010	Typically, within or below the WHO guideline, diverse sources, including industry and urban traffic.	WHO, 2023

3.4 Potential Health Impacts on Children

Exposure to $PM_{2.5}$-bound PAHs among school-aged children have been consistently associated with a broad spectrum of adverse health effects, including respiratory, carcinogenic, neurodevelopmental, cardiovascular, and immunological outcomes (Bhatnagar, 2021; Bozzola et al., 2024; Feng et al., 2025; Gale et al., 2012; Montano et al., 2025; Nwaozuzu et al., 2021; Sopian et al., 2021; Zhen et al., 2023; Annesi-Maesano et al., 2013). Respiratory outcomes are particularly pronounced, with PAH exposure linked to higher asthma prevalence, airway inflammation, and reductions in lung function parameters such as forced expiratory volume and vital capacity (Gale et al., 2012; Nwaozuzu et al., 2021). These effects are primarily attributed to oxidative stress, pro-inflammatory cytokine release, and airway hyperresponsiveness. A group researcher reported that PAH exposure significantly increases the risk of asthma exacerbation, with odds ratios rising in response to incremental increases of 0.00101–0.00110 μg/m^3 in PAH concentrations (Prapamontol et al., 2021).The elevated concentrations of combustion-derived PAHs documented in this study, particularly during the dry season (1.491 ± 0.098 μg/m^3), present substantial risks for respiratory health deterioration in schoolchildren. Also of great concern is the carcinogenicity of PAHs particularly benzo[a]pyrene. The fact that children are exposed to a disproportionately higher length of cumulative exposure, which is a physiological vulnerability, suggests that they have a higher cancer risk compared to adults (Feng et al., 2025; Sopian et al., 2021). There is also evidence of neurodevelopmental effects such as cognitive and behavioral problems. It has been linked to a lower level of cognitive ability, behavioural difficulties, and a high risk of attention deficit hyperactivity disorder and conditions within the autism spectrum induced by prenatal and early life exposures to PAHs (Feng et al., 2025; Zhen et al., 2023). Exposed children also have been shown to have cardiovascular effects (including increased blood pressure and early signs of metabolic syndrome) (Bhatnagar, 2021). Moreover, biomonitoring studies also characterize the genotoxic and epigenetic effects of PAHs, where the formation of DNA adducts and changes in the state of the epigenome are indicative of the risks to the health over the long term and an increased susceptibility to cancer (Wirnkor et al., 2019; Sopian et al., 2021; Teixeira et al., 2024; Montano et al., 2025). The long-term respiratory, cancer, neurodevelopmental, heart-related and genotoxic outcomes of $PM_{2.5}$-bind PAHs in school settings underline an immediate necessity of the preventive measures among the population. The vulnerability of children is heightened, and this is further enhanced by the duration they spend in classrooms, which increases the

general vulnerability to exposure-related injury (Zhang et al., 2023).

The high concentrations of PAH detected in this research underscore the need to develop specific actions in order to improve indoor air quality and protect the health of children. Such findings are in line with the global guidelines that urge harsher policies in the emission of emissions around schools to minimize the effects of air pollution to children.

4. Conclusion

Principal Component Analysis (PCA) coupled with Hierarchical Cluster Analysis (HCA) made it possible to effectively apportion the source of indoor $PM_{2.5}$-bound PAHs in the Nigerian school settings. The source became so widespread and industrial combustion and petrogenic volatilization also made significant contributions. The seasonal trends showed that vehicular-related PAHs were higher during the wet season suggesting that children were at high risk of health during that season.

Compared with the global hotspots, total levels of PAH were comparatively low, but the large percentage of the carcinogenic PAH is still a serious issue. This study provides an understanding of the necessity to control the traffic emission around schools more strictly and enhance the practices of fuel management. The model used, multivariate approach, offers a strong framework of indoor air quality measurement in similar urban environment in developing countries.

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