



Characterization of Indoor PM_{2.5} and Gas- and Particle-Phase Polycyclic Aromatic Hydrocarbons in Selected Households in Benin City, Nigeria

Onofuevure O.A¹, Apuyor S E^{2*}, Apuyor K.E³, Okorodudu E.O⁴, Afighor O.C⁵, Ibraheem, A.N⁶ & Edigbina, O⁷

^{1,2,4,5}Department of Industrial Chemistry, Dennis Osadebay University, Asaba, Delta State, Nigeria

^{3,7}Department of Chemistry, Dennis Osadebay University, Asaba, Delta State, Nigeria

⁶Department of Chemistry, Delta State University, Abraka, Nigeria

*Corresponding Author

DOI: <https://doi.org/10.68050/JAMS.2026.747>

Received: 09 Oct 2026; Accepted: 15 Oct 2026; Published: 19 October 2026

ABSTRACT

Fine particulate matter (PM_{2.5}) and polycyclic aromatic hydrocarbons (PAHs) can be elevated during indoor combustion, yet simultaneous measurements of particulate matter and gas- and particle-phase PAHs remain limited in Nigerian residential environments. This study characterized indoor PM_{2.5} and 17 PAHs in four selected households in Benin City, Edo State, Nigeria. Sampling was conducted in July and September 2026 across UGB1, UGB2, GRA1 and GRA2. PM_{2.5} was measured in occupied residences, while particle-bound and vapour-phase PAHs were collected using glass-fibre filters and polyurethane foam, respectively, and analysed by gas chromatography with flame-ionization detection (GC-FID). The reported sampling-period mean PM_{2.5} concentrations were 72.00 ± 14.53 , 120.60 ± 25.58 , 27.67 ± 0.58 and $40.67 \pm 23.02 \mu\text{g m}^{-3}$ for UGB1, UGB2, GRA1 and GRA2, respectively. The observed concentrations were numerically higher than the WHO 2021 24-h PM_{2.5} guideline value of $15 \mu\text{g m}^{-3}$; however, they should not be interpreted as formal 24-h guideline exceedances because the sampling protocol did not establish standardized 24-h averages. The detected ΣPAH concentrations were 26.71, 35.87, 10.56 and 30.29 ng m^{-3} for UGB1, UGB2, GRA1 and GRA2, respectively. UGB1 had a greater detected vapour-phase contribution, whereas particle-phase PAHs accounted for the larger proportion of detected ΣPAHs in UGB2, GRA1 and GRA2. Benzo(a)anthracene recorded the highest individual detected concentration, reaching 12.63 ng m^{-3} in the GRA2 particle phase. Household fuel use and generator operation provided useful contextual information for interpreting the observed PAH profiles, although the small number of independent households and absence of paired outdoor measurements limit definitive source attribution. The findings provide preliminary evidence of substantial variation in indoor PM_{2.5} and gas- and particle-phase PAH profiles among selected households in Benin City and support the need for larger paired indoor–outdoor investigations.

Keywords: indoor air pollution; PM_{2.5}; polycyclic aromatic hydrocarbons; household combustion; gasoline generators; cooking fuels; gas-particle partitioning; Benin City; Nigeria

1. INTRODUCTION

Fine particulate matter (PM_{2.5}) is one of the most significant indoor-air pollutants due to its ability to enter deep into the respiratory tract and because indoor concentration levels can be affected by both indoor activities and by infiltration from the outdoor environment. WHO guidelines for air-quality standards of 24-h PM_{2.5} exposure guidelines ($15 \mu\text{g m}^{-3}$) and annual PM_{2.5} exposure guidelines ($5 \mu\text{g m}^{-3}$) were addressed (WHO, 2021). These values are applied as general health guidelines and not as Nigerian legally enforceable indoor-air standards.



Factors affecting the residential environment include cooking, ventilation, traffic, dust, burning of garbage, and the use of petrol or diesel powered generators in Nigerian cities. Specific measurements conducted in Akure revealed significant intra-household and seasonal variations in the PM_{2.5} concentration inside the houses, where higher concentrations were observed during dry seasons and in kitchen areas (Saetae et al., 2025). In Ibadan, the indoor/outdoor difference was significant in a two-phase study of 12 households and highlighted the importance of outdoor concentrations, cooking times and the use of generators to understand residential PM_{2.5} concentrations (Shittu et al., 2025). Previously, indoor PM_{2.5} levels were also recorded in Benin City and reported to be between 27.4 and 59.6 $\mu\text{g m}^{-3}$ in wet and dry conditions with positive correlations between indoor and outdoor particulate levels (Eghomwanre et al., 2022). In a related study in Nigeria, Archibong et al. (2025) found higher level of PM_{2.5} and PM_{2.5}-bound-PAH in the classrooms of Oredo (urban) compared to the classrooms of Uhunmwonde (rural), Edo State, that indicates the importance of local emission conditions and urban setting on the interpretation of indoor air particulate and PAH measurements.

The primary sources of production of polycyclic aromatic hydrocarbons (PAHs) are incomplete combustion of organic materials and fossil fuels. Although cooking foods is not the primary contributor of PAHs to indoor air exposure, cooking fuels can indeed be a significant source of PAH exposure, and Nigerian studies have reported PAH levels in relation to cooking fuels and public eateries (Adesina et al., 2023; Adesina et al., 2022). Moreover, recent Nigerian experiments directly identified PAHs released from petrol powered generators showing that petrol powered generators can be a significant source for PAHs in areas where they are used for electricity generation (Adesina et al., 2024; Adeniran et al., 2024). Experimental studies also revealed that PAH levels in fish increased for drying with charcoal, firewood, and polythene-assisted combustion in Anambra State, further highlighting the possibility of combustion processes for introducing PAH into the environment and materials exposed to the process (Umudi et al., 2025).

PAHs in indoor air are present as both gas and particles. Their distribution is mainly influenced by molecular weight, vapour pressure, environmental conditions, aerosol characteristics and temperature. Therefore, a multi-phase measurement of particle and vapour associated PAHs is able to provide information not available from a one phase measurement. Interpretation of diagnostic PAH ratios is influenced by the phase transfer, the atmospheric reactions and degradation, and cannot be used as source apportionment data (Tobiszewski and Namieśnik, 2012; Dvorská et al., 2011).

The identification of indoor sources is difficult because several sources can be in operation at the same time and because outdoor pollutants can penetrate indoors. A recent review showed that, indoor source apportionment is influenced by the source multiplicity, physical & chemical transformation, and indoor – outdoor coupling (Saraga et al., 2023). It is particularly important in homes in Nigeria where cooking fuels and private generators can be found in conjunction with traffic and other urban sources.

The present study is thus an attempt to characterize the indoor PM_{2.5} along with both gas-phase and particle-phase PAHs in four selected households in Benin City. The specific aims were to: (i) measure the indoor PM_{2.5} reported levels in the sampling period; (ii) characterise individual PAH concentrations in both particle and vapour phase; (iii) compare the concentrations of PAHs detected in the particle and vapour phase between different households; and (iv) use qualitative source indicators such as activity details and selected diagnostic ratios, explicitly recognizing the limitations of the small number of independent households.

2. MATERIALS AND METHODS

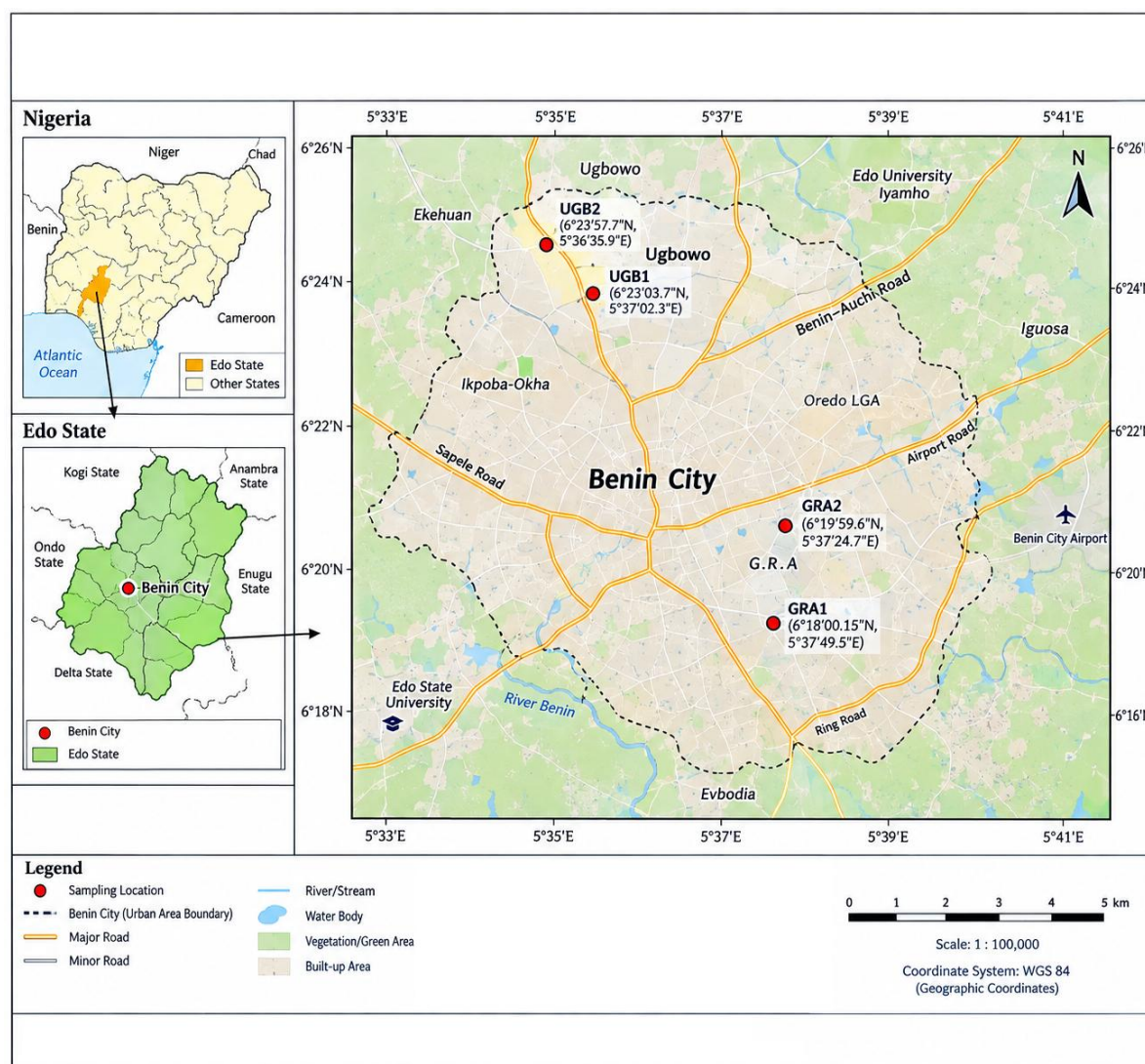
2.1 Household selection and study area

Selected residential homes in Edo State, Nigeria were sampled. Four households were designated as UGB1, UGB2, GRA1 and GRA2 with the study area coordinates reported to be between 6°18' N and 6°24' N and 5°36' E and 5°38' E respectively as shown in Table 1. The selection was based on variations between households in their fuel for cooking and their use of petrol-powered electricity generators.

Table 1: Sample location and characteristics of the four selected households

Sample Code	Sampling period	Coordinates	Elevation (m)	Household characteristics
UGB1	16–20 Jul 2026	6°23'03.7"N; 5°37'02.3" E	122	Upstairs; terrazzo; gas cooker; generator
UGB2	23–27 Jul 2026	6°23'57.7"N; 5°36'35.9" E	109	Kerosene stove; generator
GRA1	3–6 Sep 2026	6°18'00.15"N; 5°37'49.5" E	90	Kerosene stove; generator
GRA2	14–17 Sep 2026	6°19'59.6" N; 5°37'24.7" E	110	Generator operated almost throughout the night on day 3

Fig. 1. Study area and locations of the four selected households in Benin City, Edo State, Nigeria.



2.2 Indoor PM_{2.5} and PAH sampling and analysis

Indoor-air sampling was conducted in four residential homes during weekday sampling campaigns in July and September 2026. Sampling was performed for approximately 24 h per sampling day. The sampling inlets were positioned 1.5–2.0 m above floor level to approximate the human breathing zone and were placed centrally within each residence. Indoor particulate-matter and PAH measurements followed established approaches for indoor-air characterization and PAH determination (Archibong et al., 2025; Adesina et al., 2023).

2.3 PM_{2.5} Sampling and 24-Hour Average Concentration

Indoor PM_{2.5} concentrations were monitored continuously for 24 hours in each of the four selected households (UGB1, UGB2, GRA1, and GRA2) in Benin City, Nigeria, during the sampling periods in July and September 2026. Measurements were obtained using a Casella CEL-712 Microdust Pro real-time dust monitor. The instrument operates on the principle of forward light scattering, in which airborne particles scatter incident laser light and the resulting signal is used to estimate particulate mass concentration (Ukpebor et al., 2006). The instrument specifications and measurement procedures were based on the methodology described in the 2021 study by Ukpebor and colleagues. Before sampling, the instrument was checked and adjusted according to the applicable calibration procedure. A 15-second averaging interval was selected, and hourly PM_{2.5} concentrations were recorded at each sampling location during the designated sampling periods. Where applicable, a correction factor established through comparison with gravimetric measurements was used to improve the agreement between the instrument readings and reference measurements. It was operated at a nominal flow rate of approximately 2.0 L min⁻¹, in accordance with the sampling configuration used during field monitoring.

The continuous measurements recorded over each 24-hour monitoring period were used to determine the corresponding average indoor PM_{2.5} concentration for each household. Where the recorded data were available as hourly mean concentrations, the 24-hour average was calculated as:

$$C_{24h} = \frac{\sum_{i=1}^n (C_i)}{n}$$

where (C_{24h}) is the 24-hour average PM_{2.5} concentration (μg m⁻³), (C_i) is the mean concentration for hour (i), and (n) is the number of valid hourly mean measurements included in the calculation. For a complete dataset comprising 24 valid hourly means, (n=24). The resulting averages were used to characterize indoor PM_{2.5} levels in the sampled households and to support comparisons with the World Health Organization's 2021 air quality guideline for 24-hour mean PM_{2.5} concentrations of 15 μg m⁻³. These comparisons were interpreted with consideration of the limited number of households investigated.

2.4 PAH sampling

PAHs were collected simultaneously in the particulate and vapour phases. The particulate phase was retained on glass-fibre filters (GFFs), whereas the vapour phase was collected on polyurethane-foam (PUF) plugs positioned downstream of the filter, consistent with established two-phase PAH sampling methods (Adesina et al., 2023; Eghomwanre et al., 2022). The PAH sampling train was operated at an approximate flow rate of 2.0 L min⁻¹. To improve the spatial representativeness of the measurements, the sampler was repositioned within each residence during the sampling period. The sampling pump was calibrated before and after each field deployment. A sampling run was accepted when the measured flow rate remained within ±10% of the nominal flow rate. All sampling components were rinsed with dichloromethane before use. Following collection, the GFFs and PUFs were folded or compressed inward, wrapped in solvent-rinsed aluminum foil, sealed, and stored at approximately 0 °C until extraction.

The concentration of each PAH in each sampling phase was expressed in ng m⁻³ and calculated from the mass of the compound measured in the corresponding sampling medium divided by the volume of air sampled. The calculation is expressed as $C_{i,p} = m_{i,p} / V_{air}$, where $C_{i,p}$ is the concentration of PAH compound i in phase p (ng m⁻³), $m_{i,p}$ is the measured mass of that compound in the relevant filter or PUF extract (ng), and V_{air} is the sampled air volume (m³). Where applicable, the extract concentration was converted to recovered mass using the extract volume and any documented dilution or concentration factors. Sampled air volume is determined from sampling flow rate multiplied by sampling duration, with units converted to cubic metres. The reported concentrations are then recorded.

2.5 Extraction and clean-up

For PAH extraction from the quartz-fibre filters, each filter was extracted ultrasonically with a 1:1 (v/v) mixture of HPLC-grade acetone and dichloromethane (Sigma-Aldrich, USA) for 15 min. The extraction was



repeated three times, and the extracts were combined. The combined extract was passed through a 0.22- μm filter and purified using a silica-gel column (7.5 cm $\times$ 1.5 cm) containing anhydrous sodium sulfate. The PAH

fraction was eluted sequentially with 50 mL of hexane and 50 mL of dichloromethane. The eluate was concentrated to approximately 5 mL by rotary evaporation at 40 $^{\circ}\text{C}$ and then reduced to 1 mL under a gentle stream of nitrogen. The final extracts were transferred to amber 2-mL auto sampler vials and stored at 4 $^{\circ}\text{C}$ until instrumental analysis.

GFF and PUF samples were extracted separately with 10 mL of a 1:1 (v/v) dichloromethane/acetone mixture for 1 h at 28 $^{\circ}\text{C}$ using ultrasonic extraction. The extracts were concentrated under nitrogen and transferred to GC vials. The use of separate particulate- and vapour-phase sampling media, solvent extraction, clean-up, and gas-chromatographic determination is consistent with established PAH methods (Archibong et al., 2025; Adesina et al., 2023; Eghomwanre et al., 2022).

2.5 Meteorological measurements and chromatographic analysis

Temperature, relative humidity, atmospheric pressure, wind speed, and dew-point temperature were recorded onsite at 5-min intervals throughout each sampling period. These measurements were used to characterize the indoor microenvironment and evaluate its potential influence on pollutant variability (Adesina et al., 2024; Eghomwanre et al., 2022). PAHs were analysed by gas chromatography with flame-ionization detection (GC–FID) using a 30-m capillary column and helium as the carrier gas. The reported oven-temperature programme began at 70 $^{\circ}\text{C}$ and was held for 5 min, increased to 120 $^{\circ}\text{C}$ at 5 $^{\circ}\text{C min}^{-1}$, and then increased to 300 $^{\circ}\text{C}$. Detailed GC-FID operating conditions and numerical QA/QC information (including final hold time, injector and detector temperatures, injection mode, calibration range and acceptance criteria, detection limits, recovery, and use of surrogate or internal standards) were not fully documented in the available study record and should therefore be reported explicitly in the final experimental record. This limitation is acknowledged when interpreting the analytical results.

3. RESULTS

Table 2: Indoor PM_{2.5} concentrations

Household	Reported mean PM _{2.5} ($\mu\text{g m}^{-3}$)	Ratio to WHO 15 $\mu\text{g m}^{-3}$ reference
UGB1	72.00 $\pm$ 14.53	4.8
UGB2	120.60 $\pm$ 25.58	8.04
GRA1	27.67 $\pm$ 0.58	1.84
GRA2	40.67 $\pm$ 23.02	2.71

The sampling-period mean PM_{2.5} concentrations ranged from 27.67 $\pm$ 0.58 $\mu\text{g m}^{-3}$ at GRA1 to 120.60 $\pm$ 25.58 $\mu\text{g m}^{-3}$ at UGB2 as shown in Table 2. UGB2 recorded the highest mean PM_{2.5} concentration, followed by UGB1, GRA2 and GRA1. All four values were higher than the WHO 2021 24-h AQG value 15 $\mu\text{g}/\text{m}^3$.

Calculation of detected PAH sums and analytical limitations

The phase contributions were calculated as follows:

particle-phase contribution (%) = $[\Sigma\text{PAH}_{\text{particle}} / (\Sigma\text{PAH}_{\text{particle}} + \Sigma\text{PAH}_{\text{vapour}})] \times 100$; vapour-phase contribution (%) = $[\Sigma\text{PAH}_{\text{vapour}} / (\Sigma\text{PAH}_{\text{particle}} + \Sigma\text{PAH}_{\text{vapour}})] \times 100$.

In these expressions, each phase sum includes only the individual PAH concentrations reported as detected. Values reported as BDL were excluded without substitution or imputation; therefore, the calculated sums and percentages describe the detected PAH burden and may not represent the complete phase distribution.

For each household and sampling phase, the reported detected Σ PAH was calculated as the arithmetic sum of the concentrations reported for the individual PAHs detected in that phase; values reported as below detection level (BDL) were excluded rather than substituted with zero or an imputed value. The particle- and vapour-phase percentages were calculated by dividing the respective detected phase sum by the sum of the detected particle- and vapour-phase concentrations and multiplying by 100. These are therefore minimum detected sums, not reconstructed total concentrations.

Not all quality-assurance and quality-control procedures needed for full analytical validation were completed, and the original laboratory records are no longer available. The manuscript therefore cannot provide independently verifiable numerical results for method detection limits, compound-specific calibration performance, blanks, spike recoveries or analytical precision. These values have not been estimated or invented. Their absence limits independent assessment of compound identification and quantitative accuracy, so the reported PAH concentrations should be interpreted cautiously. Future studies should document field and laboratory blanks, calibration performance, detection and quantification limits, recovery data, replicate precision and confirmation of compound identities by GC-MS or another suitably selective method.

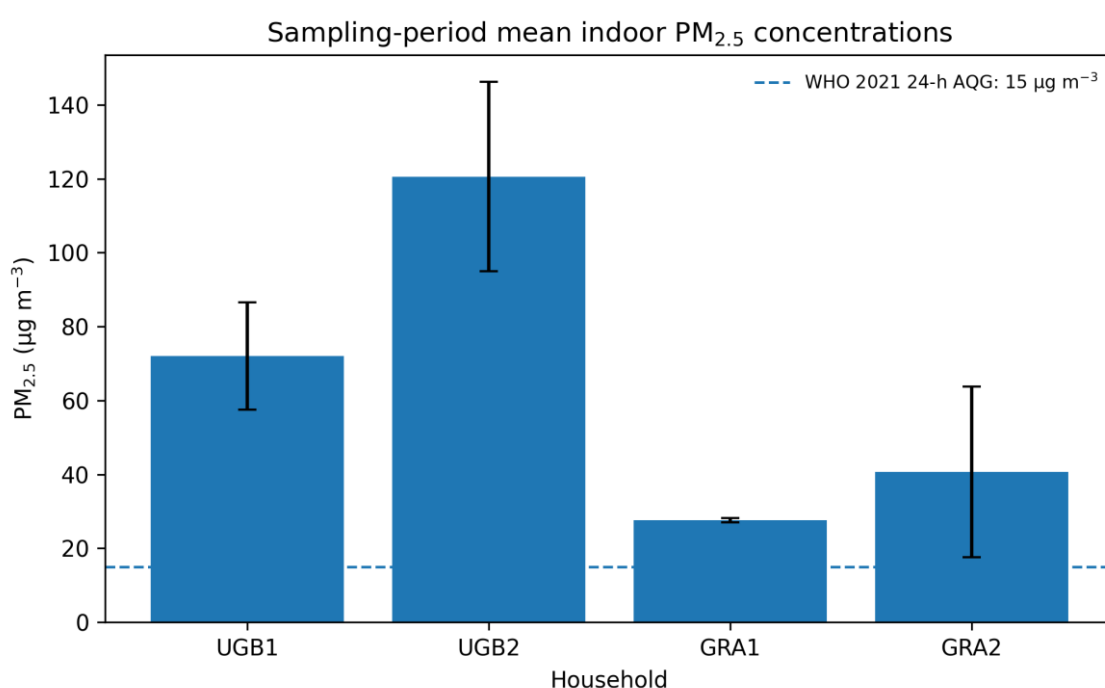


Fig. 2. sampling-period mean indoor PM_{2.5} concentrations in the four households.

Error bars in Fig 2 represent the reported standard deviations. The dashed line indicates the WHO 2021 24-h PM_{2.5} AQG of 15 µg m⁻³; it is shown for context only because the field sampling period was shorter than 24 h.

Table 3: Individual PAH concentrations in the particulate and vapour phases (ng m⁻³)

PAH compound	UGB1 GFF	UGB1 PUF	UGB2 GFF	UGB2 PUF	GRA1 GFF	GRA1 PUF	GRA2 GFF	GRA2 PUF
Naphthalene	2.43 ± 1.04	0.93 ± 0.88	0.35 ± 0.60	BLD	BLD	BLD	BLD	BLD
2-Methylnaphthalene	0.70 ± 0.31	0.46 ± 0.80	0.29 ± 0.51	BLD	BLD	BLD	BLD	BLD
Acenaphthylene*	0.70 ± 0.31	1.04 ± 1.04	2.08 ± 2.50	BLD	BLD	BLD	BLD	BLD
Acenaphthene	—	0.69 ± 1.20	BLD	BLD	BLD	BLD	1.04 ±	BLD

							0.60	
Fluorene	0.93 ± 0.09	2.31 ± 2.65	1.68 ± 2.20	BLD	BLD	BLD	BLD	BLD
Phenanthrene	0.35 ± 0.60	0.76 ± 0.70	1.62 ± 2.81	0.29 ± 0.51	BLD	BLD	BLD	BLD
Anthracene	1.33 ± 0.65	4.40 ± 6.73	1.16 ± 2.00	BLD	0.58 ± 0.40	1.04 ± 0.60	1.50 ± 0.53	1.74 ± 2.10
Fluoranthene	0.58 ± 0.72	2.08 ± 1.54	1.97 ± 1.78	2.08 ± 0.70	0.35 ± 0.60	BLD	BLD	0.12 ± 0.20
Pyrene	1.39 ± 1.59	1.39 ± 1.60	2.26 ± 3.18	0.93 ± 1.61	BLD	BLD	BLD	BLD
Benzo(a)anthracene	0.12 ± 0.20	—	0.81 ± 1.40	0.93 ± 1.61	4.05 ± 2.23	2.27 ± 2.00	12.63 ± 0.71	9.61 ± 11.42
Chrysene	1.45 ± 0.60	1.04 ± 1.04	1.16 ± 1.00	0.46 ± 0.80	0.87 ± 0.50	1.40 ± 0.89	1.50 ± 1.40	2.15 ± 2.99
Benzo(b)fluoranthene†	0.46 ± 0.80	—	BLD	BLD	BLD	BLD	BLD	BLD
Benzo(a)pyrene	BLD	0.35 ± 0.60	1.97 ± 1.71	2.33 ± 2.29	BLD	BLD	BLD	BLD
Benzo(k)fluoranthene	BLD	—	0.93 ± 1.61	3.24 ± 2.80	BLD	BLD	BLD	BLD
Indeno(1,2,3-cd)pyrene	BLD	0.24 ± 0.51	2.73 ± 1.68	2.20 ± 2.09	BLD	BLD	BLD	BLD
Dibenzo(a,h)anthracene	BLD	0.29 ± 0.51	1.74 ± 1.51	0.46 ± 0.80	BLD	BLD	BLD	BLD
Benzo(g,h,i)perylene	BLD	0.29 ± 0.51	1.27 ± 1.22	0.93 ± 0.88	BLD	BLD	BLD	BLD

BDL = below detection level.

The maximum individual PAH concentration was benzo(a)anthracene in the particle phase ($12.63 \pm 0.71 \text{ ng m}^{-3}$) as presented in Table 3, followed by the vapour-phase concentration of benzo(a)anthracene in the GRA2 ($9.61 \pm 11.42 \text{ ng m}^{-3}$). Chrysene was also found in both phases of GRA2. The comparatively wide detection of low and intermediate molecular weight PAHs was observed by UGB1, whereas several particle- and vapour-phase high molecular weight PAH were detected by UGB2.

Table 4: Detected Σ PAH concentrations and phase distribution (ng m^{-3})

Household	Σ PAH particle (ng m^{-3})	Σ PAH vapour (ng m^{-3})	Σ detected PAH (ng m^{-3})	Particle (%)	Vapour (%)
UGB1	10.44	16.27	26.71	39.1	60.9
UGB2	22.02	13.85	35.87	61.4	38.6
GRA1	5.85	4.71	10.56	55.4	44.6
GRA2	16.67	13.62	30.29	55	45

Σ PAH = Σ concentrations of detected PAHs

Based on detected values in Table 4 only, UGB2 had the largest minimum observed Σ PAH burden (35.87 ng m^{-3}), followed by GRA2 (30.29 ng m^{-3}), UGB1 (26.71 ng m^{-3}) and GRA1 (10.56 ng m^{-3}). Only one household

(UGB1) had more vapour-phase than particle-phase sum detected (60.9% vs. 39.1%). The number of particles in the particle phase accounted for about 61.4%, 55.4% and 55.0% of the detected sums in UGB2, GRA1 and GRA2, respectively.

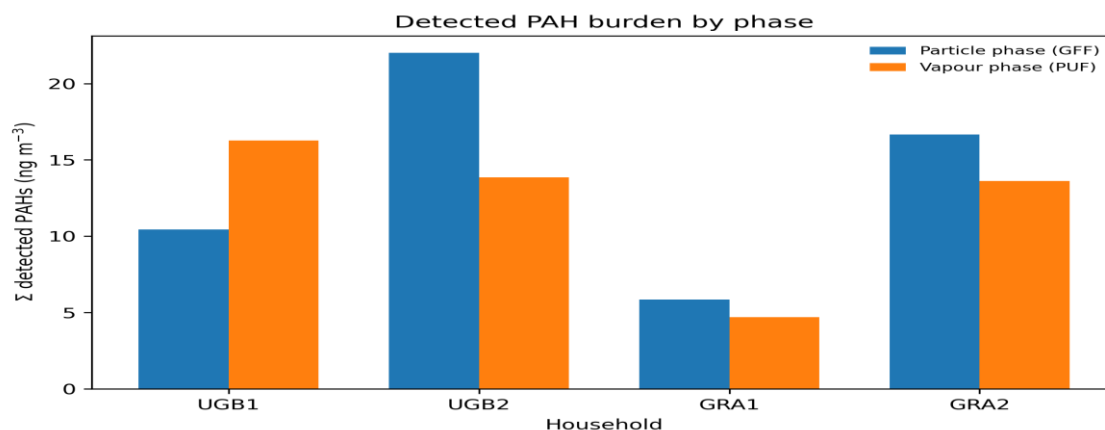


Fig. 3. Detected Σ PAH concentrations by household and phase.

BDL values are excluded; therefore, the plotted sums in Fig 3 represent minimum observed burdens rather than complete reconstructed totals.

Table 5: Detected PAH concentration by molecular ring class (ng m⁻³)

Household	2-ring	3-ring	4-ring	5-ring	6-ring
UGB1	4.52	12.51	8.05	1.34	0.29
UGB2	0.64	6.83	10.6	15.6	2.2
GRA1	0	1.62	8.94	NC	0
GRA2	0	4.28	26.01	NC	0

NA = not calculable because one or more required compounds were below the detection limit (BDL). Ratios were not assigned a numerical value when a required compound was BDL.

The four-ring compounds were significant factors in the burden of PAHs at GRA2, with benzo(a)anthracene and chrysene being the major contributors. The vapour phase contributions of the 5-ring compounds were significant in UGB2 and comparatively large in the 3-ring compounds in the vapour phase in UGB1 as shown in Table 5. The patterns are intended to reflect relative distributions, in the sense that the BDL values have been omitted, and are not inventories of ring classes.

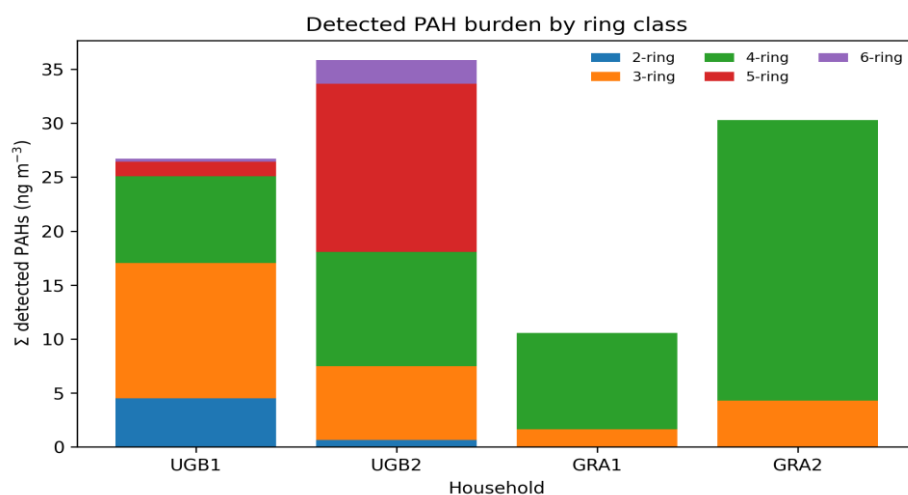


Fig. 4. Detected PAH burden by molecular ring class and household. BDL observations are excluded.



Table 6: Diagnostic PAH ratios

Household	BaA/BaP	BaA/(BaA+Chr)	Flt/(Flt+Pyr)	BaP/(BaP+Chr)	Pyr/BaP
UGB1	0.34	0.33	0.49	0.12	7.94
UGB2	0.4	0.6	0.29	0.78	0.7
GRA1	NA	0.74	NA	NA	NA
GRA2	NA	0.86	NA	NA	NA

The Flt/(Flt+Pyr) values of 0.49 and 0.29 in UGB1 and UGB2 provide only qualitative combustion information as revealed in Table 6. Diagnostic ratios can be altered by phase transfer and environmental degradation, so source attribution requires multiple lines of evidence (Tobiszewski and Namieśnik, 2012; Dvorská et al., 2011).

3.1 Individual PAH profiles and household differences

The observed PAH profiles varied among the four selected households. UGB1 showed a comparatively broad distribution of low- and intermediate-molecular-weight PAHs, whereas UGB2 showed greater detection of several higher-molecular-weight compounds. GRA2 was characterized by relatively high detected concentrations of benzo(a)anthracene and chrysene, particularly in the particle phase. These differences indicate variation in the composition of indoor PAHs among the sampled households. However, because only four independent households were investigated, the observed differences are interpreted descriptively rather than as statistically established household effects. The available measurements and household activity information provide useful source context but are insufficient to quantitatively apportion PAHs among cooking, generator emissions, and outdoor infiltration.

3.2 Correlation between meteorological parameters, PM_{2.5} and total PAH

Table 7 presents the correlation matrix for temperature, relative humidity, PM_{2.5} and total PAH in the particulate and vapour phases. The observed relationships are exploratory and should be interpreted with caution because the number of independent paired observations used for the correlation analysis is not explicitly documented in the available study record.

Correlation analysis showed no statistically significant associations between total particulate- or vapour-phase PAHs and temperature, relative humidity or PM_{2.5} (all $P > 0.05$). For particulate-phase PAHs, temperature showed a moderate positive correlation ($r = 0.560$, $P = 0.058$), whereas humidity showed virtually no correlation ($r = -0.001$, $P = 0.979$) and PM_{2.5} showed a negligible positive correlation ($r = 0.079$, $P = 0.807$). For vapour-phase PAHs, weak positive correlations were observed with temperature ($r = 0.165$, $P = 0.608$) and humidity ($r = 0.390$, $P = 0.210$), while PM_{2.5} showed a weak negative correlation ($r = -0.242$, $P = 0.448$).

Table 7: Correlation matrix between meteorological parameters, PM_{2.5} and total PAH

Total PAH (Particulate)		r	P
	Temp	0.56	0.058
	Humidity	-0.001	0.979
	P.M _{2.5}	0.079	0.807
Total PAH (Vapour)		r	P
	Temp	0.165	0.608
	Humidity	0.39	0.21
	P.M _{2.5}	-0.242	0.448



3.3 Comparison with recent Nigerian evidence

The current levels are within the general range of PM_{2.5} levels reported in the interior environments of Nigeria, but should not be compared without taking into account the averaging time and instrumentation. Continuous monitoring of the homes in the Akure study showed the mean concentrations of about 55 $\mu\text{g m}^{-3}$ in the kitchens and 48 $\mu\text{g m}^{-3}$ in the living rooms during the dry season with lower concentrations during the wet season (Saetae et al., 2025). The first phase of the Ibadan study found that daily median indoor air levels of 12 – 18 $\mu\text{g m}^{-3}$ were observed from 12 households, however, higher concentrations were observed during the Harmattan period of the longer monitoring period (Shittu et al., 2025). These studies show the significance of the length of the monitoring period, season and outdoor background. The current Benin City measurements should thus be considered as an exposure estimate in a short period of time for the house rather than for the whole city.

The environmental and public-health relevance of the measurements is considered cautiously in relation to the sampling duration and study scope.

The measurements show that attention should still be paid to fuel combustion in the home environment. The reported concentrations are found to be numerically higher than the WHO 2021 guideline of 15 $\mu\text{g m}^{-3}$ which is a health-based 24 h guideline. However, the sampling period used is too short to allow for formal calculation of 24-h guideline exceedance. The findings, however, validate the importance of better household ventilation, reducing exposure to generator exhaust, and increased adoption of cleaner cooking and electricity sources when available. Furthermore, recent studies in Nigeria have shown high levels of PM_{2.5} exposure both indoors and in the ambient air, thus confirming the importance of local monitoring (Eghomwanre et al., 2022; Shittu et al., 2025; Omokungbe et al., 2026).

4. DISCUSSION

4.1 PM_{2.5} levels in the context of Nigerian indoor-air measurements

The reported PM_{2.5} concentrations demonstrate substantial variability among the four selected households. The highest value occurred at UGB2, where the household was reported to use a kerosene stove and a generator. UGB1 also showed a high concentration and used a gas cooker and generator. These observations are consistent with the broader Nigerian literature showing that residential PM_{2.5} can vary strongly with household activities, fuel use, ventilation and outdoor conditions. Saetae et al. (2025) reported pronounced kitchen and seasonal differences in six Akure households, while Shittu et al. (2025) found that both indoor activity and outdoor concentrations contributed to residential PM_{2.5} variability in Ibadan. A Benin City study based on 45 locations also reported indoor PM_{2.5} concentrations of 27.4–59.6 $\mu\text{g m}^{-3}$ and positive indoor–outdoor correlations (Eghomwanre et al., 2022).

4.2 PAH profiles and household combustion context

The PAH profiles demonstrate that indoor pollution was chemically heterogeneous. GRA2 had the most prominent detected high-molecular-weight burden, especially benzo(a)anthracene and chrysene, while UGB1 displayed a broader mixture of lower- and intermediate-molecular-weight compounds. The coexistence of cooking appliances and generators provides plausible source context, but it does not establish source identity. Nigerian experimental evidence shows that cooking fuels can emit multiple PAHs (Adesina et al., 2023) and that generator exhaust can contain substantial PAH concentrations (Adesina et al., 2024). The present observations are therefore consistent with potential contributions from combustion activities, but direct source measurements were not made.

4.3 Gas–particle partitioning

The phase distribution varied among households. UGB1 had the largest detected vapour-phase contribution, whereas UGB2, GRA1 and GRA2 had larger particle-phase contributions. Such differences are chemically



plausible because lower-molecular-weight PAHs generally have greater volatility, while higher-molecular-weight PAHs preferentially associate with particles. However, the observed phase distribution is also influenced by temperature, aerosol characteristics, sampling duration and the efficiency of the GFF/PUF collection system. Consequently, the phase fractions should be interpreted as observed sampling-phase distributions rather than equilibrium partition coefficients.

4.4 Interpretation of source indicators

The diagnostic PAH ratios provide only qualitative information about possible combustion characteristics and should not be interpreted as definitive source signatures. The interpretation is further constrained by the small number of independent households and the presence of several potential indoor and outdoor sources. Household fuel-use information provides useful contextual evidence, but the present dataset cannot quantitatively distinguish contributions from cooking activities, generator emissions, traffic-related infiltration, and other sources. More robust source characterization would require a larger number of independent households, simultaneous indoor–outdoor measurements, detailed time-resolved activity records, information on generator operation and fuel type, ventilation characteristics, and direct measurements of relevant source emissions.

4.5 Comparison with recent Nigerian evidence

The present concentrations sit within the broad range of PM_{2.5} values reported in Nigerian indoor environments but should not be compared without considering averaging time and instrumentation. The Akure study monitored households continuously and reported mean concentrations of approximately 55 µg m⁻³ in kitchens and 48 µg m⁻³ in living rooms during the dry season, with lower wet-season values (Saetae et al., 2025). The Ibadan study reported daily median indoor concentrations of 12–18 µg m⁻³ across 12 households during its first phase but much higher values during the Harmattan period in the longer monitoring campaign (Shittu et al., 2025). These studies illustrate the importance of monitoring duration, season and outdoor background. The current Benin City measurements should therefore be regarded as a short-duration household characterization rather than a citywide exposure estimate.

4.6 Environmental and public-health relevance

The measurements demonstrate that combustion-related indoor pollution warrants continued monitoring. The WHO 2021 value of 15 µg m⁻³ is a 24-h health-based PM_{2.5} guideline, whereas the present measurements represent sampling-period concentrations rather than standardized 24-h averages. The results therefore provide preliminary evidence for further investigation of household combustion, ventilation and indoor–outdoor pollutant exchange, rather than a citywide exposure estimate.

4.7 Strengths and limitations

The principal strength of the study is the simultaneous characterization of PM_{2.5} and PAHs in both particle and vapour phases in occupied Nigerian households. The use of household-level fuel information also provides useful contextual information. The principal limitations are the small number of independent households, the absence of simultaneous outdoor measurements, the lack of detailed ventilation and activity data, the short daily PM_{2.5} sampling period, incomplete numerical QA/QC reporting, and limited specificity of GC-FID relative to GC-MS. Several diagnostic ratios are also affected by BDL observations. These limitations restrict generalization and definitive source attribution.

The study should not be interpreted as representative of all households in Benin City. Future work should include a larger stratified household sample, paired indoor/outdoor monitoring, continuous PM_{2.5} measurements, carbon monoxide and other combustion tracers, detailed ventilation and activity records, and GC-MS confirmation of PAH identities. Repeated monitoring across fuel-use conditions would permit more robust statistical modelling and source apportionment.



5. CONCLUSIONS

In this study, PM_{2.5} and gas- and particle-phase PAH were characterized in four selected households in Benin City, Nigeria. The recorded mean PM_{2.5} levels were between 27.67 and 120.60 $\mu\text{g m}^{-3}$ and the detected ΣPAH concentrations were between 10.56 and 35.87 ng m^{-3} . The highest concentration of benzo(a)anthracene in the GRA2 particle phase was 12.63 ng m^{-3} . The phase distribution of PAH varied for individual households, with UGB1 having a higher detected vapour-phase burden, and the other three households having a higher detected particle-phase burden. The information obtained from household fuel and generators is useful for assigning plausible combustion source context but is not sufficient for definitive source apportionment. Thus, the diagnostic ratios are considered qualitative indicators rather than definitive evidence of specific emission sources. The results provide a helpful preliminary chemical baseline, and can be incorporated into larger paired indoor–outdoor studies that include PM_{2.5}, PAHs, activity patterns, ventilation and source measurements

DECLARATIONS

Funding

This research received no external funding.

Declaration of competing interest

The authors confirmed that there is no competing interest

REFERENCES

1. Adesina, O. A., Ojesola, F. F., Olowolafe, T. I., & Igbafe, A. (2022). Assessment of polycyclic aromatic hydrocarbons in indoor air of local public eatery in Ado-Ekiti, Western Nigeria. *Scientific African*, 16, e01191. <https://doi.org/10.1016/j.sciaf.2022.e01191>
2. Adeniran, J. A., Jimoh, B. F., Atanda, A. S., Adewoye, L. T., Yusuf, M. N. O., Abdulraheem, K. A., Adesina, O. A. (2024). Health Risk Assessment of Polycyclic Aromatic Hydrocarbons from Cooking Fuels burning in Nigeria. *Polycyclic Aromatic Compounds*, 44(3), 1593–1608. <https://doi.org/10.1080/10406638.2023.2201459>
3. Adesina, O.A., Kolawole, O.M., Lala, M.A., et al. (2024). Characterization and risk assessment of polycyclic aromatic hydrocarbons from the emission of different power generator. *Heliyon*, 10(11), e31687. <https://doi.org/10.1016/j.heliyon.2024.e31687>
4. Archibong, U.D., Okuo, J.M., & Agho, T. (2025). Characterization and modeling of indoor PM_{2.5}-bound benzo[a]pyrene concentration in public schools: A comparative study of Oredo and Uhumwonde Local Government Areas (L.G.As), Edo State, Nigeria. *Pakistan Journal of Analytical & Environmental Chemistry*, 26(2), 240–256. <https://doi.org/10.21743/pjaec/2025.12.06>
5. Eghomwanre, A.F., Oguntoke, O., & Taiwo, A.M. (2022). Levels of indoor particulate matter and association with asthma in children in Benin City, Nigeria. *Environmental Monitoring and Assessment*, 194, 467. <https://doi.org/10.1007/s10661-022-10135-3>
6. Dvorska, A., Lammel, G., & Klanova, J. (2011). Use of diagnostic ratios for studying source apportionment and reactivity of ambient polycyclic aromatic hydrocarbons over Central Europe. *Atmospheric Environment*, 45(2), 420–427. <https://doi.org/10.1016/j.atmosenv.2010.09.063>
7. Ololade, I.A., Akindumila, O.I., Oloyede, O.J., Oloye, F.F., Asanga, O.P., Ale, T., Ololade, O.O., Joshua, M.O., & Oladoja, N.A. (2026). Cobweb as a bioindicator of polycyclic aromatic hydrocarbons in household cooking energy sources: Health risk assessment. *Environmental Pollution*, 394, 127758. <https://doi.org/10.1016/j.envpol.2026.127758>
8. Omokungbe, O.R., Olufemi, A.P., Ediagbonya, T.F., Olusola, R.A., & Ovie, O. (2026). Seasonal variability and human health risk assessment of airborne particulate matter in Ibadan Metropolis, Nigeria. *Environmental Sciences Europe*, 38, 115. <https://doi.org/10.1186/s12302-026-01400-0>



9. Saetae, S., Abulude, F.O., Arasaki, K., Ndamitso, M.M., Akinnusotu, A., Oluwagbayide, S.D., Matsumi, Y., Kawamoto, K., & Nakayama, T. (2025). Seasonal and diurnal variations of indoor PM_{2.5} in six households in Akure, Nigeria. *Atmosphere*, 16(5), 603. <https://doi.org/10.3390/atmos16050603>
10. Saraga, D.E., Querol, X., Duarte, R.M.B., Aquilina, N.J., Canha, N., Gómez Alvarez, E., Jovasevic-Stojanovic, M., Bekö, G., Byčenkienė, S., Kovacevic, R., Plauškaitė, K., & Carslaw, N. (2023). Source apportionment for indoor air pollution: Current challenges and future directions. *Science of the Total Environment*, 900, 165744. <https://doi.org/10.1016/j.scitotenv.2023.165744>
11. Shittu, A.I., Pope, R.J., Pringle, K.J., Arnold, S.R., Graham, A.M., Sideeq, H.O., Ana, G.R.E.E., & McQuaid, J.B. (2025). Quantifying residential particulate pollution and human exposure in Ibadan, Nigeria, using low-cost sensors. *Aerosol and Air Quality Research*, 25, 44. <https://doi.org/10.1007/s44408-025-00050-w>
12. Tobiszewski, M., & Namieśnik, J. (2012). PAH diagnostic ratios for the identification of pollution emission sources. *Environmental Pollution*, 162, 110–119. <https://doi.org/10.1016/j.envpol.2011.10.025>
13. Ukpebor, E. E., Ukpebor, J. E., Oviasogie, P. O., Odiase, J. I., & Egbeme, M. A. (2006). Field comparison of two total suspended particulates (TSP) samplers to assess spatial variation. *International Journal of Environmental Studies*, 63(5), 567–577.
14. Ukpebor, J. E., Omagamre, W. E., Abayode, B., Unuigbo, C. A., Dibia, E. N., & Ukpebor, E. E. (2021). Baseline concentrations of fine and coarse particulate matter in a tropical city with introduced traffic control measures. *International Journal of Environmental Pollution and Environmental Modelling*, 4(1), 28–48.
15. Umudi, E.Q., Apuyor, S.E., Clark, P.D., Eresanya, O.I., Onadje, F.O., Chikwe, I.S., Onwugbuta, G.C., Oyagbarha, E., Anyanwu, G.C., & Obruche, E.K. (2025). Assessment of the polycyclic aromatic hydrocarbons (PAHs) concentration in different fish drying methods. *Journal of Basics and Applied Sciences Research*, 3(6), 47–56. <https://doi.org/10.4314/jobasr.v3i6.6s>
16. World Health Organization. (2021). WHO global air quality guidelines: Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization. <https://www.who.int/publications/i/item/9789240034228>