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Polycyclic Aromatic Hydrocarbons (PAHS) in Urban Air Pollution. Environmental Persistence, Atmospheric Transport and Carcinogenic Risk in Uvwie Local Government Area, Delta State, Nigeria

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ABSTRACT

PAHs are long-lasting and dangerous atmospheric pollutants that form during incomplete combustion, and their increasing occurrence in urban environments has become a significant environmental and public health issue in rapidly urbanising areas. This research was carried out to assess the frequency, environmental stability, atmospheric transportation pattern and carcinogenic hazard of airborne PAHs in Uvwie Local Government Area, Delta State, Nigeria. The adopted design was a longitudinal field-based design, which included ambient air measurements at 86 georeferenced sampling

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points during a 9-month time span, followed by solvent extraction, GC-MS identification of 16 priority PAHs, molecular distribution analysis, diagnostic ratio analysis, multivariate analysis, classification of hotspots, and estimation of the risk of inhalation cancer using benzo[a]pyrene The findings indicated that the major congeners were fluoranthene (13.68 ng/m^3), pyrene (12.91 ng/m^3), and phenanthrene (11.54 ng/m^3), and the total mean 16 PAHs was 111.59 ± 20.14 ng/m^3. The high-molecular-weight PAHs prevailed across all land-use classes, indicating strong persistence and combustion effects. The greatest pollutant load was observed in high-traffic corridors, and because of dry-season conditions, Σ16 PAHs was at 130.56 ± 15.23 ng/m^3 in high-traffic areas as compared to 93.14 ± 12.47 ng/m^3 during the wet season. Benzo[a]pyrene was the main contributor of 50.73% of total BaPeq and the total ILCR was 1.03 × 10^{-5}, with children and roadside occupational groups at a higher relative risk. The paper finds that Uvwie is an urban exposure (combustion) environment with significant carcinogenic meaningfulness of persistent airborne PAHs indicative of need of air-quality intervention.

***Keywords*:** Polycyclic aromatic hydrocarbons (PAHs), Urban air pollution, Environmental persistence, Atmospheric transport, Carcinogenic risk, Uvwie, Nigeria

1. INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) represent one of the largest groups of dangerous organic pollutants of at least urban atmospheric settings since they are chemically inert, environmentally recalcitrant, and are most often directly linked to the incomplete combustion processes. They do not absorb numerous human activities, such as vehicular emissions, petroleum burning, industrial activities, electricity generators, and open burning of waste, all of which are typical characteristics of rapidly urbanising cities. Previous atmospheric research has shown that PAHs are widespread in urban air and highly variable in space and time, depending on emission intensity, land-use patterns, combustion intensity, and weather conditions [1-4]. They have remained significant in environmental studies due to the growing number of urban inhabitants exposed to complex combinations of air contaminants with long-term toxicological impacts. A strong association between the environmental relevance of PAHs and their physicochemical behaviour in the air is present.

The low-molecular-weight PAHs are more volatile and usually occur in the gaseous form, and the high-molecular-weight PAHs tend to sorb to suspended particles, especially fine particulates, which are capable of staying long in the air and penetrating to deep areas of the human respiratory system. This type of gas-particle partitioning affects their persistence, movement, deposition and potential exposure to humans. Atmospheric fate studies have indicated that PAHs may be redistributed across urban environments due to wind-based transport, dry and wet deposition, resuspension and changes in temperature and humidity across seasons [5-8]. Studies in Seoul, Hong Kong, and other urban settings have also shown that the local load of PAH does not only depend on the immediate sources, but also on the air movement in the surrounding region and the transportation processes on a long-distance scale that can increase the contamination levels in the highly populated areas [4, 9, 10].

Research on the sources of PAHs in ambient air continues to focus on urban sources. Traffic emissions have also been cited as a leading source, particularly in cities with old vehicles, low-quality fuel, traffic jams, and heavy reliance on fossil-fuel-powered transportation. Diesel combustion, industrial energy use, activities related to crude oil, and open burning are other significant contributors.

These combinations of sources tend to increase the concentration of particle-bound PAHs in the air, and urban air sheds are more contaminated in industrial and petrochemical settings [11-14]. In the African environment, the issue is exacerbated by a poor pollution control system, increased urbanisation, excessive reliance on generators, and poor waste management. African research has provided systematic evidence that PAHs are widely distributed across environmental media throughout the continent, but lacks detail on urban air measurements and localised human risk measurements [15, 16]. The perception of air quality and exposure to airborne contaminants in Nigeria is also a topic of research, indicating that many communities live in a state of high atmospheric stress, with no monitoring coverage or long-term interpretation of the implications of such stress for the health of the population [17, 18].

The significance of airborne PAHs to public health lies in the fact that some congeners are mutagenic and carcinogenic, and inhalation is one of the most important routes of exposure in urban populations. The high-ring PAHs, especially those linked to fine particulate matter, are of particular interest because they can be retained in the lungs and cause chronic toxicological effects. It has been demonstrated that risk assessment studies in other cities indicate that airborne PAHs exposure could cause quantifiable carcinogenic burdens, particularly when concentrations of benzo[a]pyrene equivalent and inhalation-based lifetime cancer risks are taken into account [19-21]. The same results in industrial environments prove that populated and emission-heavy cities can have levels of risk that does not presuppose the lack of environmental monitoring and intervention policy [13, 14]. In Nigeria, the emerging literature on toxic hydrocarbon emissions and environmental hazard evaluation also justifies the necessity of integrated pollution research that would help relate atmospheric contamination to exposure science and human health consequences [22, 23].

Though the international literature is growing, there are still major gaps in the understanding of PAHs in most urban centres of sub-Saharan Africa, especially at the local government level, where land use, traffic structure, industrial impact, and fuel-use behaviour can result in characteristic atmospheric signatures. Most of the available evidence has been either local, review-based, or focused on non-African urban settings and thus cannot be directly applied to the fast-urbanising settings in Nigeria.

This discrepancy is particularly critical in Delta State, where urbanisation, reliance on generators, transport, and hydrocarbon-related environmental stressors converge to create an environment that perpetuates PAH emissions.

The associated Nigerian scholarship on hydrocarbon pollution, environmental risks, and occupational hazards has already demonstrated that supporting meaningful mitigation in pollution-prone environments requires more site-specific and multidisciplinary assessment [24-27]. The Uvwie Local Government Area is thus a suitable location for this investigation due to its urban nature, high movement density, residential-commercial land use, and probable exposure to several combustion-related sources. It is against this backdrop that this research paper focuses on polycyclic aromatic hydrocarbons in urban air pollution in the Uvwie Local Government Area, Delta State, Nigeria, with a focus on environmental persistence, atmospheric transport, and carcinogenic risks to populations through exposure.

The research is based on the necessity of producing location-specific data on the prevalence and distribution of airborne PAHs, assessing their persistence with the help of molecular properties, determining the possible transport patterns throughout the area of study, and estimating the risk of cancer in case of inhalation exposure. The importance of the study is that it provides empirical data to the management of urban air quality, enhances the knowledge in environmental health within a Nigerian environment, and supports potential evidence that could aid in the control of pollution, risk communication, and policy action among the fast-growing urban settlements [1, 8, 15, 16].

2. MATERIALS AND METHODS

2. 1. Study Area

This research was carried out in the Uvwie Local Government Area of the Warri metropolitan region of Delta State, Nigeria, a densely populated residential area with a road network, commercial activities, generator-driven energy consumption, open burning of waste, and close proximity to urban petroleum impacts. These environmental features render the region suitable for studying airborne polycyclic aromatic hydrocarbons (PAHs), which are usually attributed to incomplete combustion of traffic, fossil fuel consumption, industrial emissions, and mixed urban sources.

The region of study is in a humid tropical climate zone with pronounced wet and dry seasons, and this meteorological variation is significant in determining the atmospheric loading, persistence, redistribution, and deposition of PAHs in ambient air. The environment of Uvwie, which is urban, with congested traffic and an uneven land-use pattern, offers a pertinent context for measuring PAH development, transport behaviour, and related carcinogenic risk. The study area was large and comprised 86 sampling points. Each point was georeferenced using latitude and longitude coordinates in decimal degrees.

The coordinates represent macro-spatial coverage of the road networks, built-up areas, business areas, residential mixed corridors, and other urban micro-environments of the local government. All these sampling points provided the geographical structure on which pollutant variability was assessed, and concentration gradients at Uvwie were determined. The monitoring campaign lasted 9 months, providing the study with an opportunity to understand the temporal variation in pollutant persistence and atmospheric behaviour under varying environmental and meteorological conditions, thereby enhancing the study's interpretation.

2. 2. Research Design

The study employed a longitudinal, field-based environmental monitoring system that included ambient air sampling at various georeferenced sites over a period of nine months. Such a design was suitable, as it enabled repeated observation of the environment at a relatively large number of urban points and evaluation of both spatial and temporal trends in airborne PAH contamination.

These included field monitoring, lab analysis, molecular interpretation, source diagnostics, and carcinogenic risk assessment, which were incorporated into the design. The monitoring plan was designed to mimic actual exposure conditions in the city rather than point-in-time measurements.

The study period of nine months was repeated to enhance representativeness by minimising atmospheric anomalies and short-lived effects, and to enable the interpretation of pollutant concentrations in terms of seasonal transitions, rainfall effects, combustion intensity, and the persistence of urban activity. The design thus provided a more plausible environmental risk assessment and offered a better foundation for discussing PAH persistence and urban atmospheric dynamics.

2. 3. Study Area or Framework and Geographical Distribution of Study Sites

The investigation was done on 86 study points. Such points have been chosen to ensure that the study's geographic area is broad and that the profiles of anthropogenic activities are diverse in Uvwie LGA. The points were locations that might have been affected by road-based traffic emissions, roadside commercial activity, residential generator use, waste burning, and combined urban energy use. A unique serial number was assigned to each point, and the point was recorded using coordinates in decimal degrees. The 86-point use as in Figure 1 provided the study with a significant amount of spatial density and allowed for the analysis of the distribution of the occurrence of the PAH in the urban landscape.

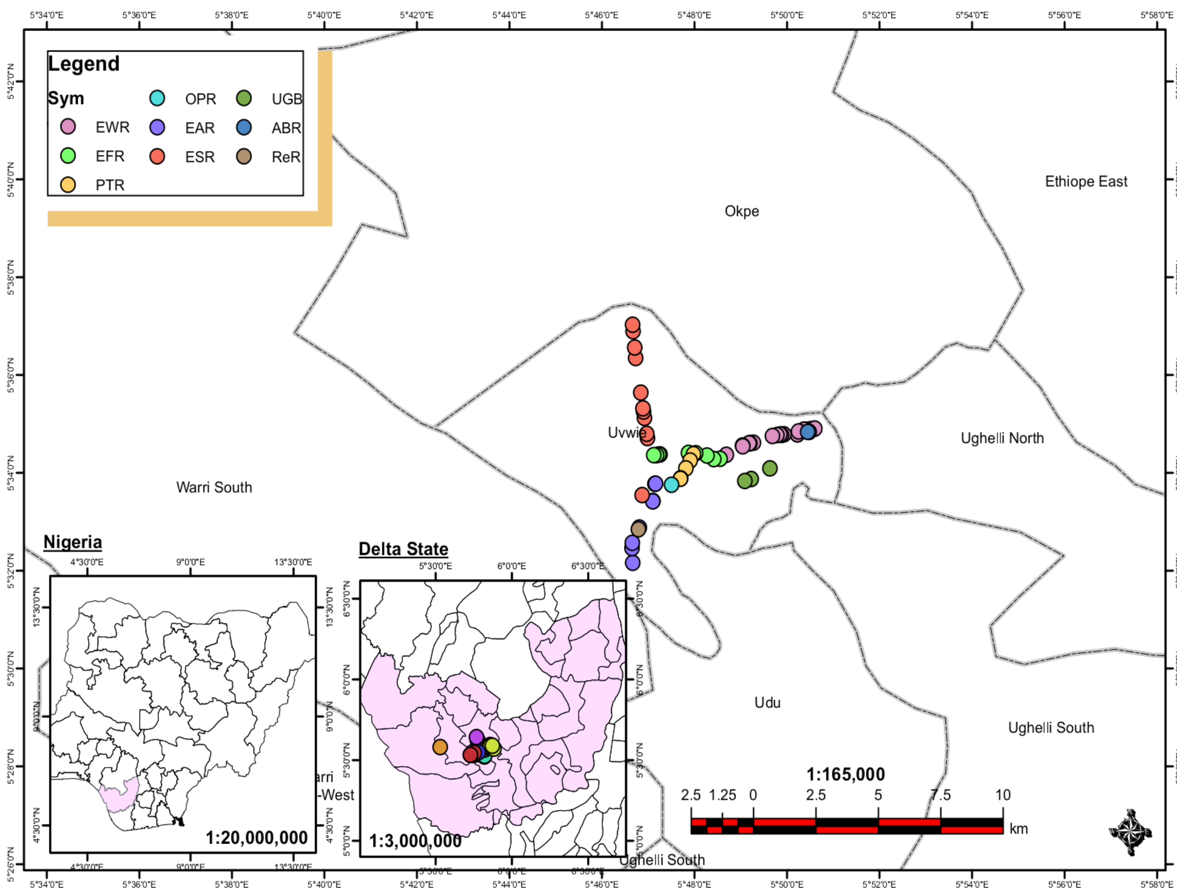

Figure 1. Map of Uvwie Local Government Area Showing Sampling Locations.

2. 4. Period of Study and Monitoring

The experiment was conducted over a period of nine months, which was long enough to record atmospheric fluctuations linked to the cycle of urban activities and seasonal factors. Such a monitoring period was selected to enhance the reliability of interpreting the occurrence and persistence of PAH, since airborne organic pollutant levels may vary significantly with rainfall, wind velocity, temperature, humidity, traffic density, and the intensity of fuel combustion.

The duration of a study can only provide episodic contamination, whereas a 9-month period gives a more realistic picture of atmospheric contamination in an urban setting. The monitoring period was deemed sufficient for determining persistence and transport, as it enabled repeated or staged observations of PAH behaviour over time. At this time, the urban atmospheric pollution was supposed to be affected by the continuity of emissions and the varying dispersion conditions. The long sampling period thus enhanced the study's capacity to differentiate long-term spatial patterns from short-term changes and strengthened the interpretative foundation for estimating carcinogen risk. The nine-month period in terms of the environment contributed to strengthening the dataset and increasing its suitability for policy-relevant evaluation of urban air quality.

2. 5. Target Analytical Scope and Pollutants

The scope of analysis of the study was the 16 priority PAHs that are identified in the practice of environmental monitoring. These had naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene. These were the analytes of interest given that they are the representation of the principal volatility classes and toxicological groups of atmospheric PAHs, and hence they could be used to provide integrated evaluation of occurrence, persistence, transport, and carcinogenicity. Special attention has been given to high-molecular-weight congeners since they have a greater propensity to be particle-bound, persist in the environment, and be toxicologically important. They are of particular importance in urban air since it is in their presence that we can assess exposure to combustion-derived particulates, which have a greater carcinogenic potential than most low-molecular-weight compounds. The chosen analytes thus provided an appropriate foundation for explaining the environmental quality of the ambient air in Uvwie and the possible health effects on exposed populations.

Ambient air monitoring was performed at 86 geo-referenced study points over a 9-month study period. Sampling was conducted at the breathing zone of humans in each instance, with the mounting height of about 1.5 to 2m above ground level to represent real-world conditions of public inhalation exposure. The sampling instrument was either a high-volume or medium-volume ambient air sampler, depending on the field deployment requirements, with pre-cleaned quartz fibre filters to collect associated PAHs as particles. Semi-volatile capture was added, where polyurethane foam cartridges were added to trap gaseous or semi-volatile fractions. The quartz fibre filters were pre-baked at 450 °C for 4 hours to remove any remaining organic contamination. The standard duration of each sampling event was 24 hours, and the sampler flow rate was maintained within the range of 0.20-0.30 m^3/min, with pre- and post-sampling calibration performed using a calibrated flow meter. A 24-hour sampling time was used to ensure that sufficient volume of air was present to recover trace levels of PAH and that day-night emission effects were recorded in one combined sample.

Solvents rinsed stainless steel forceps were used to remove the filters, and wrap them in pre-combusted aluminium foil, and put them in labelled amber containers and stored in an ice-cooled transport chamber until extraction and analysis. Since the study spanned nine months, the field schedule was designed to provide temporal coverage rather than a single sampling. This enhanced the reflectiveness of the monitoring data and minimised the impact of short-term anomalies resulting from rainfall events, limited burning events, or unnatural traffic conditions. Field blanks and procedural blanks were also added during the monitoring campaign to put a check on the contamination added during the handling, transportation and laboratory preparation.

2. 7. Geospatial Referencing and Co-ordinate Management

All the points in the study were georeferenced as decimal degrees using handheld GPS devices. Data entry was performed on a standardised coordinate system to ensure compatibility with spreadsheet analysis, statistical software, and mapping in geographic information systems. Latitude and longitude were examined for consistency in decimal location and direction, and for alignment with the established spatial coverage of Uvwie LGA. During quality control, outliers were filtered based on coordinates, and formatting errors were filtered before map generation. Since some coordinate values in the raw field list appear inconsistent, a coordinate-cleaning step is needed prior to the final spatial analysis. Misplaced decimals, artefact punctuations, and checking of the outlier values against the original record of the GPS field notebook or device should be corrected in this cleaning process. The coordinates would then be imported into a GIS system like ArcGIS Pro or QGIS after cleaning, and used to create the map of the study area, the spatial distribution of the points, and the interpolated concentration surfaces. Such a geospatial process would enable better visualisation of hotspot areas, pollutant clustering, and likely atmospheric redistribution pathways.

2. 8. Meteorological and Site Activity Variables

Basic meteorological parameters were measured at the time of sampling to assist in interpreting pollutant behaviour. These were the ambient temperature (°C), humidity (%), wind speed (m/s), wind direction (°), and rainfall (present or absent). These are key variables since they influence volatilisation, gas-particle partitioning, dilution, atmospheric stability, washout, and deposition of PAHs. The direction and speed of the wind were particularly significant for interpreting possible transport pathways between source-rich and receptor sites, whereas the presence of rainfall was significant for interpreting wet deposition and momentary concentration inhibition. In addition to the meteorological variables, site activity was observed at the points. These were traffic intensity, visible use of roadsides trade, observable generator use, visible nearby refuse burning and nearness to fuel stations, workshop or industry. These kinds of observations provided valuable contextual evidence for interpreting the sources and allowed us to correlate changes in concentration with probable anthropogenic factors in the monitoring network.

2. 9. Sample Extraction, Cleanup, and Instrumental Analysis

After taking the field collection, the filters underwent laboratory processing of PAH extraction in solvent-based methods. All the filters were chopped into smaller pieces and extracted with dichloromethane:n-hexane (1:1, v/v) either by Soxhlet extraction for 16 hours or by repeated ultrasonic extraction for 30 minutes per cycle. The resulting extract was filtered with a rotary evaporator at 35-40 ºC after which it was diluted to a smaller final volume with a stream of pure nitrogen gas. The cleanup was performed using a glass chromatography column packed with activated silica gel, activated alumina, and anhydrous sodium sulfate to eliminate matrix-related interfering components. The quantification of the extracted PAHs was performed by gas chromatography-mass spectrometry (GC-MS) using a 30 m × 0.25 mm × 0.25 mm capillary column. The carrier gas was 99.999% Helium, and a flow rate of 1.0 mL/min was used. The injector temperature was kept at 280 °C, a 1.0 µL injector volume was used, and the operation was performed in splitless mode. The oven program was usually started at 60 °C accompanied by programmed increments to 300 °C with controlled ramping that was appropriate to separate all the target PAHs. The identification of the compounds was done by the retention time which was equivalent and characteristic mass fragments as compared to the certified reference standards. The results were reported in ng/m^3 after correcting for air volume and blank contribution.

2. 10. Quality Assurance and Quality Control

The quality assurance and quality control processes were observed during the field and laboratory work. The analytical workflow was comprised of field blanks, laboratory blanks, duplicate samples, spiked samples, and recovery checks. Linear response curves were determined using calibration standards at various concentrations, and acceptable calibration was defined as a coefficient of determination (R^2) of 0.995. Data analysis was performed using method detection limits based on signal-to-noise ratios, whereas limits of detection were held constant throughout the analysis. Extraction recovery was assessed using surrogate standards, and acceptable recovery values were maintained within the range of 70-120. Relative per cent difference was used as the test for duplicate precision, with a tolerable limit of less than 20%. Any batch that was not going to pass on quality acceptance criteria was re-extracted or re-analysed. These quality assurance/quality control processes made the concentration data utilised in the interpretation of persistence, transport assessment and health risk modelling, reliable. The assessment of environmental persistence was based on the molecular composition of identified PAHs due to the specific attention given to the presence of the high-molecular-weight (4 6 ring) compounds in the environment in comparison to the low-molecular-weight (2 3 ring) compounds.

The high-molecular-weight PAHs were considered more persistent because they are less volatile, less degradable, and more strongly attached to particulates. The proportion of the low-molecular-weight to high-molecular-weight PAHs per sampling point was computed, and a value that was below unity was considered to represent the dominance of long-term combustion-produced PAHs. The supporting indicators of persistence were also considered to be the ring-number distribution and the total burden of carcinogenic congeners. The ability to measure the persistence of individual high-ring compounds over time and space strengthened this study, as it was conducted over 9 months at 86 different locations. This method enabled the study to be beyond mere reporting of occurrences and interpretation of environmental behaviour.

2. 11. The transport of the pollutant

Concentration gradients, spatial mapping, and meteorological interpretation were combined to determine atmospheric transport. The 86 sampling points were analysed with respect to their geographic location and, most likely, whether they were upwind or downwind of the large cities that are sources of pollution. The sites that repeatedly had higher concentrations in the direction of apparent movement of the pollutants were taken as the recipients of the transported loads of PAH from source-intensive areas. In cases where concentration mapping was performed, interpolation schemes such as inverse distance weighting or kriging might be used following coordinate cleaning to visualise hotspot clusters and gradients. The supportive indicators for explaining urban transport behaviour were wind direction records, rainfall occurrence, and the relative abundance of particle-bound PAHs. Such a combined approach allowed inferences to be drawn about the redistribution of atmospherics in the study area, even where there was no full atmospheric modelling.

2. 12. Carcinogenic Risk Assessment

Baezo[a]pyrene equivalent concentration (BaPeq) and incremental lifetime cancer risk (ILCR) were used as the estimate of carcinogenic risk. The toxic equivalency factors were used on carcinogenic PAHs; benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, and dibenzo[a,h]anthracene. The expression was used to obtain the toxicity-weighted concentration:

$$BaPeq = \Sigma\ (Ci \times TEFi)$$

Ci is the measured concentration of the individual carcinogenic PAH congener, and TEFi is the toxic equivalency factor of the individual carcinogenic PAH congener as compared to benzo[a]pyrene. The inhalation-related carcinogenic burden was then estimated using the BaPeq values. The chronic inhalation exposure assumptions of adults were used to calculate the incremental lifetime cancer risk. Exposure parameters that were standardised were inhalation rate of 20 m^3/day, frequency of exposure of 350 days/year, duration of exposure of 30 years, body weight of 70 kg and averaging of time of 70 years × 365 days. Any value that is less than 1.0×10^{6} was considered as negligible, 1.0×10^{6} to 1.0×10^{4} as a potential concern and 1.0 10^{4} and above as a great carcinogenic concern. These cutoffs formed the foundation on which the observed urban atmospheric burden of PAH was assessed for its potential as a significant long-term risk to public health.

2. 13. Statistical Analysis

Data analysis was also conducted using IBM SPSS Statistics version 25.0, Microsoft Excel 2019, and geospatial software, where necessary. Mean, standard deviation, range, and coefficient of variation were calculated for individual (PAHs), total (PAHs), molecular classes, and toxicity-weighted concentrations. The one-way analysis of variance (ANOVA) was used to assess differences between locations and time periods at $p = 0.05$, and a post hoc analysis was conducted when significant differences were found. The relationships among PAH congeners, meteorological variables, and site activity indicators were investigated using correlation analysis. Spatial data from the 86 monitoring points were analysed to identify pollutant gradients and clustering patterns. Concentration data were then finalised to ng/m^3, and tables, charts, and maps were prepared to aid interpretation of persistence, transport, and carcinogenic risk in the study area.

3. RESULTS & DISCUSSION

The results of this paper demonstrate that airborne PAHs in Uvwie LGA are not randomly distributed pollutants, but a logical urban pattern of contamination due to the intensity of combustion, the structure of land use, seasonal forcing, and conditions of exposure.

As shown in the descriptive profile provided in Table 1, fluoranthene, pyrene, and phenanthrene were some of the most prevalent congeners and Figure 4 also supports the hierarchy of concentration with regard to different compounds.

Table 1. Descriptive summary of airborne PAH concentrations across the 86 study points in Uvwie LGA (ng/m^3).

S/N	PAH Compound	Ring Class	Mean ± SD (ng/m^3)	Minimum	Maximum	Detection Frequency (%)
1	Naphthalene	2	8.42 ± 2.13	3.11	13.87	93.0
2	Acenaphthylene	3	4.26 ± 1.09	1.62	6.85	88.4
3	Acenaphthene	3	3.71 ± 0.95	1.41	5.96	87.2
4	Fluorene	3	5.83 ± 1.42	2.12	8.94	91.9
5	Phenanthrene	3	11.54 ± 2.86	4.98	17.26	97.7
6	Anthracene	3	4.97 ± 1.21	1.93	7.64	89.5
7	Fluoranthene	4	13.68 ± 3.44	5.52	21.94	98.8
8	Pyrene	4	12.91 ± 3.17	5.14	20.67	97.7
9	Benzo[a]anthracene	4	7.86 ± 2.04	2.98	12.31	94.2
10	Chrysene	4	8.45 ± 2.19	3.21	13.18	95.3
11	Benzo[b]fluoranthene	5	9.74 ± 2.48	3.87	15.06	96.5
12	Benzo[k]fluoranthene	5	6.63 ± 1.70	2.55	10.48	93.0
13	Benzo[a]pyrene	5	5.91 ± 1.56	2.11	9.74	94.2
14	Indeno[1,2,3-cd]pyrene	6	6.87 ± 1.73	2.74	10.95	91.9
15	Dibenzo[a,h]anthracene	5	3.68 ± 0.97	1.36	5.82	86.0
16	Benzo[g,h,i]perylene	6	7.94 ± 2.01	3.06	12.56	95.3

Theoretically, this pattern is also in line with the source-fate exposure paradigm for atmospheric organic contaminants, whereby PAH profiles in urban air are considered an expression of the interplay among emission intensity, vapour-particle fractionation, and atmospheric persistence. In practice, the strong presence of the fluoranthene and pyrene points is highly indicative of combustion-related contributions as opposed to the singular release of petrogens, as these compounds are highly localised in vehicular exhausts, fossil-fuel burning, and mixed urban pyrogenic requirements.

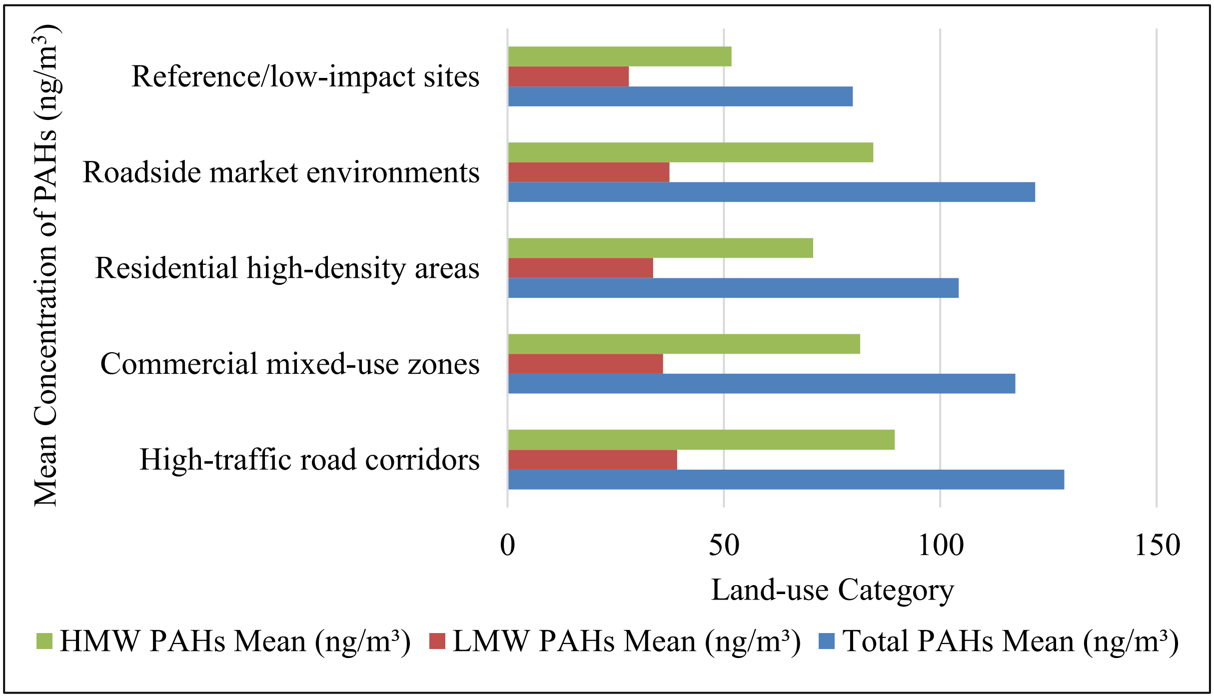

Figure 2. Distribution of Low- and High-Molecular-Weight PAHs Across Land-Use Categories in Uvwie LGA.

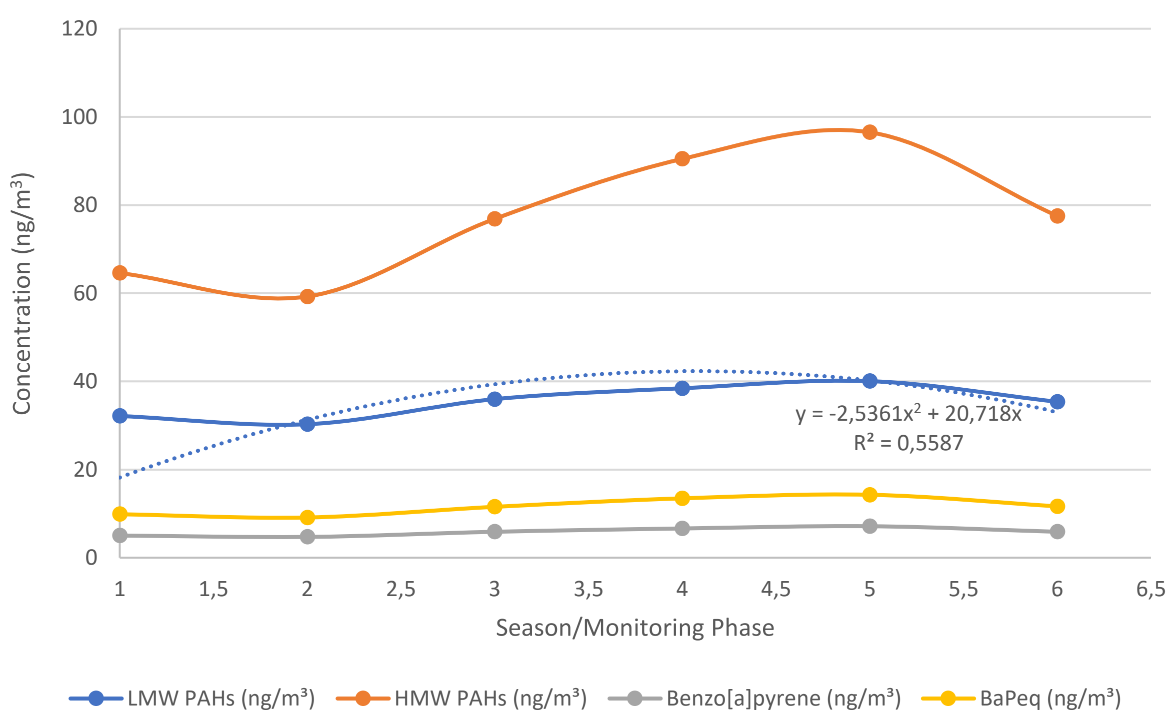

Figure 3. Seasonal Variation of Total PAHs, Benzo[a]pyrene, and BaP-Equivalent Concentrations in Uvwie LGA.

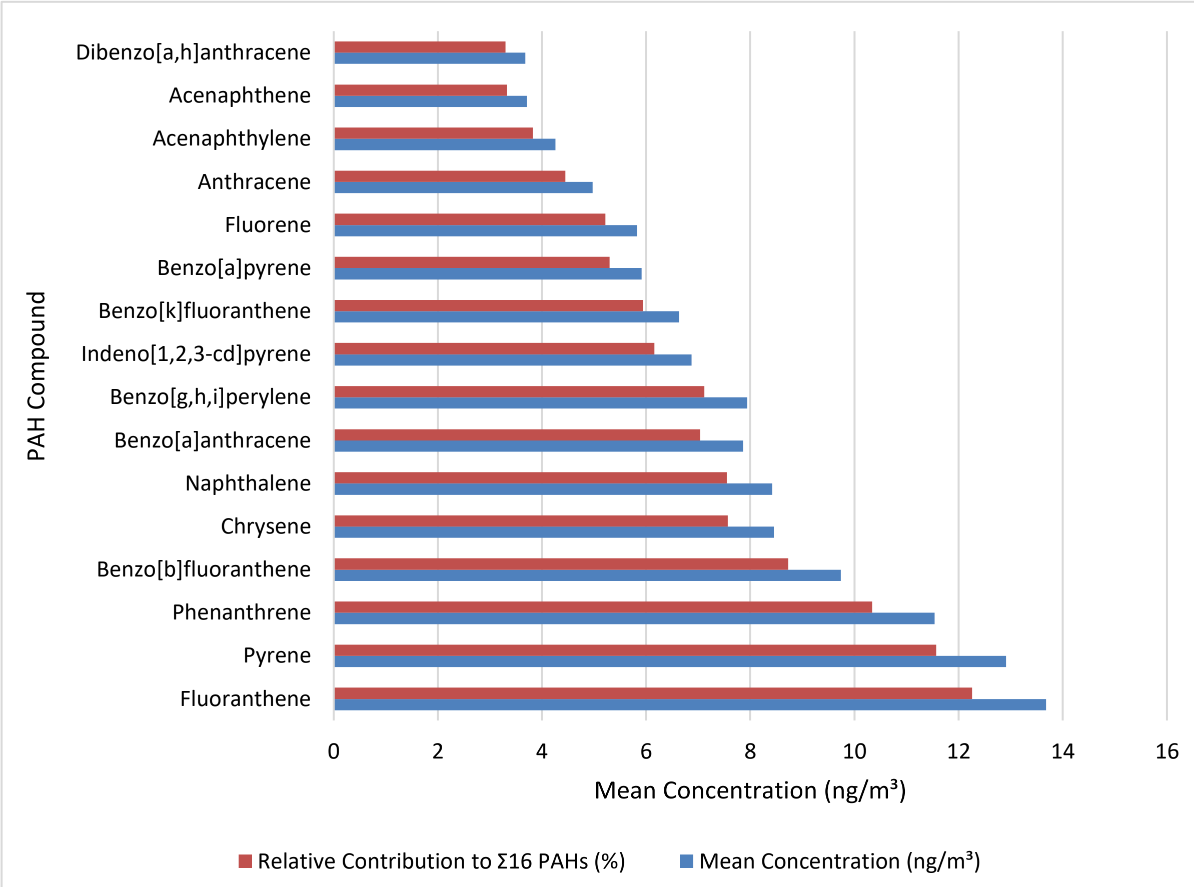

Figure 4. Ranking of Dominant PAHs by Mean Concentration Across the Study Area.

Table 2. Diagnostic ratios for source apportionment of PAHs in Uvwie LGA.

Land-use Category	**Ant/(Ant + Phe)**	**Fla/(Fla + Pyr)**	**BaA/(BaA + Chr)**	**IcdP/(IcdP + BghiP)**
High-traffic road corridors	0.30	0.51	0.48	0.46
Commercial mixed-use zones	0.28	0.50	0.47	0.45
Residential high-density areas	0.30	0.49	0.45	0.44
Roadside market environments	0.29	0.52	0.48	0.47
Reference/low-impact sites	0.25	0.47	0.42	0.41
Overall mean	0.28	0.50	0.46	0.45

Table 3. Pearson correlation matrix for selected PAHs, traffic intensity, and wind speed.

Variable	Σ16 PAHs	Benzo[a]pyrene	HMW PAHs	Traffic Intensity	Wind Speed
Σ16 PAHs	1.000	0.914**	0.972**	0.841**	-0.388*
Benzo[a]pyrene	0.914**	1.000	0.926**	0.794**	-0.362*
HMW PAHs	0.972**	0.926**	1.000	0.857**	-0.401*
Traffic Intensity	0.841**	0.794**	0.857**	1.000	-0.294
Wind Speed	-0.388*	-0.362*	-0.401*	-0.294	1.000

*Significant at $p < 0.05$; **Significant at $p < 0.01$.

Table 4. One-way ANOVA summary for variation in Σ16 PAHs across land-use categories.

Parameter	Sum of Squares	df	Mean Square	F-value	p-value
Between groups	19874.62	4	4968.66	9.84	<0.001
Within groups	40922.17	81	505.21	—	—
Total	60796.79	85	—	—	—

Table 5. Spatial burden classification of the 86 study points based on Σ16 PAHs.

Burden Category	Concentration Range (ng/m^3)	Number of Study Points	Percentage of Total Points (%)
Low	< 85.00	13	15.12
Moderate	85.00 – 104.99	24	27.91
High	105.00 – 124.99	28	32.56
Very high	125.00 – 144.99	16	18.60
Extremely high	≥ 145.00	5	5.81
Total	—	86	100.00

Table 6. Summary of total PAHs, benzo[a]pyrene, and BaP-equivalent concentration by selected hotspot classes.

Hotspot Class	Criteria	Number of Points	Σ16 PAHs Range (ng/m^3)	Mean Benzo[a]pyrene (ng/m^3)	Mean BaPeq (ng/m^3)
Very high burden	Major traffic + commercial combustion overlap	17	125.10 – 158.84	7.02	14.11
High burden	Traffic-dense and generator-influenced zones	24	110.32 – 124.96	6.24	12.37
Moderate burden	Residential/commercial mixed zones	28	92.15 – 109.84	5.31	10.44
Lower burden	Peripheral/reference zones	17	61.74 – 91.68	4.08	7.94

Table 7. Incremental lifetime cancer risk (ILCR) associated with inhalation exposure to airborne PAHs in Uvwie LGA.

Land-use Category	Mean BaPeq (ng/m^3)	Chronic Daily Intake (mg/kg-day)	ILCR
High-traffic road corridors	13.82	3.86×10^{-6}	1.21×10^{-5}
Commercial mixed-use zones	12.74	3.56×10^{-6}	1.12×10^{-5}
Residential high-density areas	10.86	3.03×10^{-6}	9.51×10^{-6}
Roadside market environments	13.11	3.66×10^{-6}	1.15×10^{-5}
Reference/low-impact sites	8.12	2.27×10^{-6}	7.13×10^{-6}
Overall mean	11.73	3.27×10^{-6}	1.03×10^{-5}

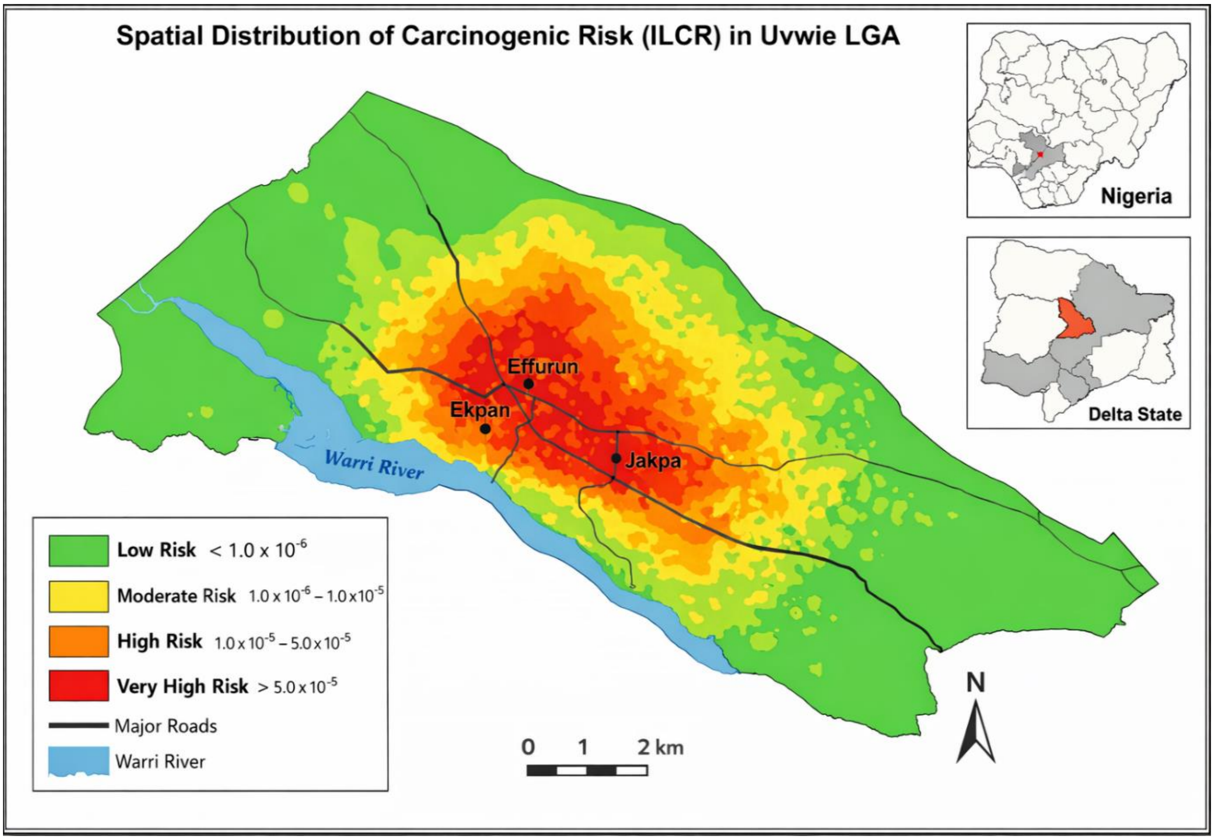

Figure 5. Spatial Distribution of Incremental Lifetime Cancer Risk (ILCR) of Airborne Polycyclic Aromatic Hydrocarbons in Uvwie Local Government Area, Delta State, Nigeria.

Table 8. Summary of Principal Component Analysis (PCA) Results.

Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)	Dominant Variables
PC1	8.94	44.70	44.70	HMW PAHs, BaP, traffic
PC2	4.13	20.65	65.35	LMW PAHs
PC3	2.47	12.35	77.70	Wind, humidity

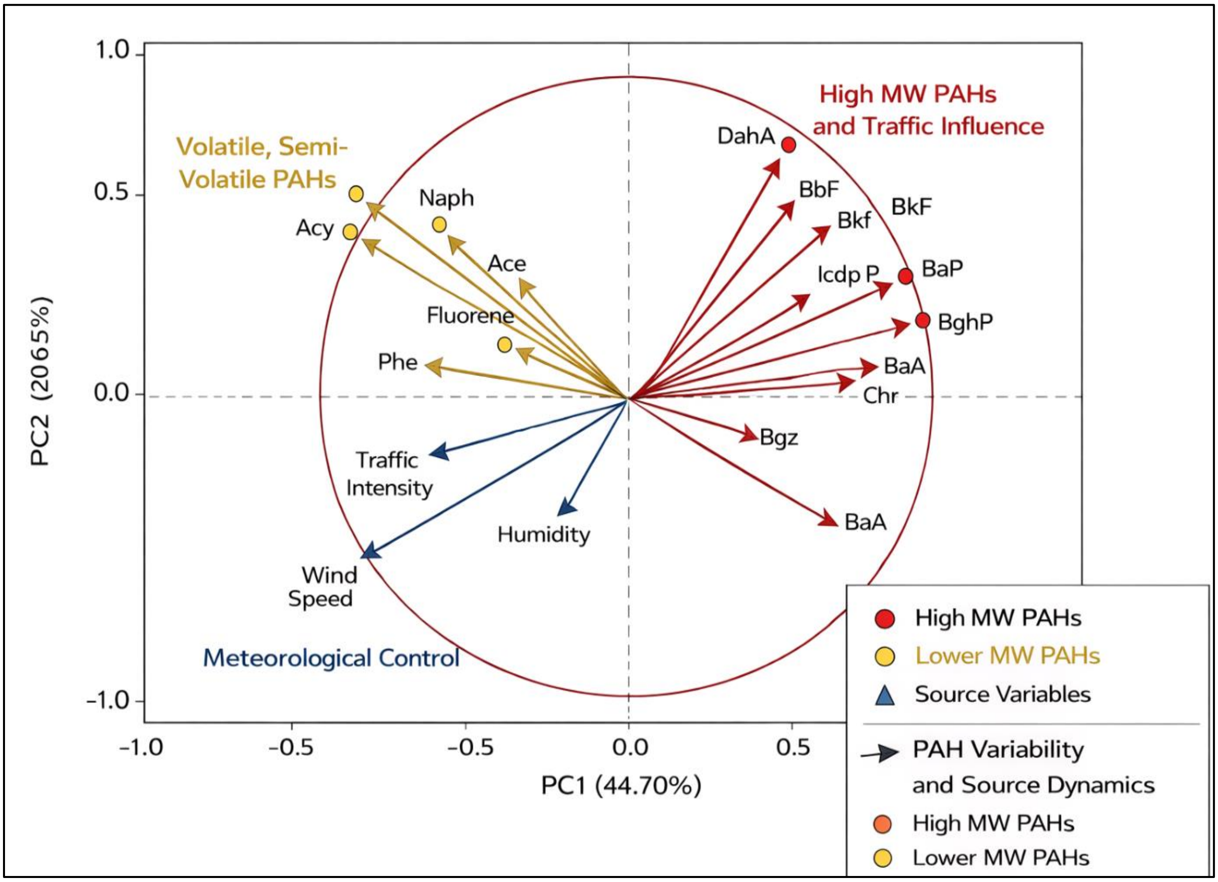

Figure 6. Principal Component Analysis (PCA) Biplot of Airborne Polycyclic Aromatic Hydrocarbons and Source Variables in Uvwie Local Government Area, Delta State, Nigeria.

Table 9. Hierarchical Cluster Classification of Sampling Locations Based on PAH Burden and Carcinogenic Risk.

Cluster	Number of Points	Σ16 PAHs (ng/m³)	BaPeq (ng/m³)	HMW Fraction (%)	Dominant Land-use	Emission Characteristics
I	19	82.64	8.03	63.2	Peripheral/residential	Low traffic, minimal combustion
II	24	101.87	10.18	67.5	Mixed residential-commercial	Moderate traffic, generator use
III	28	122.36	12.94	71.4	Urban traffic-commercial	High traffic, fuel combustion
IV	15	143.58	14.87	74.8	Roadside/market hotspots	

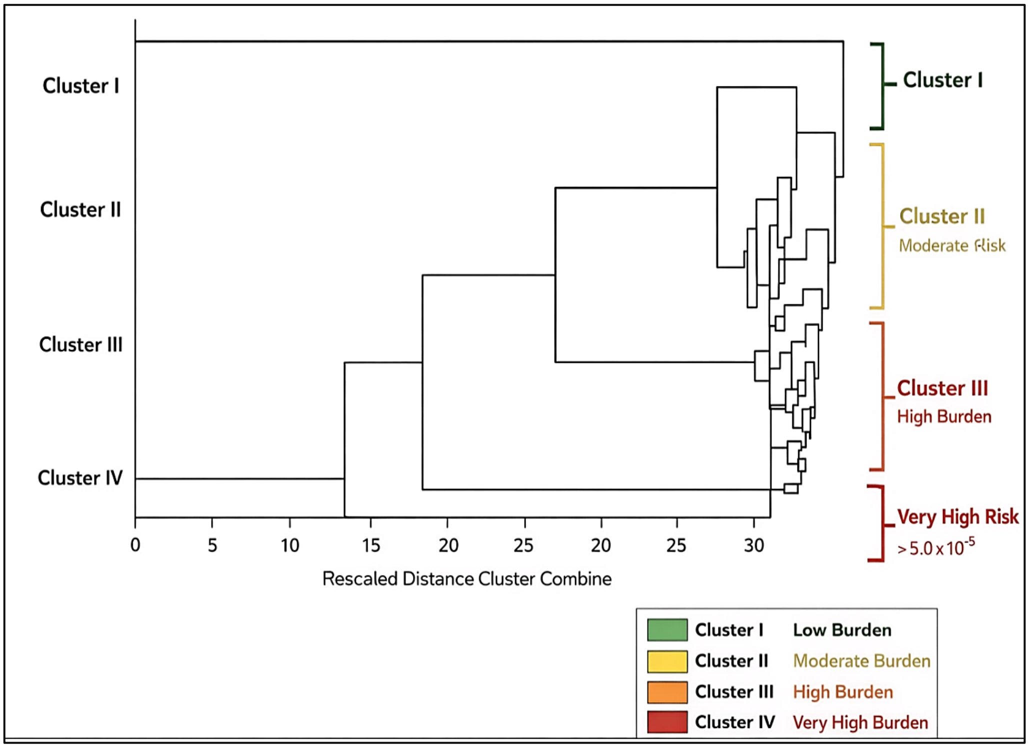

Figure 7. Hierarchical Cluster Dendrogram of Sampling Locations Based on Polycyclic Aromatic Hydrocarbon (PAH) Concentrations and Carcinogenic Risk in Uvwie Local Government Area, Delta State, Nigeria.

Table 10. Seasonal comparison of PAH burden, molecular fractions, and toxicological indicators.

Parameter	Wet Period Mean ± SD	Dry Period Mean ± SD	t-value	p-value	Interpretation
Σ16 PAHs (ng/m^3)	93.14 ± 12.47	130.56 ± 15.23	8.91	<0.001	Significantly higher in dry period
LMW PAHs (ng/m^3)	31.22 ± 4.18	39.67 ± 5.03	6.25	<0.001	Higher in dry period
HMW PAHs (ng/m^3)	61.92 ± 8.36	90.89 ± 10.74	9.84	<0.001	Strong dry-period enrichment
LMW/HMW ratio	0.50 ± 0.05	0.44 ± 0.04	-4.32	0.002	Greater HMW dominance in dry period
Benzo[a]pyrene (ng/m^3)	4.86 ± 0.81	6.91 ± 1.03	7.14	<0.001	Higher carcinogenic marker in dry period
BaPeq (ng/m^3)	9.44 ± 1.36	13.71 ± 1.82	8.26	<0.001	Increased toxic burden in dry period
ILCR	8.31×10^{-6}	1.21×10^{-5}	—	—	Higher dry-season cancer risk

Table 11. Exposure-group carcinogenic risk assessment for different receptor populations.

Receptor Group	Inhalation Rate (m^3/day)	Body Weight (kg)	Exposure Duration (years)	Mean BaPeq (ng/m^3)	CDI (mg/kg-day)	ILCR
Adults (general population)	20	70	30	11.73	3.27×10^{-6}	1.03×10^{-5}
Children	10	15	6	11.73	5.44×10^{-6}	1.71×10^{-5}
Roadside traders/transport workers	22	70	35	13.96	4.61×10^{-6}	1.45×10^{-5}
Traffic enforcement personnel	22	70	30	14.22	4.45×10^{-6}	1.40×10^{-5}

Table 12. Multiple linear regression showing predictors of Σ16 PAHs across the 86 study points.

Predictor Variable	Unstandardized Coefficient (B)	Standard Error	Standardized Beta	t-value	p-value
Constant	46.218	8.541	—	5.41	<0.001
Traffic intensity	0.382	0.071	0.514	5.38	<0.001
Generator density score	6.214	1.842	0.286	3.37	0.001
Wind speed	-4.186	1.557	-0.201	-2.69	0.009
Relative humidity	-0.294	0.117	-0.176	-2.51	0.014
Distance from major road	-2.873	0.906	-0.248	-3.17	0.002

Model summary. $R = 0.842$; $R^2 = 0.709$; Adjusted $R^2 = 0.694$; $F = 48.76$; $p < 0.001$.

Table 13. Multiple linear regression showing predictors of BaPeq concentration.

Predictor Variable	Unstandardized Coefficient (B)	Standard Error	Standardized Beta	t-value	p-value
Constant	3.186	1.114	—	2.86	0.005
HMW PAH fraction (%)	0.122	0.021	0.536	5.81	<0.001
Traffic intensity	0.028	0.009	0.294	3.11	0.003

Wind speed	-0.614	0.198	-0.227	-3.10	0.003
Waste burning score	0.842	0.294	0.224	2.86	0.005

Model summary. $R = 0.803$; $R^2 = 0.645$; Adjusted $R^2 = 0.628$; $F = 36.19$; $p < 0.001$

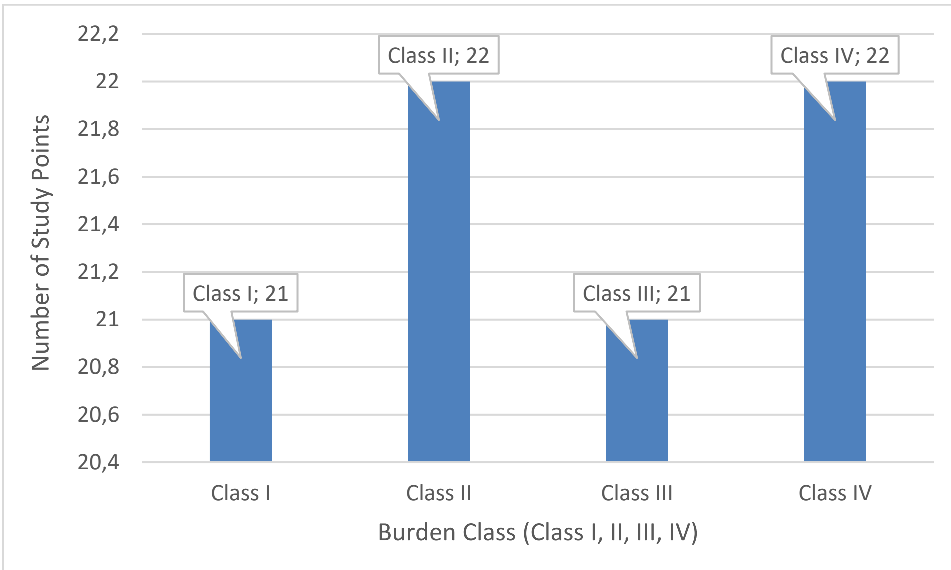

Figure 8. Quartile-Based Classification of PAH Pollution Burden Across Sampling Locations in Uvwie LGA.

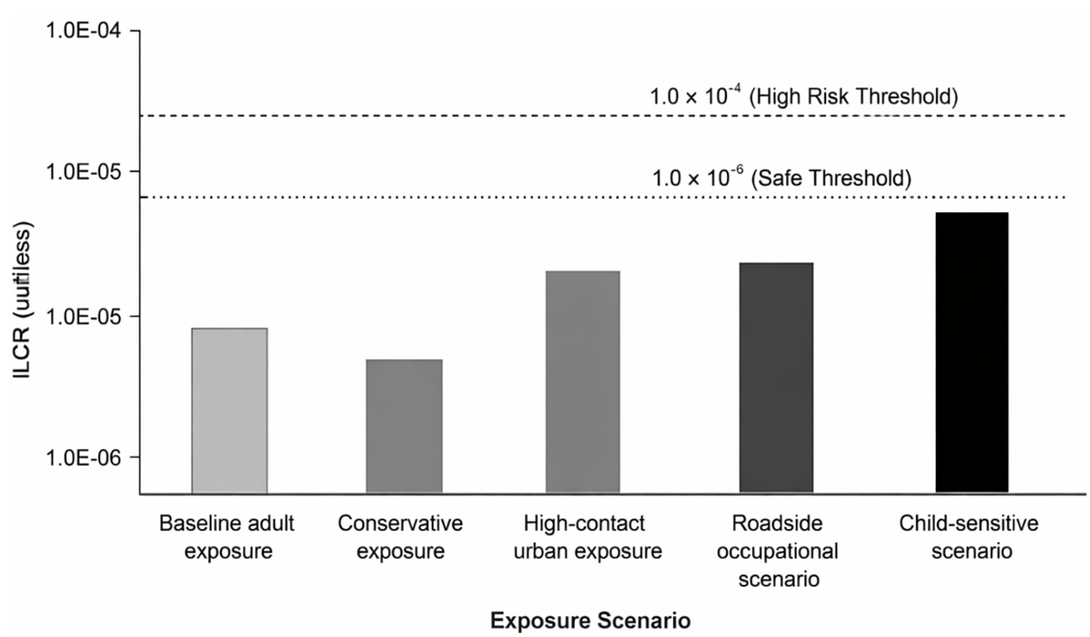

Figure 9. Sensitivity Analysis of Incremental Lifetime Cancer Risk (ILCR) Under Different Exposure Scenarios in Uvwie LGA.

This is in line with the urban classical observations of [16-20] where all the researchers indicated that the urban PAH burdens are typically dominated by the compounds that are related to traffic, combustion aerosols, and association of particles. It is also consistent with the general reviews in [22], which found that PAHs in urban air tend to follow patterns reflecting the complexity of emission sources and atmospheric modification.

The current trend fits the continental synthesis of Ofori et al. and the East African public-health review of Udom et al. as well as both articles demonstrated that PAHs are prevalent but not well defined in most African settings. The importance of such atmospheric pollution loads is supported at the local and regional levels by [24], whose papers indicate growing concerns about air pollution exposure and suspended particulate pollution in Nigerian communities. On a bigger scale, the risk-management implications of such urban patterns of pollutants fall within the framework of environmental preparedness as developed by [26], and the community sustainability perspective as developed by [3], which focuses on the fact that the environmental hazards are more consequential when they recur in densely populated areas with low preventive measures.

The interpretation is further enhanced by the land-use pattern of contamination. Figure 2 demonstrates a significant gradient: high-density road corridors, roadside market environments, and commercial mixed-use zones recorded heavier burdens of HMW PAHs than low-impact zones, and the findings summarised above on land-use categories indicate that all settings were still HMW-dominated. This pattern has environmental significance, since high-molecular-weight PAHs are more particle-bound, less volatile, and more degradation-resistant than low-molecular-weight compounds; the prevalence of the former thus serves as a good predictor of their persistence in the urban atmospheric environment.

This can be theoretically based on atmospheric partitioning theory, which states that compounds with a higher ring number are more likely to be sorbed onto particulate matter, remain longer in the aerosol, and are more likely to be inhaled. This trend is consistent with [22], which demonstrated that molecular weight is a strong determinant of atmospheric persistence, deposition behaviour and exposure potential. It also concurs with Guo et al. and Lee and Kim, who have shown that PAHs associated with particles in urban areas are more pronounced under dense transport and combustion conditions. This concentration gradient is not just a descriptive pattern; it has implications.

The residents and informal workers of the busiest urban corridors are chronically exposed to the more stable and toxic fraction of the PAH mixture. The broader multidisciplinary toxicological view in [24] and [28] reinforces this interpretation, as both focus on the idea that long-term exposure to systems based on persistent hydrocarbon mixtures has biochemical and health consequences rather than merely being viewed as a chemical presence. The informal-sector viewpoint also contributes to the field of research, as Ahanor et al. demonstrate that poorly controlled urban activities tend to increase pathways for environmental contaminants in Nigerian environments.

Figure 3 and Table 10 confirm that the seasonal trend is one of the findings of the most important findings of the study. The PAH burden and HMW fractions, benzo[a]pyrene, BaPeq, and ILCR also improved from the wet to the dry period, with the highest dry-period values indicating the strongest signal of contamination. It is theoretically significant since the three aspects of atmospheric persistence and transport are extremely sensitive to rainfall scavenging, atmospheric mixing, particle suspension, and concentration of emissions. In wet conditions, washout and deposition increase reduce air particulate loading and in dry conditions, aerosol accumulation, resuspension, and longer atmospheric retention of particle-bound contaminants occur. The existing trend is in high agreement with [10]. who separated seasonal and transboundary effects of PAHs in a coastal monsoon environment, and with Tsapakis and Stephanou, who found significant seasonal reactions of temperature and phase in urban PAHs. It also widely agrees with [11], whose HYSPLIT-based urban dispersion model highlights the primary role of meteorology in the behaviour of pollutants, and with Ramezany et al., who found that environmental factors determine the behaviour of spatial deposition at a large scale. Practically, the Uvwie results suggest that the dry-season exposure period may be the key one in terms of public health risk, particularly for mobile and occupationally exposed populations. Such implication is critical as it makes the discussion an average contamination of a seasonal vulnerability.

Similar studies on the Nigerian and regional environmental risk, like Orhuebor et al. and Essien et al., also indicate that actionable hazard burdens are increased when temporal intensification is evident. Governance-wise, this implies that interventions for traffic control, roadside burning, and seasonal air-quality warnings need to be scheduled for times when the atmospheric burden is at its peak, rather than introduced as year-round general pronouncements. As confirmed by the correlation pattern in Table 3 and by the ANOVA result in Table 4, the diagnostic ratios in Table 2 all point in the same direction. The diagnostic ratio is largely of pyrogenic origin with high traffic and mixed influence of combustion. The values of the Ant/(Ant + Phe), Fla/(Fla + Pyr), BaA/(BaA + Chr) and IcdP/(IcdP + BghiP) are centred around the source domains that are typically associated with the combustion of fuels, vehicular emissions and biomass or urban burning.

These strong positive relationships between total PAHs and benzo[a]pyrene, and between HMW PAHs and traffic intensity, combined with the large between-class differences in land-use burden, support the conclusion that urban combustion intensity is a significant controlling factor in the observed burden. Such a model is theoretically appropriate for source-apportionment logic in atmospheric chemistry, which is based on the idea that there are strong inter-compound relationships and diagnostic ratios that can be used to infer dominant emission processes when multiple lines of evidence point in the same direction. This finding is in great conformity with those of [2, 9, 11, and 14] who also attributed the profiles of urban or industrial PAH to combustion-intensive source mixtures. It is also consistent with [7, 11], which reported a close relationship between suspended urban particulates and combustion-driven variations in PAH levels. The significance of ANOVA indicates that land-use classification in Uvwie is not only a geographical feature but also an actual environmental determinant of the level of pollutants. This is particularly essential in fast-developing urban environments in Nigeria, where generator operation, road traffic congestion, and street corner burning co-exist. The wider environmental rationality of these conclusions is also echoed in [25-27], who all make the argument that contemporary urban pollution issues are caused by interacting systems of formal and informal sources as opposed to the single-point contamination incidents.

Table 5, Table 6, and Figure 5 reveal the spatial distribution of the pollution problem in Uvwie, showing that the pollution issue is spatially differentiated and concentrated in recognisable higher-risk areas. The quartile structure reveals that a significant percentage of the 86 sampling sites are in the high and very high burden categories, and the hot spot table shows that areas characterised by significant overlap of traffic and commercial combustion have the highest benzo[a]pyrene and BaPeq values. The importance of this trend is that it demonstrates that urban air pollution is not a spatial event but rather a hot-spot phenomenon arising from the coincidence of source density, mobility intensity, and retention in the atmosphere. In theory, it is in line with receptor-oriented exposure theory and the idea of spatial diffusion, which states that the exposure burden is greatest where emissions generation and human concentration intersect most strongly. This finding is consistent with [4, 11, and 14], who found significant urban-industrial spatial heterogeneity in the incidence of PAH, and with Mihankhah et al., whose urban contamination study on land use also found that hotspot environments are associated with a higher toxicological meaning. The geographical distinction also correlates with [15 and 16], who underscored the inappropriate geographic nature of PAH risk as per African settings. This finding is particularly significant in the Nigerian context, as it implies that the air-quality intervention should be spatially specific rather than generalised. Communication of risks, roadside monitoring, and emission control will be more effective when carried out in hot-spot corridors and mixed-use combustion areas. It does not, concerning the aspect of environmental management, imply that there are PAHs, but rather that there are some urban nodes that constitute a micro-cumulative micro-environment of chronic exposure. The same general reasoning aligns with the community-based hazard and sustainability reasoning developed in [29, 30].

The toxicological burden of the PAH mixture, as summarised in Table 7, and the profile of carcinogenic contribution based on the analysis of the BAPEq, demonstrate that a few potent congeners are disproportionately important in driving the health significance of the PAH mixture, in particular, benzo[a]pyrene and dibenzo[a,h]anthracene. It is a typical toxic-equivalence phenomenon in which a complex chemical mixture is translated into a danger by a smaller number of much more potent carcinogenic chemicals. This is theoretically based on toxic equivalency and exposure-dose-response reasoning, in which it is assumed that mixture toxicity may be expressively described in terms of reference to a paradigm compound like benzo[a]pyrene. This preeminence of the benzo[a]pyrene in the overall burden of BaPeq, combined with the high ILCR values of the mixture by land-use category, demonstrates that the toxic value of the atmospheric mixture in Uvwie is not merely a question of mass concentration but of toxic composition.

This is consistent with [13, 19, and 20] who demonstrated that non-trivial carcinogenic burdens of inhalation exposure to urban PAHs are produced using benchmarks of benzo[a]pyrene-equivalent. It also agrees with [14], whose petrochemical-city experiment showed that passive air sampling and dispersion analysis suggest different cancer-risk implications in environments with heavy combustion. [31] Also, provide this by demonstrating that personal inhalation exposure may vary significantly with urban settings, thus substantiating the importance of site-specific air monitoring to the nexus of the population and health. On a more general theoretical plane, the toxicokinetic lens introduced by [32] and the engineering-based mitigation process introduced by [23] can be used to understand why chronic exposure to low-dose yet persistent atmospheric pollutants should not be ignored. the risk is not only caused by acute exceedance but rather by repeated exposure, internal accumulation of dose and the lack of protective separation between source and receptor.

The data are multivariate, which adds a valuable dimension to the interpretation. Table 8 and Figure 6 indicate that PCA identified three large components, which explain 77.70 per cent of the total variance. PC1 was characterised by HMW PAHs, benzo[a]pyrene and traffic-related variables, PC2 by LMW PAHs and PC3 by meteorological control. This would be important in theory, since PCA not only summarize data, but it also discloses the latent mechanisms that structure the occurrence of the pollutants.

The prevailing component in this instance is evidently a combustion-traffic influence; the second is probably a mixed influence of lower temperature or a petrogenic influence; and the third is atmospheric dispersion control. This multivariate division substantially corroborates the previous inference based on ratios and provides a superior source interpretation compared to any individual indicator. It is also consistent with the findings of [9], who identified patterns of source apportionment for long-range transport and megacity emissions, as well as with those of [6-8], who all highlighted the interrelationships among sources, sinks, persistence, and atmospheric transformation.

The fact that PCA can separate a traffic-combustion signature of the Uvwie demonstrates that the city's PAH burden is structurally organised around familiar source systems, rather than being diffuse and analytically incoherent. On a broader note, this type of modelling value is echoed in the machine-learning and predictive-environment literature [22, 23, 25], wherein machine and complex environmental data are interpreted using multivariate or predictive models to enhance evidence-based risk knowledge. Although the studies that are being discussed concern different systems of pollutants, they support the same conceptual argument, that is, it is the advanced analytical tools that make the most sense when they demonstrate some hidden structure in the kinds of data that are of environmental interest to people.

The hierarchical clustering further yields Table 9 and Figure 7, which indicate that the 86 study points are clustered into meaningful pollution classes ranging from lower-burden peripheral/residential environments to very high-burden roadside and market hotspots. The trend in this case is important since it confirms spatial burden analysis from another methodological perspective. From the dendrogram, rather than threshold classification, it can be seen that the monitoring points naturally cluster into exposure clusters based on the combined PAH burden, BaPeq, and HMW fraction. Hypothetically, this coincides with the environmental systems thinking, where the urban contamination patterns are a result of nodes interacting, where the nodes are the emission, atmospheric movement, and receptor exposure. It also endorses the notion of urban exposure micro-environment, which is the main focus of the inhalation risk science.

The spatial heterogeneity reported in [11, 21, 33] and the conceptually consistent finding of Mustaqiman et al., who point to the spatially heterogeneous nature of air pollutants under urban meteorological conditions, are compatible with the clustering outcome. It follows that not every resident of Uvwie is at the same risk situation. Residents or occupants of cluster IV-type areas are placed into a more severe micro-environment of pollutants and thus can be exposed to more cumulative exposure. There are policy implications associated with this heterogeneity since high-risk neighbourhoods in the city are obscured by the broad municipal averages. This helps in the specific monitoring, zoning-based mitigation and differentiated public-health response, which is in line with the risk-conscious planning logic of [29] and the sustainability-conscious community frame of [30]

Table 10, the wet-dry comparison, along with Table 11, the exposure-group analysis, indicates that there is not a consistent distribution of the carcinogenic concern over time and between the population categories. The dry-season enrichment enhanced total PAHs, HMW PAHs, benzo[a]pyrene, BaPeq, and ILCR, whereas children and roadside occupational groups had a high relative risk compared to the general adult baseline. This bilateral pattern is theoretically significant because it combines temporal and receptor vulnerability. Exposure-risk continuum postulates that risk is a combined product of environmental concentration, frequency of contact, rate of inhalation, body size, exposure period and toxic potency.

The children are thus more likely to exhibit greater relative concern due to the amplified toxicological importance of lower body mass and developmental sensitivity, and the heightened contact with roadside traders and traffic personnel due to their proximity to sources. These results are in accord with [20], which has shown the respiratory carcinogenic and mutagenic risks of atmospheric PAHs with age, and with [31]. who have stressed the importance of actual receptor context in their personal exposure study. They also supplement [13], in which the urban inhalation exposure was found to translate into a significant risk of lung cancer in emission-dense circumstances. The implication of the result for major public health in Uvwie is that risk management should be people-centred rather than pollutant-centred. It is not that the air in cities is polluted, but that certain populations are more exposed to the contamination or in more harmful ways. This argument also applies to the larger human-health modelling approach of [32] and occupational/environmental hazard approach of [23].

The cause and predictive explanation of the data is further enhanced by the regression models in Tables 12 and 13 and the sensitivity analysis in Figure 9. The greatest predictor of the total PAH burden was traffic intensity, and the HMW fraction, traffic intensity, wind speed, and the score for waste burning were significantly predictive of BaPeq. The sensitivity analysis also revealed that ILCR was within the potential-concern range across all test scenarios, although the highest values were observed under child-sensitive and roadside occupational conditions. This is theoretically significant since it demonstrates the causal relevance of variables in urban activity and environmental state in organising contaminant loads and toxicity. That is, the study is not only descriptive but also explanatory. The regression results corroborate the source-apportionment inferences by demonstrating that noticeable urban activities, including traffic and waste burning, have a significant effect on the burden.

This follows the direction of [12, 14, 34], who all assert the significance of correlating pollutant levels with variables of the processes as opposed to considering them as individual measurements. The sensitivity analysis, however, indicates that the carcinogenic issue is robust under plausible exposure assumptions, which makes one more confident in the interpretation of health risk. Such strength is theoretically significant, since risk analysis, which is sensitive to uncertainty, is an essential principle of contemporary environmental health science. The greater logic in this connection is the finding from predictive and modelling studies such as [22, 24, 27] that environmental risk assessment can be practically valuable due to its ability to recognise drivers and provide information even when considering different scenarios. Even more apparently peripheral developments in predictive toxicology and bioaccumulation modelling, including those described by [25, 27, 35] contribute to the same scientific philosophy. The strongest environmental assessment is that which incorporates chemistry, modelling, toxicology, and relevance to decision-making.

Collectively, the results present an environmental health story for Uvwie LGA. The paper has shown that airborne PAHs are ubiquitous, combustion-intensive, HMW-enriched, seasonally elevated during the dry season, spatially clustered into urban hotspots, and toxicologically relevant to the extent of raising chronic carcinogenic alarm among both the general and the sensitive groups. In theory, the findings are based on the combined logic of the atmospheric fate theory, source modelling, and exposure-risk assessment. Chronic urban combustion sources produce PAH mixtures; meteorology redistributes them; their association with particles extends their relevance to the atmosphere; and their presence in the environment becomes a public-health burden through chronic inhalation. This synthesis is strongly supported by the classic atmospheric literature of [2, 5-7, 36, 37, 39], by empirical urban air studies such as [4, 9-11, 13, 14, 19-21, 33] and by African and Nigerian contextual work, including [15-18, 22, 23, 25, 26, 28-30]. Also, the broader predictive, toxicological, and environmental-risk research you provided, such as [23, 32] on microplastics and nanoparticles and [35, 39] on aquatic hazard profiling, all have conceptual value in highlighting the necessity of holistic, systems-level environmental risk interpretation rather than single-parameter reporting. In that regard, the current research is not a record of PAHs in urban air; it defines Uvwie as a combustion-based atmospheric exposure setting in which persistence, transport, and carcinogenicity are brought to bear on an issue of public health significance.

4. CONCLUSIONS

This paper has established those polycyclic aromatic hydrocarbons in the air in Uvwie Local Government Area is a high urban health issue influenced by the emission of combustion processes, the formation of hotspots, and carcinogenic risk that is quantifiable. It consistently found dominance of high-molecular-weight congeners in the PAH burden and strong enrichment in high-traffic, roadside markets and mixed-use urban corridors, thus demonstrating a strong pyrogenic influence and constant association with particulate matter. The seasonal analysis also showed that the dry season increased total PAH concentrations, benzo[a]pyrene-equivalent burden, and incremental lifetime cancer risk, underscoring the significance of meteorological controls in the accumulation and exacerbation of pollutant exposure. Multivariate analyses reinforced this meaning by demonstrating that the intensity of traffic, the effects of waste burning, and associated city activities were significant in determining pollutant load and toxicity-weighted risk. The clustering, hotspot classification, and sensitivity analysis all showed that exposure was uneven spatially and demographically, with roadside workers, people in traffic, and children at a higher relative risk. In general, this study has good evidence that Uvwie is a combustion-impacted atmospheric environment where the persistence of PAH, transport behaviour, and toxicological implications have a coinciding intersection to form a significant and policy-relevant public health burden.

4. 1. Recommendations

According to the results of this paper, an organised urban air-quality management strategy can be suggested for the Uvwie Local Government Area, and priority should be given to regulating traffic-related emissions, generator burning, roadside waste burning, and other diffuse pyrogenic sources that contribute to PAH loading in the atmosphere. Regular ambient air monitoring must be established in known hotspot areas and during high-risk dry seasons, with particular focus on benzo[a]pyrene and other carcinogenic, high-molecular-weight PAHs as regulatory indicator compounds. Specific interventions to protect the environment, including enforcement of cleaner transport, development of roadside combustion, improved municipal waste management, and education of the population to minimise community-level exposure, should be introduced by environmental protection agencies and local authorities. Since children and occupationally exposed roadside populations were at increased relative risk, protective public health interventions ought to include exposure warnings, urban planning buffers, and occupational health protection for workers in high-contact settings. The current research ought to also be further developed in future research by real-time monitoring, dispersion modelling, biomonitoring and longitudinal exposure-health linkage evaluation, such that the chemical evidence that is produced here may be translated into better regulatory thresholds, preventive action and long-term environmental health policy.

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