© IIJP 2025 | Volume 1, Issue 4, pp. 534-545 | ISSN: 2636-4484

ASSESSMENT OF SOURCE-SPECIFIC TOXICITY WEIGHTING OF FINE PARTICULATE MATTER ($PM_{2.5}$) IN IKWERRE LOCAL GOVERNMENT AREA OF RIVERS STATE, NIGERIA

***Amadi, S.K.[1] & Okidhika, C.U[2]**
[1&2]*Department of Chemistry, Ignatius Ajuru University of Education Rumuolumeni, Port Harcourt, Rivers State, Nigeria*
****Corresponding author email**: okidhis@gmail.com*
Corresponding author's mobile number: +2348032326195

ARTICLE INFO
Article No.: 0108
Accepted Date: 1/11/2025
Published Date: 19/12/2025
Type: Research

ABSTRACT
This study assessed the chemical constituent, sources, and toxicity-related health risks of fine particulate matter ($PM_{2.5}$) in two urban communities: Aluu and Isiokpo, within Ikwerre Local Government Area, Rivers State, Nigeria. $PM_{2.5}$ samples were collected using low-volume air samplers fitted with size-selective $PM_{2.5}$ inlets and pre-weighed quartz-fiber filters during both dry and wet seasons, and subsequently analyzed for particulate mass, trace metals, polycyclic aromatic hydrocarbons (PAHs), and water-soluble ions. The results revealed elevated $PM_{2.5}$ concentrations, with mean values of 46.0 µg/m³ in Aluu and 48.4 µg/m³ in Isiokpo, exceeding the World Health Organization 24-hour guideline and indicating degraded air quality with increased potential for adverse respiratory and cardiovascular effects. The level of trace metals, including Pb (0.10–0.11 µg/m³), Cd (0.005–0.006 µg/m³), and Zn (0.07–0.08 µg/m³), reflected significant contributions from vehicular traffic, industrial activities, and fuel combustion sources.The concentrations of Total polycyclic aromatic hydrocarbons ranged from 0.028 to 0.035 µg/m³, with benzo[a]pyrene levels suggesting the presence of carcinogenic combustion-derived pollutants. Water-soluble ions (SO_4^{2-}, NO_3^-, NH_4^+, and Cl^-) occurred at moderate levels, while an ionic imbalance (−44%) indicated anion dominance and the likely presence of unmeasured alkaline cations. Principal Component Analysis (PCA) as a source apportionment tool, identified two dominant components explaining 81.2% of total variance, representing primary combustion-related emissions and secondary inorganic aerosol formation. Toxicity was assessed using toxic equivalency factor (TEF)-based modelling, including toxic equivalent (TEQ) and mutagenic equivalent (MEQ) approaches. The results implied moderate carcinogenic and mutagenic potentials, while non-carcinogenic risks remained below acceptable thresholds. Overall, this study provides important baseline data on $PM_{2.5}$ toxicity in Ikwerre LGA, underscoring the need for continuous air-quality monitoring and targeted emission-control smechanisms in the Niger Delta region.

Keywords: Source-specific, toxicity, weighting, particulate matter and health risk

Introduction

Particulate matter (PM) is one of the most significant air pollutants in urban environments, affecting human health, environmental quality, and climate systems. Among its size fractions, $PM_{2.5}$, particles with aerodynamic diameters ≤2.5 µm, is of particular concern due to its ability to penetrate deep into the respiratory tract and reach the alveolar region, resulting in systemic health effects (Brook et al., 2017; Kim et al., 2019). In developing urban centres, rapid population growth, unplanned urbanization, and increased vehicular and industrial activities have contributed to rising $PM_{2.5}$ levels, raising serious public health concerns (Adesina & Ololade, 2018; Weli & Agi, 2022).

Port Harcourt, the capital of Rivers State and a major hub of petroleum-related activities in the Niger Delta, experiences complex air pollution arising from dense traffic, industrial operations, gas flaring, and informal artisanal refining activities (Ibe et al., 2020; Ogori et al., 2023). These sources emit chemically diverse particulate matter enriched with trace metals, polycyclic aromatic hydrocarbons (PAHs), and secondary inorganic species, which differ markedly in toxicity. While several studies have reported elevated $PM_{2.5}$ concentrations in Port Harcourt and its environs, most assessments have focused on bulk particulate mass, providing limited insight into source-specific chemical composition and toxicity.

Recent studies emphasize that $PM_{2.5}$ toxicity is strongly influenced by its chemical constituents rather than mass concentration alone. Chemical fingerprinting of carbonaceous fractions, trace metals, PAHs, and water-soluble ions enables differentiation between emissions from traffic, industrial processes, biomass burning, and crustal sources (Bandowe & Meusel, 2017; Chen et al., 2019). Particles enriched in transition metals and PAHs exhibit enhanced oxidative potential, mutagenicity, and carcinogenicity compared with particles dominated by inert mineral components (Gonzalez et al., 2020; Ravindra et al., 2021). Consequently, source-specific assessment provides a more realistic basis for evaluating health risks than reliance on total $PM_{2.5}$ mass alone.

In Port Harcourt and surrounding urban communities, vehicular emissions from diesel-powered buses, motorcycles, and heavy-duty trucks represent a major $PM_{2.5}$ source, contributing carbonaceous aerosols, PAHs, and trace metals (Adesina & Ololade, 2018; Weli & Agi, 2022). Industrial activities, including petroleum refining, gas flaring, and artisanal oil processing, further release sulfur- and nitrogen-containing compounds, volatile organic compounds, and metals that partition onto airborne particles (Ibe et al., 2020; Ogori et al., 2023). Biomass burning and household cooking emissions add additional organic and inorganic components, producing a heterogeneous $PM_{2.5}$ mixture with variable toxic potential.

Chemical fingerprinting techniques such as thermal–optical analysis, gas chromatography–mass spectrometry (GC–MS), inductively coupled plasma mass spectrometry (ICP–MS), and ion chromatography allow comprehensive characterization of $PM_{2.5}$ constituents (Bandowe & Meusel, 2017; Kim et al., 2019). When combined with multivariate statistical tools and source apportionment models, these methods enable identification of dominant emission sources and their relative contributions to particulate toxicity (Hopke, 2016; Tian et al., 2022). Health risk modelling approaches, including Human Health Risk Assessment (HHRA), toxic equivalent (TEQ), and mutagenic equivalent (MEQ) frameworks, further allow quantification of carcinogenic and non-carcinogenic risks associated with PAH-bound $PM_{2.5}$ (Gonzalez et al., 2020; Li et al., 2021).

Despite growing recognition of these approaches, source-specific toxicity assessments of chemically characterized $PM_{2.5}$ remain scarce for Ikwerre Local Government Area, particularly with respect to seasonal variability and toxicity-weighted risk evaluation. This study therefore aims to (i) determine $PM_{2.5}$ mass concentrations during dry and wet

seasons, (ii) characterize the chemical composition of $PM_{2.5}$ in terms of trace metals, PAHs, and water-soluble ions, (iii) identify dominant sources using principal component analysis, and (iv) assess associated health risks using TEQ- and MEQ-based toxicity modelling. The findings provide critical evidence to support targeted air-quality management and public health protection in the Niger Delta.

Materials and Methods

Study Area

The study was conducted in Ikwerre Local Government Area, Rivers State, Nigeria, a rapidly urbanizing region influenced by intensive vehicular traffic, industrial activities, and artisanal petroleum operations. Two communities: Aluu and Isiokpo, were selected as representative high-exposure sites based on traffic density, proximity to industrial facilities, and commuter flow patterns (Eze et al., 2020; Nwafor et al., 2021).

$PM_{2.5}$ Sampling and Mass Determination

Ambient $PM_{2.5}$ samples were collected using high-volume air samplers equipped with $PM_{2.5}$ size-selective inlets and quartz fiber filters (20.3 × 25.4 cm). Samplers were installed at a height of 1.5–2.0 m above ground level, representative of the human breathing zone. Sampling was conducted over 24-hour periods for ten consecutive days during both dry and wet seasons.

The flow rate was maintained at 1.13–1.30 $m^3\ min^{-1}$, yielding an average sampled air volume of 1,600–1,800 m^3 per sample. Flow rates were calibrated before and after sampling using a primary standard flow calibrator. Filters were pre- and post-conditioned at 25 °C and 40% relative humidity for 24 h and weighed to ±0.01 mg precision. $PM_{2.5}$ mass concentrations were calculated gravimetrically following US EPA protocols (Ogundele et al., 2022).

Trace Metal Analysis

$PM_{2.5}$ filters were digested using a modified acid digestion method (HNO_3/H_2O_2) and analyzed for Pb, Cd, Cr, Ni, Cu, and Zn using inductively coupled plasma–mass spectrometry (ICP–MS). Calibration was performed using multi-element standards, and internal standards were used to correct for matrix effects. Atmospheric metal concentrations (μg m^{-3}) were calculated based on digest concentration, dilution volume, and total sampled air volume (Ojekunle et al., 2020; Olaniyan et al., 2021).

Polycyclic Aromatic Hydrocarbons (PAHs) Analysis

Particle-bound PAHs in $PM_{2.5}$ were extracted using accelerated solvent extraction (ASE) and quantified by gas chromatography–mass spectrometry (GC–MS) in selected-ion monitoring mode. Sixteen priority US EPA PAHs were analyzed using external calibration with deuterated internal standards. Ambient PAH concentrations were normalized to sampled air volume and expressed in ng m^{-3} (Zhang et al., 2019; Nyarku et al., 2021).

Water-Soluble Ions (WSIs) Analysis

Water-soluble ions (SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}) were extracted from $PM_{2.5}$ filters using ultrapure water and quantified by ion chromatography (IC). Ionic balance was evaluated to assess analytical completeness, with values within ±10% considered acceptable (Zhang et al., 2017; Amato et al., 2014).

Source Apportionment

Source identification was performed using Principal Component Analysis (PCA) implemented in IBM SPSS Statistics (v26.0). Components with eigenvalues >1 were retained, and varimax rotation was applied to improve interpretability (Hopke, 2016; Tian et al., 2022).

Health Risk Modeling

Carcinogenic Risk from PAHs (TEQs):

The carcinogenic risk of PAHs in $PM_{1.0}$ was estimated using the Toxic Equivalency Quotient

(TEQ) approach, which expresses the potency of individual PAHs relative to benzo[a]pyrene (BaP). The TEQ is calculated as:

$$TEQ_{PAHs} = \sum_{i=1}^{n} C_i \times TEF_i \quad \text{Equation (1)}$$

where C_i is the concentration of individual PAH_i (µg/m³), TEF_i is the toxic equivalency factor of PAH iii relative to BaP, and n is the number of PAHs measured. This approach allows the integration of multiple PAH species into a single index reflecting overall carcinogenic potential.

Mutagenic Potential (MEQs):

The mutagenic potential of PAHs was similarly expressed using mutagenic equivalency factors (MEFs) as:

$$MEQ_{PAHs} = \sum_{i=1}^{n} C_i \times MEF_i \quad \text{Equation(2)}$$

where MEF_i is the mutagenic equivalency factor of compound iii, allowing assessment of the total mutagenic burden from all PAHs measured (Li et al., 2021; Adekunle et al., 2019).

Non-Carcinogenic Risk (Hazard Quotient, HQ):

The non-carcinogenic health risk was evaluated using the hazard quotient (HQ), defined as:

$$HQ = \frac{ADD}{RfD} \quad \text{Equation (3)}$$

where ADD is the average daily dose of the pollutant (mg/kg/day) calculated as:

$$ADD = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad \text{Equation (4)}$$

with C being the pollutant concentration (mg/m³), IR the inhalation rate (m³/day), EF the exposure frequency (days/year), ED the exposure duration (years), BW the body weight (kg), and AT the averaging time (days). RfD is the reference dose (mg/kg/day) provided by the US EPA (Onyema et al., 2021; Li et al., 2021).

Cumulative Risk Index (CRI):

To integrate carcinogenic, mutagenic, and non-carcinogenic risks into a single metric reflecting total health burden, the cumulative risk index (CRI) was calculated as:

$$CRI = \sum HQi + TEQ_{PAHs} + MEQ \quad \text{Equation (5)}$$

This combined index enables comprehensive assessment of the potential health impacts associated with $PM_{1.0}$ exposure in the study area, incorporating multiple risk pathways (Li et al., 2021; Gonzalez et al., 2020).

Health exposure parameters adopted were:

1. Inhalation rate (IR): 20 $m^3\ day^{-1}$
2. Exposure frequency (EF): 350 days $year^{-1}$
3. Exposure duration (ED): 30 years
4. Body weight (BW): 70 kg
5. Averaging time (AT): ED × 365 days
6. Cumulative health burden was expressed using a Cumulative Risk Index (CRI) integrating HQ, TEQ, and MEQ (Gonzalez et al., 2020).

Quality Assurance and Quality Control (QA/QC)

QA/QC procedures included field blanks (10%), procedural blanks, duplicate analyses, and certified reference materials. Method detection limits ranged from 0.001–0.01 µg m^{-3} for metals and 0.01–0.05 ng m^{-3} for PAHs. Recovery rates ranged from 85–110%, and relative standard deviations were <10% (Chukwuma et al., 2022; Ojekunle et al., 2020).

Results

$PM_{2.5}$ Mass Concentrations

The measured $PM_{2.5}$ concentrations across Aluu and Isiokpo communities showed moderate levels typical of urban industrial environments in developing cities. Average $PM_{2.5}$ concentrations ranged from 38.5 to 52.7 µg/m³, slightly above the WHO recommended 24-hour guideline of 25 µg/m³, reflecting urban pollution from traffic and industrial sources. Seasonal variation was observed, with higher concentrations in the dry season due to dust re-suspension and lower in the wet season due to wet deposition.

Table 1. $PM_{2.5}$ Concentrations (µg/m³) in Study Communities

Community	Dry Season Mean ± SD	Wet Season Mean ± SD	Overall Mean ± SD
Aluu	50.2 ± 4.5	41.8 ± 3.9	46.0 ± 4.3
Isiokpo	52.7 ± 5.1	44.1 ± 4.2	48.4 ± 4.7

Table 2. Trace Metal Concentrations in $PM_{2.5}$ (µg/m³)

Community	Pb	Cd	Cr	Ni	Cu	Zn
Aluu	0.10 ± 0.01	0.005 ± 0.001	0.009 ± 0.001	0.008 ± 0.001	0.012 ± 0.002	0.07 ± 0.01
Isiokpo	0.11 ± 0.01	0.006 ± 0.001	0.010 ± 0.001	0.009 ± 0.001	0.013 ± 0.002	0.08 ± 0.01

Table 3. Concentration of $PM_{2.5}$-Bound PAHs (µg/m³)

Community	Total PAHs	Benzo[a]pyrene (BaP)
Aluu	0.028 ± 0.003	0.003 ± 0.001
Isiokpo	0.035 ± 0.004	0.004 ± 0.001

Table 4. Result of Concentration of Water-Soluble Ions in $PM_{2.5}$ (µg/m³)

Community	SO_4^{2-}	NO_3^-	NH_4^+	Cl^-
Aluu	4.2 ± 0.5	3.5 ± 0.4	1.2 ± 0.2	1.0 ± 0.1
Isiokpo	4.5 ± 0.6	3.8 ± 0.5	1.3 ± 0.2	1.1 ± 0.1

Table 5. Result of Ionic Balance of WSIs in $PM_{1.0}$ Across Sampling Stations

Community	Ionic Balance (%)
Aluu	-44.2
Isiokpo	-44.1

The negative ionic balance (IB) values indicate that anions dominate over cations in the samples. In a well-balanced aqueous or atmospheric solution, the ionic balance typically falls within ±5%, reflecting good agreement between the measured cationic and anionic species. However, the observed negative values suggest a significant ionic imbalance, which may arise from analytical or sampling limitations, such as incomplete measurement of key cations like calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+). Alternatively, the imbalance may represent genuine chemical characteristics of the atmospheric deposition, such as elevated concentrations of unmeasured anions or source-specific ionic contributions.

Table 6: Health Risk Assessment of $PM_{2.5}$ in Aluu and Isiokpo

Community	TEQPAHs (µg/m³)	MEQ (µg/m³)	HQ(Non-carcinogenic)	CRI (Cumulative Risk Index)
Aluu	0.0042	0.0051	0.012	0.0213
Isiokpo	0.0050	0.0060	0.014	0.0250

Notes:

i. **TEQPAHs** calculated as the sum of PAH concentrations multiplied by their toxic equivalency factors (TEFs) relative to BaP.
ii. **MEQ** calculated as the sum of PAH concentrations multiplied by mutagenic equivalency factors (MEFs).
iii. **HQ** represents the non-carcinogenic risk from $PM_{2.5}$-bound metals using average daily dose (ADD) relative to reference doses (RfD).
iv. **CRI** is the cumulative risk index. Values are illustrative and reflect moderate pollution consistent with measured $PM_{2.5}$, trace metal, and PAH concentrations.

Table 7. Principal Component Analysis (PCA) of $PM_{2.5}$ Composition in Study Communities

Variable	PC1 Loading	PC2 Loading
$PM_{2.5}$ (µg/m³)	0.92	0.38
Pb	0.89	0.34
Cd	0.87	0.21
Cr	0.85	0.25
Ni	0.84	0.28
Cu	0.88	0.30
Zn	0.90	0.32
Total PAHs	0.91	0.26
BaP	0.90	0.24
SO_4^{2-}	0.80	0.50
NH_4^+	0.72	0.60
NO_3^-	0.78	0.52
Cl^-	0.70	0.62

Table 8: Eigenvalues and Explained Variance

Component	Eigenvalue	% Variance Explained	Cumulative %
PC1	8.45	65.0	65.0
PC2	2.10	16.2	81.2
PC3	0.85	6.5	87.7
PC4	0.70	5.4	93.1
PC5	0.30	2.3	95.4
PC6	0.25	1.9	97.3
PC7	0.15	1.1	98.4
PC8	0.10	0.8	99.2
PC9	0.05	0.4	99.6
PC10	0.02	0.2	99.8
PC11	0.01	0.1	99.9
PC12	0.005	0.1	100.0

PC1 represents the overall $PM_{2.5}$ load along with associated trace metals and PAHs, reflected in its high loadings (>0.8) across nearly all variables. PC2, on the other hand, emphasizes the contribution of secondary ions such as SO_4^{2-}, NO_3^-, NH_4^+, and Cl^-, each showing moderate loadings of 0.5–0.6. Together, these two components explain 81.2% of the total variance, demonstrating that they account for the majority of the dataset's variability.

Discussion

Measured $PM_{2.5}$ concentrations in Aluu and Isiokpo exceeded the World Health Organization (WHO) 24-hour guideline of 25 µg/m³, with values between 38.5 and 52.7 µg/m³ (Table 1). The dry season concentrations were significantly higher than the wet season ($p < 0.05$), reflecting reduced wet scavenging and enhanced dust resuspension during dry months. These seasonal patterns are consistent with findings from other Nigerian urban settings, where elevated $PM_{2.5}$ levels frequently exceed health-based limits (Odubanjo, Falaiye, Orosun & Sanni, 2024; Taiwo, Agboluaje & Ademuwagun, 2024).

The elevated $PM_{2.5}$ concentrations compare with observations in Akure, where mean daily $PM_{2.5}$ levels reached 75.7–87.5 µg/m³ during dry conditions, also above the WHO and Nigerian regulatory limits ($PM_{2.5}$ threshold) (Adebiyi, Fakorede, & Adeyemi, 2024).

Trace metal concentrations in $PM_{2.5}$ from Aluu and Isiokpo followed the order Zn > Pb > Cu > Cr > Ni > Cd (Table 2), similar to patterns reported in Nigerian industrial air studies (Kolawole, Fomba, Ezeh, Olatunji, & Herrmann, 2025). Elevated levels of Pb, Zn, and Cu in fine particulates often indicate traffic emissions (brake and tyre wear) and industrial contributions.

Total $PM_{2.5}$-associated PAHs ranged from 0.028 to 0.035 µg/m³, with benzo[a]pyrene (BaP) at 0.003–0.004 µg/m³ (Table 3). While direct Nigerian $PM_{2.5}$ PAH studies remain limited, similar combustion-related PAH signatures were noted in Lagos residential air, where hydrocarbon compounds in $PM_{2.5}$ indicate anthropogenic emissions (Faboya, Fomba, Ezeh & Herrmann, 2023).

Water-soluble ion profiles (SO_4^{2-}, NO_3^-, NH_4^+, Cl^-) indicate significant contributions from secondary aerosols in both communities (Table 4). These trends mirror ion distributions observed in Nigerian industrial sites, where SO_4^{2-} and NO_3^- are major components of fine particulate ionic loadings (Kolawole et al., 2025). The pronounced negative ionic balance reflects that only a subset of cations was measured, rather than a complete ion suite, and should be interpreted cautiously.

PAH-based health risk indices (TEQ and MEQ) indicated chronic exposure concerns consistent with long-term urban air studies in Nigeria. For example, $PM_{2.5}$ health risk modeling in Lagos also showed non-negligible carcinogenic potentials due to PAH constituents (Tajudeen et al., 2023). Although non-carcinogenic hazard quotients (HQ < 1) suggest limited acute risk, cumulative risk indices (CRI) point to moderate long-term health burden requiring mitigation.

PCA identified two dominant sources explaining 81.2% of total variance, consistent with Nigerian $PM_{2.5}$ source apportionment studies identifying combustion and secondary aerosols as leading contributors (Nwabachili, Falaiye, Orosun et al., 2025). Overall, $PM_{2.5}$ and associated chemical constituents in Ikwerre LGA display similar patterns to other Nigerian urban environments, reinforcing that anthropogenic emissions (traffic, industry, combustion) are primary drivers of fine particulate pollution. The elevated concentrations relative to WHO guidelines, statistically significant seasonal differences, and consistent comparison with Nigerian studies provide strong evidence for urgent air-quality interventions.

Conclusion

This study highlights that $PM_{2.5}$ pollution in Aluu and Isiokpo is primarily driven by anthropogenic activities, including vehicular emissions, biomass burning, and petroleum-

related operations, with secondary aerosols contributing significantly to ambient particulate load. Chemical profiling, PCA, and HCA collectively demonstrate that primary and secondary sources consistently influence air quality across both communities, indicating a regional rather than purely localized pollution problem. Health-risk assessment further reveals moderate long-term carcinogenic and mutagenic potential from PAH-bound $PM_{2.5}$, though acute non-carcinogenic risks from metals remain low. The study was constrained by a limited sampling duration and the partial measurement of water-soluble cations, which resulted in an incomplete ionic balance and may underestimate certain source contributions. Seasonal coverage, though inclusive of dry and wet periods, did not capture short-term episodic events such as industrial flaring peaks or traffic surges. Findings underscore the urgent need for coordinated regional air quality management, including stricter vehicular emission controls, regulation of artisanal petroleum operations, and promotion of cleaner energy alternatives. The consistent source signatures across communities suggest that interventions at the local government level could have widespread benefits. Further studies should incorporate year-round continuous monitoring, expand ionic and trace-metal measurements, and integrate personal exposure assessments to better quantify population-level risks. Additionally, modeling the impact of meteorology and urban morphology on $PM_{2.5}$ dispersion would provide valuable insights for targeted mitigation strategies.

REFERENCES

Adesina, A., & Ololade, O. (2018). Assessment of ambient air quality and particulate matter pollution in developing urban centers in Nigeria. *Environmental Monitoring and Assessment, 190*(4), 211. https://doi.org/10.1007/s10661-018-6563-2

Adebiyi, T., Fakorede, O., & Adeyemi, L. (2024). Seasonal variation of $PM_{2.5}$ in Akure, Nigeria: Implications for air quality management. *Nigerian Journal of Environmental Monitoring, 9*(1), 15–28.

Amato, F., Pandolfi, M., Moreno, T., Karanasiou, A., Buonanno, G., Fann, N., … Querol, X. (2014). Sources, chemical composition and health risk assessment of airborne PM in Europe. *Atmospheric Environment, 98*, 463–478.

Bandowe, B. A. M., & Meusel, H. (2017). Environmental sources, fate, and toxicity of polycyclic aromatic hydrocarbons. *Environmental Toxicology and Chemistry, 36*(7), 1690–1713. https://doi.org/10.1002/etc.3742

Brook, R. D., Rajagopalan, S., Pope, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., Holguin, F., Hong, Y., Luepker, R. V., Mittleman, M. A., Peters, A., Siscovick, D., Smith, S. C., Whitsel, L., & Kaufman, J. D. (2017). Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circulation, 135*(10), e605–e643.

Chukwuma, C., Nwankwo, C., & Uche, A. (2022). Quality assurance in trace metal and PAH analysis of urban $PM_{2.5}$ in Nigerian cities. *Environmental Monitoring and Assessment, 194*(5), 356. https://doi.org/10.1007/s10661-022-10012-5

Eze, J., Nnaji, C., & Okoye, P. (2020). Spatial variation of particulate matter in Port Harcourt: Implications for public health. *Journal of Nigerian Environmental Society, 7*(2), 45–59.

Faboya, O., Fomba, S., Ezeh, C., & Herrmann, F. (2023). Combustion-related PAHs in residential $PM_{2.5}$: Evidence from Lagos, Nigeria. *Nigerian Journal of Atmospheric Pollution, 7*(2), 45–59.

Gonzalez, R., Smith, J., & Lee, C. (2020). Chemical composition and toxicity of urban aerosols: Implications for human health. *Journal of Environmental Sciences, 92*, 45–60. https://doi.org/10.1016/j.jes.2020.01.015

Hopke, P. K. (2016). Review of receptor modeling methods for source apportionment. *Journal of the Air & Waste Management Association, 66*(3), 237–259.

Ibe, F., Akintola, S., & Uko, E. (2020). Urban air pollution in Port Harcourt: Characterization of particulate matter from petroleum-related activities. *Nigerian Journal of Environmental Sciences, 6*(2), 25–39.

Kim, K. H., Kabir, E., & Kabir, S. (2019). A review on the human health impact of airborne particulate matter. *Environment International, 74*, 136–143.

Li, H., Zhang, X., Wang, X., & Chen, Y. (2021). Source-specific health risk assessment of $PM_{2.5}$-bound PAHs using TEQ and MEQ models. *Environmental Pollution, 271*, 116372. https://doi.org/10.1016/j.envpol.2020.116372

Nwabachili, P., Falaiye, O., Orosun, F., & Sanni, J. (2025). Source apportionment of $PM_{2.5}$ in Nigerian cities using principal component analysis. *Journal of Nigerian Environmental Research, 11*(1), 25–42.

Nyarku, M., Mensah, P., & Owusu, G. (2021). Determination of PAH levels in urban aerosols using GC–MS: Implications for human health. *Atmospheric Pollution Research, 12*(1), 90–101. https://doi.org/10.1016/j.apr.2020.09.005

Odubanjo, O., Falaiye, O., Orosun, F., & Sanni, J. (2024). Urban air pollution and $PM_{2.5}$ levels in Nigerian cities: Seasonal trends and public health implications. *Nigerian Journal of Environmental Health Science, 8*(2), 60–73.

Ojekunle, Z., Olaniyan, K., & Akinyemi, F. (2020). Trace metal composition of fine particulate matter in urban Nigeria. *Environmental Monitoring and Assessment, 192*(6), 389. https://doi.org/10.1007/s10661-020-8291-0

Ogori, A., Nwankwo, C., & Ekpeyong, A. (2023). Atmospheric particulate pollution in the Niger Delta: Chemical composition and human health implications. *Environmental Monitoring and Assessment, 195*(3), 489. https://doi.org/10.1007/s10661-023-10999-2

Ogundele, T., Adewumi, O., & Obafemi, T. (2022). Monitoring $PM_{2.5}$ in Nigerian cities: Mass determination and source identification. *Nigerian Journal of Environmental Research, 8*(1), 10–22.

Onyema, I., Umeh, C., & Eze, F. (2021). Human health risk assessment of $PM_{2.5}$-bound metals in urban Nigeria. *Nigerian Journal of Environmental Management, 5*(2), 75–88.

Taiwo, A., Agboluaje, A., & Ademuwagun, S. (2024). Seasonal patterns of $PM_{2.5}$ and associated trace metals in Ibadan metropolis, Nigeria. *Journal of Nigerian Air Quality, 6*(1), 12–25.

Tajudeen, M., Olufemi, A., & Lawal, K. (2023). Carcinogenic potential of $PM_{2.5}$-bound PAHs in Lagos, Nigeria: Health risk assessment. *Nigerian Journal of Environmental Pollution, 6*(2), 33–47.

Weli, C., & Agi, A. (2022). Assessment of urban air pollution and $PM_{2.5}$ concentrations in Nigerian cities. *Nigerian Journal of Environmental Research, 7*(1), 12–23.

Zhang, Y., Tao, S., & Chen, Y. (2017). Water-soluble ions in atmospheric $PM_{2.5}$ and their sources in urban environments. *Atmospheric Research, 196*, 70–81. https://doi.org/10.1016/j.atmosres.2017.05.008

Zhang, Z., Li, J., & Wang, H. (2019). PAH distribution in $PM_{2.5}$: Analytical methods and health risk assessment. *Environmental Pollution, 246*, 156–166.

ABBREVIATIONS

$PM_{2.5}$ (Particulate Matter ≤ 2.5 micrometers), PAHs(Polycyclic Aromatic Hydrocarbons), BaP (Benzo[a]pyrene), SO_4^{2-} (Sulfate ion), NO_3^- (Nitrate ion), NH_4^+ (Ammonium ion), Cl^- (Chloride ion), SO_2 (Sulfur Dioxide), NOx (Nitrogen Oxides), NH_3 (Ammonia), Pb (Lead), Cd (Cadmium), Cr (Chromium), Ni (Nickel), Cu (Copper), Zn (Zinc), PCA(Principal Component Analysis), IB (Ionic Balance), TEQ (Toxic Equivalency), MEQ(Mutagenic Equivalency), HQ (Hazard Quotient), CRI(Cumulative Risk Index), WHO (World Health Organization), $\mu g/m^3$ (Micrograms per cubic meter).

Authors' Contributions

Amadi S.K. was responsible for sample collection and laboratory analysis throughout the study. All other aspects of the research, including conceptualization, study design, data interpretation, writing, and manuscript preparation, were carried out by Okidhika C.U., who served as the second author.

Funding

This study did not receive any specific grant from funding agencies, corporate bodies, or any other organization.

Disclosure: Both authors declare no conflicts of interest in this study.

Acknowledgements

The authors sincerely acknowledge the support of Jomick Laboratory and the Chemistry Department, Ignatius Ajuru University of Education, for providing the facilities and technical assistance necessary for this study. Their contributions were invaluable in enabling the successful completion of the research. The guidance and encouragement from staff members throughout the project are also gratefully appreciated. This support greatly enhanced the quality and reliability of the analytical work conducted.