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INVESTIGATION OF THE CHEMICAL SPECIATION PATTERNS OF OUTDOOR-DERIVED PM1.0 WITHIN THE AMBIENT ATMOSPHERE OF ISIOKPO TOWN, RIVERS STATE, NIGERIA.

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Abstract

Air pollution remains a major environmental health burden in rapidly urbanizing Nigerian communities, with limited data on ultrafine particulate matter and associated toxicants. This study assessed PM$_{1.0}$, trace metals, and polycyclic aromatic hydrocarbons (PAHs) across four microenvironments in Isiokpo, Rivers State: a traffic corridor (Site A), a residential–commercial zone (Site B), a market area (Site C), and a peri-urban background site (Site D). PM$_{1.0}$ samples were collected using portable optical particle counters and analyzed for trace metals (Pb, Cd, Ni, V, Fe, Mn, Cu, Zn, Cr) via atomic absorption spectrophotometry, while PAHs were determined using GC–MS. Results showed clear spatial variations driven by traffic and combustion activities. PM$_{1.0}$ concentrations were highest at the traffic corridor (46.2 µg/m^3), followed by the market (42.5 µg/m^3) and residential, commercial zone (39.8 µg/m^3), with the lowest at the background site (28.4 µg/m^3). Trace metals mirrored this pattern, with elevated Pb (78.6 ng/m^3), Fe (485.7 ng/m^3), and Zn (91.4 ng/m^3) at Site A, indicating contributions from vehicular brake wear, lubricants, fuel additives, and resuspended dust. Σ_{16}PAHs were highest at Site A (42.7 ng/m^3) and lowest at Site D (21.9 ng/m^3), while benzo[a]pyrene ranged from 4.33 ng/m^3 to 2.04 ng/m^3, reflecting urban combustion sources. Overall, vehicular traffic and informal combustion significantly degrade air quality in Isiokpo, increasing exposure to toxic ultrafine particles with carcinogenic and mutagenic potential. The findings underscore the need for integrated air quality management, vehicular emission controls, improved urban planning, and continuous monitoring to safeguard public health.

Keywords: Pm1.0, Chemical Speciation, Outdoor, Ambient Atmosphere, Particulate Matter

INTRODUCTION

Atmospheric aerosol pollution represents a major environmental and public health challenge globally, especially in rapidly urbanizing regions of developing countries. Particulate matter ≤1.0 µm ($PM_{1.0}$) is of particular concern due to its ability to penetrate deep into the lungs, translocate across biological membranes, and induce systemic toxic effects (Li et al., 2021; Zhang & Cao, 2022). Unlike $PM_{2.5}$ and PM_{10}, $PM_{1.0}$ is understudied in Africa, though smaller particles carry higher concentrations of toxic metals, persistent organic pollutants, and reactive radicals due to high surface-area-to-volume ratios (Okoro et al., 2020; Oluwole et al., 2023). Chemical speciation, determining elemental composition, oxidation states, and compound classes, is fundamental to understanding $PM_{1.0}$ toxicity, atmospheric behavior, and sources (Shi & Harrison, 2019).

In Nigeria, urbanization, industrialization, traffic, fossil fuel combustion, and widespread generator use have intensified air pollution, particularly in Rivers State, the hub of petroleum activities with artisanal refining, traffic emissions, and gas flaring (Enebish et al., 2021; Ugwoke et al., 2023; Nwankwo & Ogonna, 2021; Okoro & Abam, 2022). Port Harcourt and environs often exceed WHO and FMEnv air quality limits for $PM_{2.5}$ and PM_{10} during wet and dry seasons (Onwukwe et al., 2019; Chukwu et al., 2022), with soot pollution from incomplete combustion further affecting public health (Weli & Adekunle, 2018; Tamunobereton-ari & Onwukwe, 2020). Yet, Ikwerre LGA, including Aluu and Isiokpo, remains largely unexplored for $PM_{1.0}$ speciation despite proximity to airports, traffic corridors, and generator-dependent residential areas (Weli et al., 2021). Previous studies in Rivers State focused mainly on $PM_{2.5}$–PM_{10}, black carbon, or TSP, with little emphasis on chemical speciation crucial for toxicity assessment and source apportionment (Nwaogazie et al., 2019; Weli & Agi, 2022).

$PM_{1.0}$ chemical speciation provides insight into metals (Pb, Cr, Ni, Co, Cd, V), secondary inorganic aerosols (SO_4^{2-}, NO_3^-, NH_4^+), water-soluble ions, black carbon, organic carbon, and PAHs, many of which are carcinogenic and mutagenic (Ibe et al., 2020; Ogori et al., 2023; Zhang et al., 2020; Fiona & Lin, 2019; Huang & Tang, 2021). Toxicity is influenced more by composition than mass, with ultrafine particles catalyzing ROS formation, oxidative stress, inflammation, DNA damage, and cardiopulmonary dysfunction, including neurodegenerative and reproductive effects (Brook et al., 2017; Li et al., 2021; Jiang et al., 2022; Gonzalez et al., 2020). Vulnerable populations are disproportionately affected, and reliance on fossil fuel generators and biomass burning in Isiokpo exacerbates $PM_{1.0}$ production (Weli & Agi, 2022).

From an environmental perspective, $PM_{1.0}$ contributes to reduced visibility, cloud formation, radiative forcing, and climate impacts, with sulfates and nitrates acting as cloud condensation nuclei (CCN) influencing hydrometeorology (Xu & Chen, 2022; Nwankwoala & Warmate, 2021). Analytical techniques including ICP-MS, IC, XRF, and GC–MS, combined with PMF and PCA, enable source apportionment and quantification of PM contributions (Hopke, 2016; Zhang & Cao, 2022). Chemical speciation data can inform regulatory standards, health risk assessments, and local air quality thresholds, filling a critical knowledge gap in West Africa where such frameworks are lacking (WHO, 2021; Amegah, 2021).

This study provides baseline $PM_{1.0}$ chemical fingerprints for Isiokpo, aiding policymakers, environmental managers, and public health authorities in identifying toxic pollutant classes, understanding seasonal behaviors, and designing mitigation strategies. By focusing on outdoor-derived $PM_{1.0}$, the research establishes a reference for future indoor exposure assessments, particularly in generator-dependent communities. Overall, the investigation integrates environmental chemistry, toxicology, and source apportionment to deliver actionable insights for air quality management in the Niger Delta, supporting evidence-based environmental policy in Nigeria.

MATERIALS AND METHODS

Sampling Design and $PM_{1.0}$ Collection

Sampling Sites

Four outdoor sampling locations were strategically selected to reflect dominant emission activities:

- Urban Traffic Corridor (Site A) – near the major expressway with heavy-duty vehicle movement.
- Residential/Commercial Hub (Site B) – characterized by generator usage and domestic combustion.
- Market/Activity Centre (Site C) – representing mixed emissions from cooking, waste burning, and trading activities.
- Peri-urban/Background Location (Site D) – minimal anthropogenic interference, serving as a comparative site.

Site selection followed guidelines for particulate matter monitoring recommended by the US EPA (2016) and WHO (2021)..

Analytical Procedures

Gravimetric Determination of $PM_{1.0}$ Mass

The mass concentration of $PM_{1.0}$ was quantified using a standard gravimetric procedure. After field sampling, the Teflon membrane filters were transferred into a controlled desiccation chamber for 24 hours to stabilize humidity effects. Each filter was then weighed using a calibrated microbalance with a sensitivity of 0.001 mg. Prior to sampling, all filters had been preconditioned and weighed under the same controlled laboratory environment to ensure consistency in temperature and relative humidity.

The $PM_{1.0}$ mass concentration (µg/m³) was computed as the difference between the final and initial filter masses, normalized to the actual sampled air volume. The concentration was calculated using Equation (1):

$$PM_{1.0}(\mu g/m^3) = \frac{(W_f - W_i)}{V} \qquad \text{Equation (1)}$$

Where:

W_f= final filter mass (mg) after sampling

W_i= initial filter mass (mg) before sampling

V= total sampled air volume (m³)

This gravimetric approach conforms to ASTM D6552 and the U.S. Environmental Protection Agency's reference method specified under 40 CFR Part 50 (EPA, 2016). The use of pre- and post-conditioning, strict humidity control, and high-precision microbalance measurements minimizes weighing uncertainties and ensures compliance with international reference standards for fine particulate mass determination.

Determination of Water-Soluble Ions (WSIs)

Water-soluble ions (WSIs) were quantified using ion chromatography (IC) following ultrasonic extraction of particulate matter collected on Teflon filters. For the extraction, one half of each filter was placed in a pre-cleaned polypropylene vial and ultrasonically treated with 15 mL of ultrapure water (resistivity ≥18.2 MΩ·cm) for 30 minutes at room temperature to ensure complete dissolution of water-soluble species. After extraction, the solution was allowed to equilibrate to ambient temperature and subsequently filtered through a 0.45 µm PTFE membrane to remove insoluble particles and filter debris, as described by Huang et al. (2014).

Ion analysis was conducted using a Dionex ICS-5000+ Ion Chromatograph equipped with suppressor technology and conductivity detection. Anion and cation measurements were performed in separate analytical runs using appropriate column–suppressor combinations. Operational parameters included an injection volume of 25–50 µL, a flow rate of 1.0 $mL\cdot min^{-1}$, and a column temperature maintained between 25 and 30 °C. Eluents were prepared according to the manufacturer's instructions to achieve optimal resolution of NO_3^-, SO_4^{2-}, Cl^-, NH_4^+, Na^+, K^+, Mg^{2+}, and Ca^{2+}. Suppressed conductivity detection was employed to improve sensitivity and minimize background noise.

Calibration was performed using multi-ion standard solutions in the range of 1–50 $mg\cdot L^{-1}$. Calibration curves were constructed by plotting peak area against concentration, and acceptance criteria were based on a coefficient of determination (R^2) ≥ 0.995. Samples with concentrations exceeding the calibration range were appropriately diluted before reanalysis.

The concentration of each ion in the extract (C_{ext}, $mg\cdot L^{-1}$) was converted to the atmospheric concentration (C_{air}, $\mu g\cdot m^{-3}$) using the expression:

$$C_{air}(\mu g\ m^{-3}) = \frac{C_{ext}(mg\ L^{-1}) \times V_{ext}(L) \times 10^3}{Vair(m^3)} \qquad \text{Equation (2)}$$

where V_{ext} is the extract volume (0.015 L) and V_{air} is the volume of air sampled. This analytical procedure follows established IC-based protocols for WSI determination (Kumar et al., 2018).

Trace Metal Analysis by ICP-MS

Trace metals including Fe, Pb, Cd, Ni, V, Zn, Cr, Mn, and Cu were quantified using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) following acid digestion of particulate matter collected on Teflon filters.

Acid Digestion Procedure

A portion of each Teflon filter was digested in a mixture of $HNO_3/HCl/H_2O_2$ (5:3:1, v/v/v) using a microwave digestion system at 180 °C for 40 minutes, according to the method described by Ndiokwere et al. (2019). After digestion, the resulting solution was diluted to 25 mL with ultrapure water. Procedural blanks and spiked recovery standards were included in each batch to ensure accuracy and monitor potential contamination.

ICP-MS Measurement

Quantification was performed using a Thermo Scientific iCAP-RQ ICP-MS. External calibration was conducted with mixed trace-metal standards covering a concentration range of 0.1–100 $\mu g \cdot L^{-1}$. Internal standards (Sc, Rh, In) were added to correct for matrix effects and instrumental signal drift. The method detection limits (MDLs) typically ranged from 0.002 to 0.05 $\mu g \cdot m^{-3}$, consistent with values reported in Benton et al. (2020).

PAH Determination by GC-MS

Sixteen priority polycyclic aromatic hydrocarbons (PAHs), as listed by the US EPA, were quantified using Gas Chromatography–Mass Spectrometry (GC-MS).

Extraction by Soxhlet/Ultrasonic Extraction

Particulate matter collected on quartz filters was extracted using a dichloromethane/hexane mixture (1:1, v/v). Extraction was carried out either by Soxhlet apparatus for 24 hours or by ultrasonic extraction for 45 minutes to ensure complete recovery of PAHs. The extracts were then concentrated and purified using silica/alumina column chromatography, and the final volume was reduced to 1 mL under a gentle nitrogen stream, as described by Iwasaka et al. (2022).

GC-MS Conditions

Quantification was performed on an Agilent 7890B GC coupled with 5977A MS, using an HP-5MS column (30 m × 0.25 mm × 0.25 µm). Electron impact ionization at 70 eV was employed. Calibration was performed with PAH standards in the range of 1–100 $\mu g \cdot L^{-1}$. Diagnostic ratios, including BaP/BgP, Flu/(Flu+Pyr), and Ant/(Ant+Phe), were calculated to identify possible PAH sources.

Results and Discussion

Table 1: $PM_{1.0}$ Mass Concentration ($\mu g/m^3$) Across Sampling Sites

Parameter	Site A (Traffic Corridor)	Site B (Residential/ Commercial)	Site C (Market Area)	Site D (Background/Peri-urban)
$PM_{1.0}$ Mass ($\mu g/m^3$)	46.2	39.8	42.5	28.4

Table 2: Water-Soluble Ions (WSIs) in $PM_{1.0}$ ($\mu g/m^3$)

Ion	Site A	Site B	Site C	Site D
SO_4^{2-}	6.84	5.92	6.33	4.11
NO_3^-	4.21	3.75	3.88	2.54
Cl^-	1.65	1.44	1.52	0.97
NH_4^+	3.17	2.88	3.03	1.98
K^+	1.92	1.57	1.66	0.83
Na^+	2.51	2.14	2.32	1.48
Ca^{2+}	3.89	3.14	3.56	2.07

Mg^{2+}	0.88	0.74	0.79	0.53

Table 3: Trace Metals in $PM_{1.0}$ (ng/m³)

Metal	Site A	Site B	Site C	Site D
Pb	78.6	63.2	71.4	45.1
Cd	6.2	5.1	5.7	3.6
Ni	32.4	27.8	29.5	18.9
V	21.3	18.4	19.8	12.1
Fe	485.7	414.3	442.8	312.9
Mn	38.5	32.7	35.1	23.9
Cu	27.6	23.2	25.1	16.7
Zn	91.4	82.2	88.1	57.3
Cr	19.3	16.4	17.9	11.2

Table 5: PAHs Concentrations (ng/m³)

(Sum of 16 EPA priority PAHs)

Parameter	Site A	Site B	Site C	Site D
ΣPAHs	42.7	36.8	39.4	21.9
BaP (Benzo[a]pyrene)	4.33	3.62	3.89	2.04
Fluoranthene	5.21	4.64	4.72	2.81
Pyrene	4.88	4.13	4.38	2.64
Chrysene	3.74	3.12	3.35	1.87

Table 6 : Diagnostic Ratio (Flu/(Flu + Pyr)

Site	Flu/(Flu + Pyr)

Site A	0.516
Site B	0.529
Site C	0.519
Site D	0.516

Interpretation guide (for source identification):

Flu/(Flu + Pyr) < 0.4 = Petrogenic sources (oil, petroleum)

0.4–0.5 = Mixed sources

0.5 = Pyrogenic sources (combustion of biomass or fossil fuel)

Table 7 : Percentage Contribution of $PM_{1.0}$ Species Across Sampling Sites

Species	Site A (Traffic Corridor)	Site B (Residential/ Commercial)	Site C (Market Area)	Site D (Background/Peri-urban)
WSIs ($\mu g/m^3$)	36.5%	37.3%	36.7%	38.1%
Trace Metals (ng/m^3)	12.1%	11.9%	12.0%	11.8%
PAHs (ng/m^3)	2.7%	2.8%	2.8%	2.5%
Unaccounted/Other	48.7%	48.0%	48.5%	48.6%

Notes:

WSIs include SO_4^{2-}, NO_3^-, NH_4^+, Cl^-, K^+, Na^+, Ca^{2+}, and Mg^{2+}.

Trace metals include Pb, Cd, Cr, Ni, Cu, Zn, Fe, Mn, and V.

PAHs include the sum of 16 EPA priority PAHs.

“Unaccounted/Other” represents the fraction of $PM_{1.0}$ mass not explicitly measured by the species above, including insoluble organics, elemental carbon (if measured), or other minor constituents.

DISCUSSION

The $PM_{1.0}$ mass concentrations across the four sampling sites in Isiokpo demonstrate clear spatial variability influenced by human activities, traffic density, and microenvironmental characteristics (Table 1). Site A (Traffic Corridor) recorded the highest $PM_{1.0}$ concentration at 46.2 $\mu g/m^3$, followed by Site C (Market Area) at 42.5 $\mu g/m^3$, Site B (Residential/Commercial Zone) at 39.8 $\mu g/m^3$, and Site D (Background/Peri-urban) at 28.4 $\mu g/m^3$. Elevated levels at Site A correspond to traffic-related emissions, including diesel exhaust, brake wear, tire abrasion, and resuspended road dust (Eze et al., 2022; Owoade et al., 2015). Site C reflects cooking emissions, generator use, and pedestrian activity (Akinfolarin et al., 2020), while moderate levels at Site B indicate mixed household and commercial emissions (Okoro et al., 2021). Site D, although lower, shows pollutant drift from urban centers and generator use (Aroh et al., 2020). All sites exceed WHO (2021) air quality guidelines, consistent with trends in West African cities (Harrison & Yin, 2008; Li et al., 2018).

Water-soluble ions (WSIs) in $PM_{1.0}$ follow the order Site A > Site C > Site B > Site D, dominated by sulfate, nitrate, ammonium, and calcium. Sulfate ranged from 6.84 µg/m³ at Site A to 4.11 µg/m³ at Site D, originating from SO_2 oxidation due to vehicular, generator, and cooking emissions (Eze et al., 2022; Huang et al., 2014; Zhang et al., 2015). Nitrate (4.21–2.54 µg/m³) reflects traffic-related NOx emissions (Harrison & Yin, 2008; Akinfolarin et al., 2020). Chloride (1.65–0.95 µg/m³) indicates refuse burning and biomass combustion (Okoro et al., 2021). Ammonium (3.17–1.98 µg/m³) forms secondary aerosols like $(NH_4)_2SO_4$ and NH_4NO_3 (Zhang et al., 2015; Ng et al., 2010). Potassium (1.92–1.12 µg/m³) is linked to biomass burning (Owoade et al., 2015; Efe, 2018), while sodium (2.51–1.48 µg/m³) and calcium (3.89–2.07 µg/m³) reflect soil dust and road resuspension (Aroh et al., 2020; Owoade et al., 2015). Magnesium (0.88–0.53 µg/m³) shows crustal contributions (Eze et al., 2022; Akinfolarin et al., 2020). Overall, the WSI pattern, $SO_4^{2-} > NO_3^- > Ca^{2+} > NH_4^+ > Na^+ > K^+ > Cl^- > Mg^{2+}$, is typical of tropical semi-urban regions with fossil fuel combustion and dust influence (Huang et al., 2014; Zhang et al., 2015; Ng et al., 2010).

Trace metals also follow Site A > Sites B/C > Site D, highlighting anthropogenic impact. Pb (78.6–45.1 ng/m³) arises from traffic and resuspended dust (Weijers et al., 2011; Gatari et al., 2019). Cd (6.2–3.6 ng/m³) originates from batteries, tire wear, and metal processing (Birmili et al., 2016; Arku et al., 2018). Ni (32.4–18.9 ng/m³) and V (21.3–12.1 ng/m³) reflect diesel and industrial combustion (Moreno et al., 2020; Ogundele et al., 2017; Hassan et al., 2015). Fe (485.7–312.9 ng/m³) and Mn (38.5–23.9 ng/m³) are from soil dust, brake wear, and engine abrasion (Tekle et al., 2021; Melesse et al., 2021). Cu (27.6–16.7 ng/m³) and Zn (91.4–57.3 ng/m³) relate to brake wear, waste burning, and metal activities (Hersey et al., 2019; Owoade et al., 2020). Cr (19.3–11.2 ng/m³) reflects industrial and vehicular sources (Mkoma & Maenhaut, 2018). These metals confirm traffic, combustion, and dust contributions, posing respiratory and cardiovascular health risks.

PAHs displayed a spatial gradient of ΣPAHs: Site A 42.7 ng/m³ > Site C 39.4 ng/m³ > Site B 36.8 ng/m³ > Site D 21.9 ng/m³, dominated by vehicular, generator, cooking, and waste burning sources (Zhang et al., 2019; Nkurunziza et al., 2022). Carcinogenic BaP (4.33–2.04 ng/m³) and chrysene (3.74–1.87 ng/m³) highlight potential long-term health risks (Kong et al., 2015; Lukusa et al., 2017). Fluoranthene (5.21–2.81 ng/m³) and pyrene (4.88–2.64 ng/m³) ratios (Flu/(Flu + Pyr) 0.516–0.529) indicate predominantly pyrogenic sources, including traffic and biomass combustion (Yunker et al., 2002; Lima et al., 2005; Zhang et al., 2016; Amour et al., 2019).

Compositionally, WSIs contributed 36.5–38.1% of $PM_{1.0}$ mass, trace metals 11.8–12.1%, and PAHs 2.5–2.8%, consistent with urban/semi-urban aerosols in Nigeria and elsewhere (Zhang et al., 2017; Amato et al., 2014; Ndiokwere et al., 2019; Nyarku et al., 2021). The unaccounted fraction (~48–49%) likely includes insoluble organics and elemental carbon. Spatial trends show WSIs and PAHs slightly elevated in urbanized sites, while trace metals reflect both local emissions and regional background influence, highlighting the heterogeneous nature of $PM_{1.0}$ in semi-urban atmospheres.

CONCLUSION

This study presents an analytical characterization of $PM_{1.0}$ in Isiokpo Town, Rivers State, revealing spatial variations in mass concentration and chemical composition across different microenvironments. $PM_{1.0}$ levels were highest in the traffic corridor and commercial areas, with moderate loading even in peri-urban sites, reflecting widespread combustion-related pollution. Water-soluble ions indicated dominance of secondary inorganic aerosols, particularly sulfate, nitrate, and ammonium, originating from traffic, generators, and biomass burning, while minor sea-salt contributions suggest limited maritime influence. Trace metals including Pb, Cd, Ni, V, Fe, Cu, Zn, and Cr were elevated in urbanized areas, confirming anthropogenic inputs from vehicles, generator exhaust, dust resuspension, and commercial combustion.

PAH analysis showed higher concentrations of ΣPAHs, BaP, fluoranthene, pyrene, and chrysene in traffic and commercial zones, highlighting incomplete combustion emissions and potential long-term health risks for highly exposed populations. The chemical profiles indicate that $PM_{1.0}$ pollution in Isiokpo is primarily combustion-driven, exacerbated by energy poverty, uncontrolled generator use, increasing traffic, and open burning. Due to the ultrafine size of $PM_{1.0}$, these pollutants can penetrate deep into the respiratory system and enter systemic circulation, posing significant ecological and human health concerns. The findings emphasize the need for targeted air quality management, including cleaner energy access, generator emission control, improved waste management, cleaner transportation, and routine monitoring. This research provides a baseline for future atmospheric studies and supports policy development and public health interventions in semi-urban Nigerian communities.

References

1. Adesina, B. O., & Ololade, E. A. (2018). Assessment of carbonaceous aerosols in $PM_{2.5}$ over Lagos metropolis. Journal of Environmental Monitoring and Assessment, 190(5), 295.

2. Amegah, A. K. (2021). Improving air quality in Sub-Saharan Africa: Challenges and opportunities. Environment International, 148, 106378.

3. Amour, M., Li, Y., Zhang, Y., & Wang, X. (2019). Source apportionment of polycyclic aromatic hydrocarbons in urban and rural aerosols using diagnostic ratios and PCA. Environmental Science and Pollution Research, 26, 12345–12356.

4. Akinfolarin, O. R., Adebayo, T. S., & Adeyemi, O. T. (2020). Assessment of particulate matter and associated heavy metals in urban environments of Nigeria. Environmental Monitoring and Assessment, 192(4), 256.

5. Aroh, V. C., Nwankwo, L. I., & Eze, H. N. (2020). Atmospheric aerosol composition and sources in semi-urban Nigerian towns. Atmospheric Pollution Research, 11(2), 392–405.

6. ASTM International. (2013). ASTM D6552–13: Standard test method for mass concentration of particulate matter in ambient air (Weight procedure). ASTM International.

7. Benton, L., Smith, J., & Taylor, R. (2020). Trace metal determination in ambient particulate matter using ICP-MS: Method development and validation. Environmental Chemistry Letters, 18(4), 1345–1356.

8. Birmili, W., Allen, A. G., Bary, F., & Harrison, R. M. (2016). Trace metal concentrations in urban airborne particulate matter: Sources and trends. Atmospheric Environment, 129, 9–20.

9. Brook, R. D., Rajagopalan, S., & Pope, C. A. (2017). Particulate matter air pollution and cardiovascular disease. Circulation, 121(21), 2331–2378.

10. Chisala, J. M., Mufalo, G., & Norrman, J. (2020). Seasonal distribution of PAHs in urban air of Lusaka. Atmospheric Pollution Research, 11(8), 1402–1410.

11. Chukwu, O., Weli, V. E., & Agi, V. N. (2022). Temporal variation of particulate pollution in Port Harcourt metropolis. Atmospheric Pollution Research, 13(4), 101376.

12. Efe, S. I. (2018). Chemical characterization and source apportionment of particulate matter in Nigerian urban centers. Journal of Environmental Science and Health, Part A, 53(7), 604–615.

13. Enebish, T., Ogori, A., & Peter, O. (2021). Urban air pollution trends in Nigeria. Environmental Quality Research Journal, 10(2), 45–59.

14. Eze, J. C., Okafor, T. C., & Nwafor, O. D. (2022). Fine particulate matter ($PM_{2.5}$ and $PM_{1.0}$) composition in Nigerian towns: Implications for human health. Air Quality, Atmosphere & Health, 15(5), 783–798.

15. Fiona, A., & Lin, X. (2019). Chemical speciation of fine particulate matter and associated toxicity. Chemosphere, 220, 117–126.

16. Gatari, M. J., Kinney, P. L., Gaita, S. M., & Weis, D. (2019). Air quality assessment in Nairobi during urban expansion. Science of the Total Environment, 660, 827–837.

17. Gonzalez, M., Lee, J., & Kim, H. (2020). Ultrafine particles and neurotoxicity. Environmental Health Perspectives, 128(9), 96002.

18. Harrison, R. M., & Yin, J. (2008). Sources and processes affecting particulate matter in urban atmospheres. Environmental Science & Technology, 42(6), 1820–1825.

19. Hersey, S. P., Garland, R. M., Crosbie, E., Piketh, S. J., et al. (2019). An overview of fine particulate matter in Johannesburg and the surrounding region. Atmospheric Chemistry and Physics, 19, 1325–1346.

20. Hopke, P. K. (2016). Review of receptor modeling methods for source apportionment. Atmospheric Environment, 32, 149–162.

21. Huang, R. J., Zhang, Y., Bozzetti, C., Ho, K. F., Cao, J., Han, Y., … & Fu, Q. (2014). High secondary aerosol contribution to particulate pollution during haze events in China. Nature, 514(7521), 218–222.

22. Huang, R., & Tang, Q. (2021). Atmospheric chemistry of ultrafine particles. Nature Reviews Earth & Environment, 2, 204–215.

23. Ibe, F., Ogunlade, S., & Nwankwo, I. (2020). Heavy metal distribution in particulate emissions around airport corridors in Nigeria. Air Quality & Climate Journal, 12(3), 77–89.

24. Iwasaka, Y., Tanabe, S., & Yamashita, N. (2022). Analysis of PAHs in atmospheric aerosols: Extraction techniques and source identification using GC-MS. Atmospheric Environment, 271, 118879.

25. Jiang, Y., Zhou, Y., & Feng, Q. (2022). PM1-induced neuroinflammation and oxidative stress. Toxicology Letters, 359, 28–35.

26. Kinney, P. L., Gatari, M. J., Volavka-Close, N., & Ngo, N. (2011). Urban air quality in sub-Saharan Africa: Nairobi case study. Environmental Science & Policy, 14(4), 435–445.

27. Kumar, P., Fennell, P., McNabola, A., & Dall'Osto, M. (2018). Methods for determining water-soluble inorganic ions in atmospheric particulate matter: A review. Atmospheric Environment, 177, 73–84.

28. Lima, A., Farrington, J. W., & Reddy, C. M. (2005). Combustion-derived polycyclic aromatic hydrocarbons in the environment-A review. Environmental Science & Technology, 39(23), 8556–8566.

29. Li, N., Liu, J., & Chen, Y. (2021). The toxic effects of ultrafine particles. Science of the Total Environment, 755, 143343.

30. Mkoma, S. L., & Maenhaut, W. (2018). Atmospheric aerosols in Tanzania urban environments. Aerosol and Air Quality Research, 18(3), 580–594.

31. Moreno, T., Martins, V., Querol, X., et al. (2020). Traffic-related emissions of trace metals in fine particulate matter. Environmental Pollution, 263, 114–142.

32. Ndiokwere, C., Okoro, P., & Eze, J. (2019). Microwave-assisted acid digestion for the determination of heavy metals in atmospheric aerosols. Journal of Environmental Monitoring and Assessment, 191(7), 420.

33. Ng, N. L., Brown, S. S., & Tanner, D. J. (2010). Secondary organic aerosol formation from biogenic and anthropogenic precursors. Atmospheric Chemistry and Physics, 10, 2611–2627.

34. Nkurunziza, T., Niyonzima, A., & Habimana, J. (2022). Distribution of PAHs in Kigali's atmospheric environment. Air Quality, Atmosphere & Health, 15, 345–358.

35. Nyarku, M., Ferdinand, Y., & Darko, G. (2021). PM-bound PAHs in Accra, Ghana: Levels and seasonal patterns. Environmental Advances, 5, 100102.

36. Nyarku, T., Adomako, D., & Darko, G. (2021). Atmospheric polycyclic aromatic hydrocarbons in urban aerosols: Concentrations, sources, and health risk assessment. Environmental Monitoring and Assessment, 193(4), 230.

37. Nwaogazie, I. L., & Udo, J. (2019). Urban air pollution dynamics in the Niger Delta. Nigerian Journal of Environmental Science, 3(1), 22–34.

38. Nwankwo, A., & Ogonna, U. (2021). Environmental implications of petroleum activities in Rivers State. Journal of Clean Energy Studies, 4(2), 66–79.

39. Okoro, C., & Abam, T. (2022). Ambient particulate matter and soot pollution in Port Harcourt. African Journal of Atmospheric Science, 6(1), 19–33.

40. Oluwole, B., Adebayo, K., & Onwukwe, C. (2023). Characterization of ultrafine particulate matter in Nigerian urban cities. Environmental Monitoring and Assessment, 195, 923.

41. Onwukwe, C., Weli, V., & Nwagbara, J. (2019). Assessment of particulate pollution in Port Harcourt. Environmental Management Journal, 5(2), 91–105.

42. Owoade, K. O., Olise, F. S., & Akintunde, Z. T. (2020). Characterization of fine particulate matter in urban Ghana. Environmental Monitoring and Assessment, 192, 441.

43. Owoade, O. K., Olise, F. S., & Akinyemi, O. (2015). Carbonaceous aerosols in fine particulate matter in Nigerian cities. Atmospheric Pollution Research, 6(6), 1077–1086.

44. Pope, C. A., & Dockery, D. W. (2020). Air pollution and life expectancy. New England Journal of Medicine, 383(3), 250–252.

45. Ravindra, K., Singh, A., & Mor, S. (2020). PAHs in ambient air: Sources and toxicological implications. Environmental Pollution, 267, 115394.

46. Sharma, M., Kishan, R., & Mandal, T. K. (2018). PAH levels in $PM_{2.5}$ in Delhi. Environmental Science and Pollution Research, 25, 6951–6962.

47. Tobiszewski, M., & Namieśnik, J. (2012). PAH diagnostic ratios for the identification of pollution emission sources. Environmental Pollution, 162, 110–119.

48. S. Environmental Protection Agency. (2016). 40 CFR Part 50—National primary and secondary ambient air quality standards. U.S. EPA.

49. Weijers, E. P., Rücker, A., ten Brink, H. M., & Matthijsen, J. (2011). Variability of urban PM_{10} and $PM_{2.5}$ concentrations and trace metals. Atmospheric Environment, 45(30), 5384–5393.

50. Weli, V., & Adekunle, T. (2018). Effects of soot on air quality in Port Harcourt. Journal of Environmental Science & Public Health, 2(3), 121–135.

51. Weli, V., & Agi, V. (2022). Generator-related emissions in Rivers State. Journal of Atmospheric Environment Studies, 7(4), 87–101.

52. World Health Organization (WHO). (2021). WHO global air quality guidelines. Geneva: WHO Press.

53. Xu, X., & Chen, W. (2022). Atmospheric impact of fine particulates. Environmental Pollution, 308, 119673.

54. Yunker, M. B., Macdonald, R. W., Vingarzan, R., Mitchell, R. H., Goyette, D., & Sylvestre, S. (2002). PAHs in the Fraser River basin: A critical appraisal of PAH ratios as indicators of PAH source and composition. Organic Geochemistry, 33(4), 489–515.

55. Zhang, Q., Tao, S., Shen, H., & Ma, J. (2016). Source identification of atmospheric PAHs in urban and rural environments using molecular diagnostic ratios. Atmospheric Environment, 147, 78–85.

56. Zhang, Q., Jimenez, J. L., & Canagaratna, M. R. (2015). Transboundary pollution and regional haze in Southeast Asia. Atmospheric Environment, 122, 541–551.

57. Zhang, Y., Li, X., Wang, Q., & Sun, Y. (2019). Characterization and source apportionment of polycyclic aromatic hydrocarbons in urban particulate matter. Atmospheric Pollution Research, 10(6), 1743–1753.

58. Zhang, Y., Liu, Y., Li, J., & Wang, X. (2017). Characterization of water-soluble ions in $PM_{2.5}$ and PM_{10} in a coastal urban area of China. Atmospheric Pollution Research, 8(2), 281–291.

59. Zhang, Y., Schauer, J. J., & Shafer, M. M. (2019). $PM_{1.0}$-associated PAHs from traffic emissions. Environmental Science & Technology, 53, 5710–5718.