



Seasonal Assessment of Indoor Air Quality in Coastal Communities of Akwa Ibom State, Nigeria

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Abstract

This study assessed the seasonal dynamics and pollutant interactions of indoor air quality (IAQ) across three coastal communities in Akwa Ibom State, Nigeria, viz, Ibeno, Eastern Obolo, and Ikot Abasi, during the wet and dry seasons. IAQ parameter measurements were carried out to determine concentrations of particulate matter (PM₁, PM₂, PM₅, PM₁₀), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen monoxide (NO), nitrogen dioxide (NO₂), ozone (O₃), relative humidity (RH), and temperature (TEMP) using Portable Air Quality Monitors (Fluke 985 Particle Counter, Fluke 975 AirMeter, and Aeroqual Series 500 Monitor). Descriptive statistics, correlation matrix analysis, and Principal Component Analysis (PCA) were used to explore spatial-seasonal variations and pollutant interrelationships. Elevated pollutant levels were recorded during the dry season, especially for PM and combustion gases, driven by limited ventilation, fuel-based cooking, and poor indoor air circulation. Ibeno recorded high PM concentrations in the dry season, while Ikot Abasi showed CO and NO_x peaks, indicating indoor fuel usage. Eastern Obolo had moderate pollution but strong seasonal contrasts, with wet seasons showing lower pollutants accumulation but higher RH levels. Correlation analysis revealed strong positive relationships among PM₁, PM₂, PM₅, PM₁₀, CO, and CO₂ in the dry season, pointing to indoor combustion as a common source, while O₃ showed weak or negative correlations with NO, reflecting typical indoor photochemistry. PCA identified three main components: PC1 (over 50% variance) linked to PMs and combustion gases, PC2 to gaseous pollutants (NO, NO₂, O₃), and PC3 to meteorological factors (RH, TEMP). These patterns were consistent across locations but varied by season and space. The results underscore the health risks of poor indoor air quality in rural and peri-urban households and highlight the need for cleaner fuels, better ventilation, and seasonal exposure management. The combination of correlation analysis and PCA provides a strong basis for understanding pollutant dynamics and guiding community-based IAQ interventions.

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1.0 Introduction

Indoor air quality (IAQ) is a major variable that influences public health, especially in coastal and low-lying communities where natural and anthropogenic factors interact to influence indoor environments. Globally, people spend up to 90% of their time indoors, in homes, schools, and workplaces, making indoor conditions critical to well-being (Dimitroulopoulou *et al.*, 2023; Mendes *et al.*, 2024). IAQ is influenced by air contaminants, thermal comfort, and psychosocial factors, and improved conditions have been linked to better health outcomes (Jones, 1999; Vilčeková *et al.*, 2017; Mannan & Al-Ghamdi, 2021; Dimitroulopoulou *et al.*, 2023; Deng *et al.*, 2024; Gilbert & Hartmann, 2024; Mendes *et al.*, 2024). Despite growing awareness, IAQ long received less attention than outdoor pollution, even though evidence shows indoor air is often more contaminated (Mannan & Al-Ghamdi, 2021). Poor IAQ is associated with respiratory diseases, cardiovascular disorders, and reduced cognitive function, and heightened risks for vulnerable groups such as children, the elderly, and those with pre-existing conditions (WHO, 2010, 2014; Abdel-Salam, 2021; Mannan & Al-Ghamdi, 2021; Dimitroulopoulou *et al.*, 2023). In extreme cases, poor IAQ can lead to fatal health conditions, particularly with high CO or PM exposure (Morawska, 2010; Amegah & Jaakkola, 2016; WHO, 2024).

In developing countries, IAQ remains a critical health challenge due to poverty, reliance on biomass fuels, poor ventilation, overcrowding, rapid urbanization, and weak enforcement of standards. Many households still depend on wood, charcoal, dung, crop residues, and kerosene for cooking and heating (Maes & Verbist, 2012; Amegah & Jaakkola, 2016;

McCarron *et al.*, 2020; Łaska & Ige, 2023; WHO, 2024; Mamuya & Bachwenkizi, 2025). In Nigeria's rural and peri-urban areas, these factors, combined with substandard housing, drive high indoor pollution and poses serious health risks (Addo & Olajide, 2021; Agbo, 2022; Mamuya & Bachwenkizi, 2024). Such fuels emit particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO₂), and volatile organic compounds (VOCs), which accumulate indoors under poor ventilation. Chronic exposure heightens the risk of noncommunicable diseases. In urban areas, indoor air is further compromised by vehicular emissions, industrial activities, and infiltration of outdoor pollutants. The resulting high pollutant levels disproportionately affect women and children in low- and middle-income settings (WHO, 2024).

Akwa Ibom State, in Nigeria's Niger Delta region, is shaped by a complex interplay of industrial activities and traditional livelihoods. The region hosts extensive oil and gas operations, including exploration, production, gas flaring and venting, bunkering, and artisanal refining, that collectively contribute significantly to environmental pollution and degraded air quality (Ite & Ibok, 2013; Ite *et al.*, 2013; Ite *et al.*, 2016; Lala *et al.*, 2023; Ite & Ite, 2024a; Ite & Ite, 2024b). Over the past six decades, industrialization and urbanization have led to rising emissions from various sources, with toxic effects influenced by factors like physical and chemical properties, reaction characteristics, disintegration time, and atmospheric dispersion (Kampa & Castanas, 2008; Kelly *et al.*, 2012; Ite & Ibok, 2013; Ite *et al.*, 2013; Ite *et al.*, 2016; Manisalidis *et al.*, 2020; Lala *et al.*, 2023; Ite & Ite, 2024a). Many

coastal communities in the Niger Delta region depend on fishing, farming, and biomass fuel use for cooking and lighting, practices that further exacerbate indoor air pollution. The overlap of industrial emissions with household-level combustion sources creates a multifaceted exposure scenario, heightening risks of poor outdoor and indoor air quality and associated human health impacts. While much research has focused on outdoor pollution and the environmental impacts of oil and gas activities (Nriagu *et al.*, 2016), indoor environments, where people spend over 80% of their time, remain understudied. For instance, a comparative study of indoor air quality in schools in Akwa Ibom State reported significantly higher particulate matter levels in industrial zones across both rainy and dry seasons (Ite *et al.*, 2019). Earlier work highlighted the health risks of oil and gas exploration in the region (Ite *et al.*, 2013), while more recent research stressed the need to monitor pollutants like particulate matter, carbon monoxide, and nitrogen dioxide in low-income, coastal households reliant on indoor cooking (Ite & Ite, 2024a). Despite extensive industrial and petroleum-related activities, there is a scarcity of localized empirical data on the indoor air environment within the coastal communities in Akwa Ibom State of Nigeria.

This study aims to assess the indoor air quality across selected coastal communities in Akwa Ibom State, viz, Ibeno, Eastern Obolo, and Ikot Abasi, during both dry and rainy seasons. It focuses on major pollutants such as particulate matter (PM₁, PM₂, PM₅, PM₁₀), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen monoxide (NO), nitrogen dioxide (NO₂), and ozone (O₃) alongside comfort parameters such as relative humidity (RH), and temperature (TEMP). This study aligns with global IAQ research trends emphasizing the health implications of indoor pollutants and situates the study within the specific environmental and

industrial context of Akwa Ibom State (Mannan & Al-Ghamdi, 2021; Basil *et al.*, 2024). By integrating seasonal variations and spatial differences, this research seeks to provide a baseline for public health policy, environmental planning, and community-level interventions tailored to the region's socio-environmental realities.

2.0 Materials and Methods

2.1 Residential Buildings Selection and Sampling Sites

This study was conducted in selected residential environments within the vicinity of three coastal oil and gas producing host communities, viz, Ibeno, Eastern Obolo, and Ikot Abasi Local Government Areas (LGA) of Akwa Ibom State, Nigeria (Figure 1). Akwa Ibom State, located in the South–South geopolitical zone, is one of the major oil–producing states in Nigeria's Niger Delta region, and a major contributor to the country's economy. Coastal communities in Akwa Ibom State are increasingly affected by industrial activities such as petroleum exploration and production, gas flaring and venting, petrochemical processing, and marine transportation. These activities contribute to environmental degradation and significantly deteriorate IAQ through the infiltration of outdoor pollutants into living spaces.

Ibeno Local Government Area occupies the largest Atlantic coastline of more than 129 km in Akwa Ibom State (4°32' 02''N, 4°36'02''N and 7°48''E, 8°17'42''E) and based on data from 2006 Nigeria's national census (NPC, 2009), it is home to 74, 840 people and ExxonMobil. It is renowned for its extensive Atlantic coastline, which makes it the LGA with the longest seashore in Nigeria. Ibeno shares boundaries with Eastern Obolo to the west, Esit Eket and Eket LGAs to the north, and the Atlantic Ocean to the south and east. The area serves as a major hub for oil and gas activities in the Niger Delta, hosting facilities of multinational companies such as ExxonMobil Producing Nigeria

Unlimited – Qua Iboe Terminal (QIT). Apart from gas flaring and venting associated with petroleum exploration and production in the Nigeria's Niger Delta (Ite & Ibok, 2013), fossil

fuel combustion and emissions from vehicular traffic are the main sources of atmospheric heavy metals in most host communities in Akwa Ibom State (Ite *et al.*, 2014).

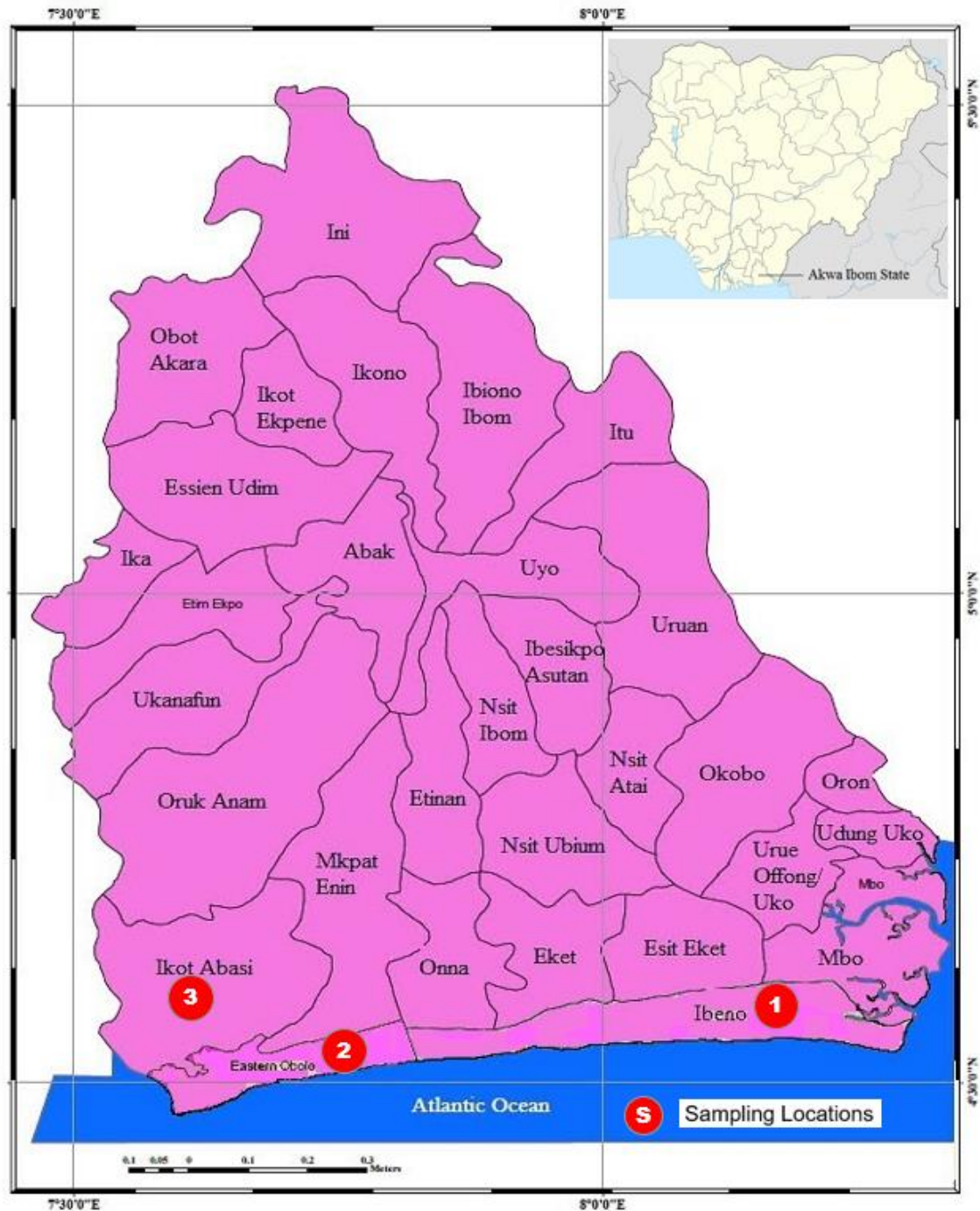


Figure 1: Map of Akwa Ibom State showing different Local Government Areas

Eastern Obolo Local Government Area (LGA) is situated within the Niger Delta fringe, between the Imo and Qua Iboe River estuaries. Geographically, it lies between latitudes $4^{\circ}28'N$ and $4^{\circ}53'N$ and longitudes $7^{\circ}50'E$ and $7^{\circ}55'E$. The LGA is bordered to the north by Mkpat Enin, to the northeast by Onna, to the west by

Ikot Abasi, to the southeast by Ibeno, and to the south by the Atlantic Ocean. Eastern Obolo lies along the coastline of the Qua Iboe River and covers a land area of approximately 117.00 km^2 . According to the 2006 National Population Census (NPC, 2009), the LGA is home to an estimated 60,543 inhabitants. Eastern Obolo

holds strategic economic importance as it hosts Amni International Petroleum Development Company Limited (AMNI) and Sterling Oil Exploration & Energy Production Company Limited (SEEPCO) – a significant independent oil and gas exploration and production company in Nigeria.

Ikot Abasi is a Local Government Area (LGA) located in the south-western corner of Akwa Ibom State, Nigeria, covering an area of approximately 451.73 km². It lies between latitude 4°42'N and 4°30'N, and longitude 7°30'E and 7°48'E. It shares boundaries with Oruk Anam LGA to the north, Mkpato Enin and Eastern Obolo LGAs to the east, and the Atlantic Ocean to the south. To the west, the Imo River forms a natural boundary separating it from Rivers State. Ikot Abasi holds strategic economic importance as it hosts the Aluminium Smelter Company of Nigeria (ALSCON) – the largest aluminium smelter plant in Africa and the Ikom Power Company (IPC), one of Nigeria's first independent power plants (Ite *et al.*, 2019). In addition, Ikot Abasi also play host to several other companies, viz, Sterling Global Petrochemical and Fertilizer Company, Banner Energy Limited, and several logistics & services companies. Figure 1 shows location maps for the three selected residential buildings within the study area, which were located within a minimal proximity to the oil and gas industrial facilities/installations. Indoor air quality parameters were measured in one residential environment/building randomly selected within each of the three coastal communities in Akwa Ibom State. The present research was carried out in naturally ventilated living rooms, and the windows in the rooms were kept open during the monitoring period. Table 1 presents the characteristics of the selected living rooms for this study.

2.2 Monitoring Protocol

Indoor air quality measurements were carried in selected households across the three coastal

communities during both the rainy (June – July) and dry (November – December seasons of 2022, with each season monitored over 21 days. Data were collected for three hours daily, morning, afternoon, and evening, using calibrated portable air quality monitors. Particulate matter (PM₁, PM₂, PM₅, and PM₁₀) with a Fluke 985 Particle Counter (six channels and particle size range of 0.3 – 10.0 µm) (Ite *et al.*, 2017; Ite *et al.*, 2019). Temperature, relative humidity, carbon monoxide (CO), and carbon dioxide (CO₂) were simultaneously recorded with a Fluke 975 AirMeter, which compensates for barometric pressure changes and supports continuous data logging. Nitrogen monoxide (NO), nitrogen dioxide (NO₂), and ozone (O₃) were monitored using an Aeroqual Series 500 Portable Air Quality Monitor. To simulate the occupants' breathing zone, instruments were placed about 1 m from walls and mounted on flat surfaces at a height of 1.5 m (Jo & Lee, 2006; Cavaleiro Rufo *et al.*, 2016; Al-Hemoud *et al.*, 2017; Ite *et al.*, 2019).

2.3 Statistical Analysis

Multiple statistical analysis techniques were used to compare IAQ parameters, and data were analysed using descriptive statistics, including means, medians, ranges, and standard deviations. Descriptive statistics were used to characterize the measured IAQ parameters, and correlation analysis was conducted using Pearson correlation coefficients to evaluate linear relationships among pollutants and comfort parameters. Principal Component Analysis (PCA) was employed to identify dominant factors influencing indoor air quality. Statistical analyses were conducted to determine and evaluate the impact of relevant parameters on the particle concentrations and occupants' exposure in the naturally ventilated living room. A value of $p < 0.05$ was considered statistically significant. All data analyses were carried out, and the airborne PM distribution profiles are presented using a scientific data analysis and

graphing software package – SigmaPlot[®], Version 14 (Systat Software Inc., USA).

3.0 Results and Discussion

3.1 Descriptive Results and Seasonal Variations

This study investigated the indoor air quality (IAQ) in selected three coastal communities of Akwa Ibom State, viz, Ibeno, Eastern Obolo and Ikot Abasi, during both the dry and rainy seasons. The parameters measured include particulate matter (PM₁, PM₂, PM₅, PM₁₀), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen monoxide (NO), nitrogen dioxide (NO₂), ozone (O₃), relative humidity (RH), and temperature (TEMP) (Table 2A – F). Descriptive statistics of daily average indoor air

quality (IAQ) parameters are presented in Table 3. PM levels were significantly elevated during the dry season across all the study locations (Figure 2 – 5). The results provide critical insight into how location-specific activities and seasonal dynamics shape indoor air pollution profiles.

3.1.1 Seasonal Variations in Ibeno

During the dry season, Ibeno recorded extremely high levels of PM₁ (6455.91 µg/m³) and PM₂ (3492.43 µg/m³) far exceeding the WHO 24-hour guideline of 15 µg/m³ for PM_{2.5}, posing a serious health risks (WHO, 2021). The elevated levels suggest emissions from gas flaring, petrochemical operations, indoor combustion, and poor ventilation, consistent with previous reports of industrial pollution in the Niger Delta (Ite *et al.*, 2013; Ngele *et al.*, 2020).

Table 1: Overview of living room characteristics

| | LIVING ROOM 1 (Mkpanak, Ibeno) | LIVING ROOM 2 (Iko, Eastern Obolo) | LIVING ROOM 3 (Ikot Abasi, Ikot Abasi) |
|------------------------------|-----------------------------------|---------------------------------------|---|
| Number of occupants | 3 | 3 | 4 |
| Floor area (m ²) | 16 | 16.5 | 17 |
| Number of Doors | 2 | 2 | 3 |
| Number of windows | 3 | 3 | 3 |
| Number of Fans | 1 | 1 | 1 |
| Cleaning Frequency | Once daily | Once daily | Once daily |

Coarser PM fractions (PM₅ and PM₁₀) were lower but still significant. Gaseous pollutants such as CO (2.07 ppm) and CO₂ (363.48 ppm) indicate indoor combustion and inadequate ventilation. Although CO concentrations measured were below the WHO indoor air quality limit of 9 ppm (8-hour) (WHO, 2021), long-term exposure or repeated exposure to low-level CO can still pose significant health risks, particularly in vulnerable groups such as children, the elderly, and those with pre-existing conditions. NO₂ (16.22 ppm) significantly

exceeds WHO's 1-hour indoor guideline of 0.2 ppm (WHO, 2021), indicating combustion-related indoor sources and/or inefficient fuel burning. Indoor ozone (29.80 ppm) was also elevated, which may be associated with photochemical reactions or electrical appliances, though O₃ is usually lower indoors due to deposition (Brown, 2001). Comfort parameters showed high relative humidity (79.51%) and temperature (30.33°C), conditions linked to mould growth, fatigue, and thermal discomfort (Tsutsumi *et al.*, 2007; Wolkoff *et al.*, 2021).

Table 2: Sampling data for different sampling locations during dry and wet seasons

(A) Location 1 - Ibeno (Dry Season)

| DAYS | PM ₁ ($\mu\text{m}/\text{m}^3$) | PM ₂ ($\mu\text{m}/\text{m}^3$) | PM ₅ ($\mu\text{m}/\text{m}^3$) | PM ₁₀ ($\mu\text{m}/\text{m}^3$) | CO (ppm) | CO ₂ (ppm) | NO (ppm) | NO ₂ (ppm) | O ₃ (ppm) | RH (%) | TEMP (°C) |
|------|---|---|---|--|-------------|--------------------------|-------------|--------------------------|-------------------------|-----------|--------------|
| 1 | 6184.00 | 3980.00 | 155.00 | 47.00 | 2.45 | 358.45 | 15.40 | 30.00 | 30.87 | 79.90 | 25.97 |
| 2 | 6983.02 | 3344.00 | 151.00 | 53.00 | 2.12 | 378.31 | 17.80 | 31.00 | 28.50 | 79.90 | 26.60 |
| 3 | 6138.00 | 3215.00 | 154.00 | 49.00 | 2.41 | 388.45 | 15.90 | 29.50 | 27.90 | 79.90 | 25.40 |
| 4 | 6999.00 | 3507.02 | 155.00 | 54.00 | 1.78 | 358.45 | 18.20 | 31.20 | 28.99 | 79.80 | 24.60 |
| 5 | 6898.02 | 3611.00 | 149.00 | 57.00 | 1.91 | 366.57 | 16.10 | 29.00 | 28.40 | 79.90 | 26.20 |
| 6 | 6352.00 | 3256.00 | 147.02 | 50.00 | 1.94 | 358.45 | 14.60 | 28.00 | 32.00 | 78.60 | 24.90 |
| 7 | 6166.00 | 3567.00 | 148.00 | 53.00 | 2.16 | 358.54 | 15.10 | 28.50 | 31.90 | 78.60 | 26.80 |
| 8 | 6894.02 | 2984.02 | 149.00 | 59.00 | 2.18 | 358.45 | 14.00 | 29.20 | 32.00 | 79.90 | 25.50 |
| 9 | 6273.00 | 3882.00 | 148.00 | 57.00 | 2.11 | 368.51 | 15.40 | 31.10 | 31.10 | 79.90 | 25.60 |
| 10 | 6268.00 | 3295.00 | 152.00 | 59.02 | 1.96 | 358.45 | 16.70 | 29.00 | 29.40 | 79.90 | 25.40 |
| 11 | 6187.00 | 3565.02 | 159.00 | 53.00 | 1.99 | 358.17 | 17.00 | 29.70 | 31.50 | 79.80 | 24.80 |
| 12 | 6798.02 | 3489.00 | 153.00 | 55.00 | 1.95 | 358.45 | 16.20 | 29.60 | 29.90 | 79.90 | 25.20 |
| 13 | 6152.00 | 3595.00 | 154.00 | 60.00 | 2.18 | 381.45 | 15.40 | 30.00 | 30.56 | 78.60 | 26.70 |
| 14 | 6244.00 | 3664.00 | 159.00 | 53.00 | 2.12 | 355.33 | 17.40 | 31.10 | 31.40 | 78.60 | 26.80 |
| 15 | 6898.02 | 3611.00 | 149.00 | 51.02 | 1.91 | 366.57 | 16.20 | 28.99 | 29.98 | 79.90 | 26.20 |
| 16 | 6352.00 | 3256.00 | 147.02 | 50.00 | 1.94 | 358.45 | 15.00 | 29.87 | 31.20 | 78.60 | 24.90 |
| 17 | 6166.00 | 3567.00 | 148.00 | 53.00 | 2.16 | 358.54 | 17.90 | 29.64 | 30.40 | 78.60 | 26.80 |
| 18 | 6894.02 | 3211.00 | 149.00 | 59.00 | 2.18 | 358.45 | 16.70 | 30.20 | 30.70 | 79.90 | 25.50 |
| 19 | 6273.00 | 3882.00 | 148.00 | 57.00 | 2.11 | 368.51 | 17.00 | 31.10 | 30.98 | 79.90 | 25.60 |
| 20 | 6268.00 | 3295.00 | 152.00 | 59.02 | 1.96 | 358.45 | 15.80 | 29.45 | 28.00 | 79.90 | 25.40 |
| 21 | 6187.00 | 3565.02 | 159.00 | 62.00 | 1.99 | 358.17 | 16.90 | 29.68 | 31.20 | 79.80 | 24.80 |

(B) Location 1 - Ibeno (Wet Season)

| DAYS | PM ₁ ($\mu\text{m}/\text{m}^3$) | PM ₂ ($\mu\text{m}/\text{m}^3$) | PM ₅ ($\mu\text{m}/\text{m}^3$) | PM ₁₀ ($\mu\text{m}/\text{m}^3$) | CO (ppm) | CO ₂ (ppm) | NO (ppm) | NO ₂ (ppm) | O ₃ (ppm) | RH (%) | TEMP (°C) |
|------|---|---|---|--|-------------|--------------------------|-------------|--------------------------|-------------------------|-----------|--------------|
| 1 | 2491.00 | 1254.00 | 56.00 | 18.00 | 1.15 | 220.11 | 14.20 | 20.00 | 16.90 | 79.90 | 25.10 |
| 2 | 2188.00 | 1311.00 | 54.00 | 18.00 | 1.14 | 225.22 | 14.70 | 19.70 | 19.70 | 80.20 | 22.60 |
| 3 | 2508.02 | 1390.00 | 49.00 | 18.00 | 1.15 | 224.13 | 14.00 | 18.90 | 18.90 | 79.90 | 23.20 |
| 4 | 2356.00 | 1206.02 | 49.00 | 22.00 | 1.18 | 220.11 | 13.90 | 16.50 | 18.20 | 81.00 | 24.20 |
| 5 | 2291.00 | 1020.02 | 40.00 | 24.00 | 1.12 | 227.11 | 15.10 | 18.20 | 18.20 | 79.90 | 25.20 |
| 6 | 1991.00 | 1287.00 | 57.00 | 18.00 | 1.25 | 228.15 | 13.10 | 18.40 | 18.40 | 78.60 | 23.80 |
| 7 | 2098.00 | 1310.02 | 41.00 | 24.00 | 1.12 | 220.14 | 15.10 | 19.00 | 17.40 | 78.60 | 24.80 |
| 8 | 2296.00 | 1154.00 | 46.00 | 17.00 | 1.21 | 226.11 | 17.00 | 18.20 | 18.20 | 79.90 | 25.50 |
| 9 | 2234.02 | 1311.00 | 53.00 | 18.00 | 1.14 | 220.18 | 13.60 | 19.50 | 17.80 | 79.90 | 25.60 |
| 10 | 2008.00 | 1298.00 | 46.00 | 19.01 | 1.17 | 220.11 | 13.70 | 18.50 | 18.50 | 80.00 | 25.40 |
| 11 | 2106.00 | 1206.00 | 54.00 | 22.01 | 1.15 | 225.11 | 14.60 | 18.90 | 18.90 | 79.80 | 24.80 |
| 12 | 2172.00 | 1020.02 | 42.00 | 22.00 | 1.25 | 220.11 | 15.00 | 18.20 | 18.20 | 79.90 | 25.20 |
| 13 | 2601.02 | 1075.00 | 40.00 | 21.00 | 1.25 | 228.22 | 13.80 | 18.40 | 18.40 | 78.60 | 23.70 |
| 14 | 1978.00 | 1014.00 | 61.00 | 24.00 | 1.20 | 220.11 | 14.20 | 16.70 | 19.70 | 78.60 | 24.10 |
| 15 | 2591.00 | 1287.00 | 42.00 | 18.00 | 1.25 | 228.15 | 14.00 | 18.90 | 18.90 | 79.40 | 23.80 |
| 16 | 2098.00 | 1510.02 | 54.00 | 24.00 | 1.12 | 220.14 | 13.90 | 18.20 | 18.20 | 78.60 | 24.80 |
| 17 | 2296.00 | 1054.00 | 46.00 | 17.00 | 1.21 | 226.11 | 14.00 | 18.00 | 17.60 | 79.90 | 25.50 |

| | | | | | | | | | | | |
|----|---------|---------|-------|-------|------|--------|-------|-------|-------|-------|-------|
| 18 | 2234.02 | 1311.00 | 53.00 | 21.00 | 1.14 | 220.18 | 15.00 | 19.70 | 19.70 | 79.90 | 25.60 |
| 19 | 2308.00 | 1298.00 | 46.00 | 19.01 | 1.17 | 220.11 | 15.10 | 18.90 | 18.90 | 80.00 | 25.40 |
| 20 | 2188.00 | 1311.00 | 54.00 | 21.00 | 1.14 | 225.22 | 14.70 | 18.20 | 18.20 | 79.90 | 25.60 |
| 21 | 2408.02 | 1390.00 | 52.00 | 19.00 | 1.15 | 224.13 | 14.00 | 19.20 | 19.20 | 81.10 | 25.40 |

(C) Location 2 - Eastern Obolo (Dry Season)

| DAYS | PM ₁ ($\mu\text{m}/\text{m}^3$) | PM ₂ ($\mu\text{m}/\text{m}^3$) | PM ₅ ($\mu\text{m}/\text{m}^3$) | PM ₁₀ ($\mu\text{m}/\text{m}^3$) | CO (ppm) | CO ₂ (ppm) | NO (ppm) | NO ₂ (ppm) | O ₃ (ppm) | RH (%) | TEMP ($^{\circ}\text{C}$) |
|------|---|---|---|--|-------------|--------------------------|-------------|--------------------------|-------------------------|-----------|--------------------------------|
| 1 | 5677.00 | 2980.00 | 145.00 | 38.00 | 1.45 | 251.00 | 10.00 | 25.00 | 16.90 | 79.90 | 25.70 |
| 2 | 5373.00 | 2744.00 | 138.00 | 43.02 | 1.74 | 248.02 | 9.90 | 26.00 | 19.70 | 79.90 | 25.60 |
| 3 | 5938.02 | 3015.02 | 140.00 | 39.00 | 1.61 | 251.00 | 11.00 | 26.00 | 18.90 | 79.90 | 25.40 |
| 4 | 5299.00 | 3207.00 | 147.00 | 44.00 | 1.77 | 273.00 | 10.10 | 25.00 | 18.20 | 79.80 | 24.60 |
| 5 | 5898.02 | 2936.00 | 139.00 | 46.00 | 1.51 | 248.21 | 11.20 | 29.50 | 18.20 | 79.90 | 25.20 |
| 6 | 5152.00 | 2956.02 | 137.00 | 45.00 | 1.64 | 392.00 | 10.20 | 20.50 | 18.40 | 78.60 | 24.90 |
| 7 | 5166.02 | 2867.00 | 138.00 | 42.00 | 1.60 | 244.22 | 11.00 | 22.00 | 17.40 | 78.60 | 24.80 |
| 8 | 5894.01 | 2784.00 | 141.00 | 43.00 | 1.58 | 265.41 | 10.90 | 24.00 | 18.20 | 79.90 | 25.50 |
| 9 | 5373.02 | 2812.01 | 138.00 | 44.00 | 1.41 | 241.00 | 11.40 | 22.00 | 17.80 | 79.90 | 25.60 |
| 10 | 5868.02 | 2995.00 | 142.01 | 45.00 | 1.64 | 245.23 | 11.00 | 22.00 | 18.50 | 79.90 | 25.40 |
| 11 | 5187.00 | 2965.00 | 149.00 | 43.02 | 1.71 | 255.25 | 12.10 | 21.00 | 18.90 | 79.80 | 24.80 |
| 12 | 5798.00 | 2989.02 | 143.00 | 41.00 | 1.52 | 249.61 | 11.00 | 20.40 | 18.20 | 79.90 | 25.20 |
| 13 | 5252.00 | 2895.00 | 144.00 | 45.00 | 1.52 | 241.00 | 10.50 | 20.70 | 18.40 | 78.60 | 24.70 |
| 14 | 5344.00 | 2764.00 | 139.00 | 43.00 | 1.62 | 300.11 | 11.00 | 21.50 | 14.00 | 78.60 | 24.80 |
| 15 | 5166.02 | 2867.00 | 138.00 | 42.00 | 1.60 | 244.22 | 10.00 | 22.30 | 14.00 | 78.60 | 24.80 |
| 16 | 5894.01 | 2784.00 | 141.00 | 43.00 | 1.58 | 265.41 | 9.90 | 21.90 | 18.20 | 79.90 | 25.50 |
| 17 | 5373.02 | 2812.01 | 138.00 | 44.00 | 1.41 | 241.00 | 11.00 | 21.80 | 17.60 | 79.90 | 25.60 |
| 18 | 5373.00 | 2744.00 | 138.00 | 43.02 | 1.74 | 248.02 | 10.10 | 20.50 | 14.00 | 79.90 | 25.60 |
| 19 | 5938.02 | 3015.02 | 140.00 | 39.00 | 1.61 | 251.00 | 10.00 | 22.00 | 18.90 | 79.90 | 25.40 |
| 20 | 5299.00 | 3207.00 | 147.00 | 44.00 | 1.77 | 273.00 | 10.20 | 21.00 | 18.20 | 79.80 | 24.60 |
| 21 | 5898.02 | 2936.00 | 139.00 | 46.00 | 1.51 | 248.21 | 10.10 | 20.00 | 19.20 | 79.90 | 25.20 |

(D) Location 2 - Eastern Obolo (Rainy Season)

| DAYS | PM ₁ ($\mu\text{m}/\text{m}^3$) | PM ₂ ($\mu\text{m}/\text{m}^3$) | PM ₅ ($\mu\text{m}/\text{m}^3$) | PM ₁₀ ($\mu\text{m}/\text{m}^3$) | CO (ppm) | CO ₂ (ppm) | NO (ppm) | NO ₂ (ppm) | O ₃ (ppm) | RH (%) | TEMP ($^{\circ}\text{C}$) |
|------|---|---|---|--|-------------|--------------------------|-------------|--------------------------|-------------------------|-----------|--------------------------------|
| 1 | 2999.00 | 2154.00 | 66.00 | 27.00 | 1.65 | 278.23 | 14.20 | 38.70 | 16.90 | 81.14 | 25.97 |
| 2 | 3188.00 | 1911.00 | 64.00 | 26.40 | 1.50 | 267.24 | 14.70 | 42.20 | 19.70 | 79.90 | 26.60 |
| 3 | 3008.00 | 1990.00 | 55.00 | 26.00 | 1.85 | 260.22 | 14.00 | 43.00 | 18.90 | 82.00 | 25.40 |
| 4 | 2556.02 | 2306.00 | 59.00 | 26.00 | 1.68 | 265.35 | 13.90 | 42.00 | 18.20 | 79.80 | 26.00 |
| 5 | 3191.00 | 2020.02 | 60.02 | 29.00 | 1.12 | 275.25 | 14.00 | 41.10 | 18.20 | 79.90 | 26.42 |
| 6 | 3121.02 | 2187.01 | 58.00 | 28.00 | 1.25 | 264.21 | 13.10 | 42.10 | 18.40 | 78.60 | 24.90 |
| 7 | 3198.00 | 2010.00 | 51.00 | 34.00 | 1.12 | 261.21 | 15.10 | 41.00 | 17.40 | 82.00 | 26.80 |
| 8 | 3296.02 | 2054.00 | 66.02 | 27.00 | 1.21 | 275.26 | 13.40 | 42.20 | 18.20 | 79.90 | 25.50 |
| 9 | 3934.00 | 2311.02 | 63.00 | 29.00 | 1.14 | 264.25 | 13.60 | 40.00 | 17.80 | 79.90 | 25.60 |
| 10 | 3008.00 | 2298.00 | 66.00 | 26.00 | 1.27 | 274.44 | 13.70 | 38.90 | 18.50 | 80.00 | 25.40 |
| 11 | 3106.00 | 2206.00 | 64.00 | 25.40 | 1.15 | 260.21 | 14.60 | 41.00 | 18.90 | 78.98 | 24.80 |
| 12 | 3972.02 | 2020.02 | 62.00 | 27.00 | 1.24 | 265.22 | 14.00 | 41.10 | 18.20 | 81.20 | 25.52 |
| 13 | 3001.00 | 2175.00 | 60.02 | 28.00 | 1.25 | 280.21 | 13.80 | 40.00 | 18.40 | 78.60 | 26.70 |
| 14 | 3178.00 | 2194.00 | 61.00 | 26.00 | 1.20 | 260.44 | 14.20 | 41.30 | 19.70 | 81.60 | 26.80 |

| | | | | | | | | | | | |
|----|---------|---------|-------|-------|------|--------|-------|-------|-------|-------|-------|
| 15 | 3191.00 | 2020.02 | 60.02 | 29.00 | 1.12 | 275.25 | 14.00 | 42.00 | 18.90 | 79.90 | 26.42 |
| 16 | 3121.02 | 2187.01 | 58.00 | 28.00 | 1.25 | 264.21 | 13.90 | 40.00 | 18.20 | 78.60 | 26.00 |
| 17 | 3198.00 | 2010.00 | 51.00 | 34.00 | 1.12 | 261.21 | 14.00 | 39.00 | 17.60 | 78.60 | 26.80 |
| 18 | 3296.02 | 2054.00 | 66.02 | 27.00 | 1.21 | 275.26 | 15.00 | 40.00 | 19.70 | 78.90 | 25.50 |
| 19 | 3934.00 | 2311.02 | 63.00 | 29.00 | 1.12 | 264.25 | 15.10 | 38.00 | 18.90 | 79.99 | 26.00 |
| 20 | 3308.00 | 2298.00 | 66.00 | 26.00 | 1.29 | 274.44 | 13.20 | 39.00 | 18.20 | 81.10 | 25.40 |
| 21 | 3106.00 | 2206.00 | 64.00 | 27.00 | 1.15 | 260.21 | 14.20 | 41.30 | 19.20 | 80.00 | 24.80 |

(E) Location 3 -Ikot Abasi (Dry Season)

| DAYS | PM ₁ ($\mu\text{m}/\text{m}^3$) | PM ₂ ($\mu\text{m}/\text{m}^3$) | PM ₅ ($\mu\text{m}/\text{m}^3$) | PM ₁₀ ($\mu\text{m}/\text{m}^3$) | CO (ppm) | CO ₂ (ppm) | NO (ppm) | NO ₂ (ppm) | O ₃ (ppm) | RH (%) | TEMP (°C) |
|------|---|---|---|--|-------------|--------------------------|-------------|--------------------------|-------------------------|-----------|--------------|
| 1 | 7468.00 | 3980.00 | 177.00 | 57.00 | 2.45 | 358.45 | 15.40 | 30.60 | 32.87 | 79.90 | 26.97 |
| 2 | 6983.02 | 3344.00 | 171.00 | 53.00 | 2.32 | 378.31 | 17.80 | 31.90 | 29.50 | 79.90 | 26.60 |
| 3 | 6438.00 | 4112.00 | 168.00 | 49.00 | 2.41 | 388.45 | 15.90 | 30.00 | 31.10 | 79.90 | 25.40 |
| 4 | 6999.00 | 3507.02 | 167.00 | 54.00 | 2.50 | 358.45 | 18.20 | 31.20 | 30.99 | 79.80 | 24.60 |
| 5 | 6898.02 | 3611.00 | 172.00 | 57.00 | 2.95 | 366.57 | 16.10 | 32.10 | 31.40 | 79.90 | 26.20 |
| 6 | 6352.00 | 3256.00 | 172.00 | 60.00 | 2.60 | 358.45 | 14.60 | 28.00 | 32.00 | 78.60 | 24.90 |
| 7 | 7111.00 | 3567.00 | 159.00 | 53.00 | 2.16 | 358.54 | 15.10 | 28.50 | 31.90 | 78.60 | 26.80 |
| 8 | 6894.02 | 3998.00 | 168.00 | 59.00 | 2.68 | 358.45 | 14.00 | 29.20 | 32.00 | 79.90 | 25.50 |
| 9 | 6573.00 | 3882.00 | 175.00 | 57.00 | 2.11 | 368.51 | 15.40 | 31.10 | 31.10 | 79.90 | 25.60 |
| 10 | 7168.00 | 3595.00 | 164.00 | 61.00 | 3.00 | 381.45 | 16.70 | 29.00 | 29.40 | 79.90 | 25.40 |
| 11 | 6897.00 | 3565.02 | 169.00 | 53.00 | 2.40 | 358.17 | 17.00 | 32.00 | 31.50 | 79.80 | 24.80 |
| 12 | 6798.02 | 3489.00 | 171.00 | 55.00 | 2.90 | 358.45 | 16.20 | 29.60 | 31.90 | 79.90 | 25.20 |
| 13 | 7152.00 | 4121.00 | 167.00 | 60.00 | 2.18 | 381.45 | 15.40 | 30.00 | 30.56 | 78.60 | 26.70 |
| 14 | 6744.00 | 3664.00 | 179.00 | 53.00 | 2.42 | 375.33 | 17.40 | 31.10 | 31.40 | 78.60 | 26.80 |
| 15 | 6898.02 | 3611.00 | 166.00 | 51.02 | 2.40 | 366.57 | 16.20 | 28.99 | 31.98 | 79.90 | 26.20 |
| 16 | 6852.00 | 3956.00 | 164.00 | 62.00 | 2.70 | 358.45 | 15.00 | 29.87 | 31.20 | 78.60 | 24.90 |
| 17 | 6866.00 | 3567.00 | 172.00 | 53.00 | 2.16 | 358.54 | 17.90 | 29.64 | 30.40 | 78.60 | 26.80 |
| 18 | 6894.02 | 3911.00 | 172.00 | 59.00 | 2.80 | 358.45 | 16.70 | 30.20 | 30.70 | 79.90 | 25.50 |
| 19 | 7273.00 | 4111.00 | 164.00 | 59.00 | 2.11 | 368.51 | 17.00 | 31.10 | 30.98 | 79.90 | 25.60 |
| 20 | 6998.00 | 3495.00 | 172.00 | 59.02 | 2.40 | 398.45 | 15.80 | 31.10 | 30.80 | 79.90 | 25.40 |
| 21 | 6987.00 | 3995.02 | 169.00 | 62.00 | 2.60 | 358.17 | 16.90 | 30.20 | 31.20 | 79.80 | 24.80 |

(F) Location 3 - Ikot Abasi (Wet Season)

| DAYS | PM ₁ ($\mu\text{m}/\text{m}^3$) | PM ₂ ($\mu\text{m}/\text{m}^3$) | PM ₅ ($\mu\text{m}/\text{m}^3$) | PM ₁₀ ($\mu\text{m}/\text{m}^3$) | CO (ppm) | CO ₂ (ppm) | NO (ppm) | NO ₂ (ppm) | O ₃ (ppm) | RH (%) | TEMP (°C) |
|------|---|---|---|--|-------------|--------------------------|-------------|--------------------------|-------------------------|-----------|--------------|
| 1 | 2591.00 | 1254.00 | 66.00 | 21.00 | 1.40 | 230.20 | 14.20 | 20.00 | 16.90 | 79.90 | 25.10 |
| 2 | 2808.00 | 1311.00 | 54.00 | 19.00 | 1.20 | 225.22 | 13.44 | 19.70 | 18.22 | 76.00 | 22.60 |
| 3 | 2508.02 | 1390.00 | 60.00 | 22.00 | 1.18 | 224.13 | 14.00 | 18.90 | 18.90 | 79.90 | 23.20 |
| 4 | 2356.00 | 1206.02 | 59.00 | 23.00 | 1.24 | 220.11 | 13.90 | 16.50 | 18.20 | 78.00 | 24.20 |
| 5 | 2291.00 | 1420.02 | 53.00 | 24.00 | 1.22 | 237.11 | 15.10 | 18.20 | 17.68 | 79.90 | 25.20 |
| 6 | 2200.00 | 1287.00 | 57.00 | 17.80 | 1.25 | 228.15 | 13.10 | 18.40 | 18.40 | 77.00 | 23.80 |
| 7 | 2598.00 | 1310.02 | 51.00 | 24.00 | 1.12 | 228.00 | 12.55 | 19.00 | 17.40 | 78.60 | 24.56 |
| 8 | 2296.00 | 1554.00 | 56.00 | 17.00 | 1.21 | 226.11 | 13.55 | 18.20 | 15.52 | 79.90 | 25.50 |
| 9 | 2234.02 | 1311.00 | 53.00 | 18.00 | 1.14 | 231.00 | 13.60 | 19.50 | 17.80 | 79.90 | 25.60 |
| 10 | 2608.00 | 1298.00 | 58.00 | 19.01 | 1.17 | 227.00 | 13.70 | 18.50 | 18.50 | 74.00 | 25.40 |
| 11 | 2506.00 | 1206.00 | 54.00 | 22.01 | 1.50 | 225.11 | 14.60 | 18.90 | 18.90 | 16.80 | 24.80 |
| 12 | 2872.00 | 1720.02 | 61.00 | 22.00 | 1.25 | 220.11 | 15.00 | 18.20 | 18.20 | 79.90 | 25.20 |
| 13 | 2601.02 | 1575.00 | 57.00 | 21.00 | 1.25 | 228.22 | 13.80 | 18.40 | 18.40 | 78.60 | 23.70 |
| 14 | 2355.00 | 1014.00 | 61.00 | 24.00 | 1.20 | 235.11 | 14.20 | 16.70 | 19.70 | 78.60 | 24.10 |

| | | | | | | | | | | | |
|----|---------|---------|-------|-------|------|--------|-------|-------|-------|-------|-------|
| 15 | 2591.00 | 1287.00 | 59.00 | 18.00 | 1.25 | 228.15 | 14.00 | 18.90 | 18.90 | 79.40 | 23.80 |
| 16 | 2898.00 | 1510.02 | 60.00 | 24.00 | 1.12 | 220.14 | 13.90 | 18.20 | 18.20 | 78.60 | 24.80 |
| 17 | 2296.00 | 1554.00 | 57.00 | 17.00 | 1.21 | 226.11 | 14.00 | 18.00 | 17.60 | 79.90 | 25.50 |
| 18 | 2234.02 | 1311.00 | 53.00 | 21.00 | 1.33 | 236.00 | 15.00 | 19.70 | 16.45 | 79.90 | 26.00 |
| 19 | 2308.00 | 1398.00 | 62.00 | 18.50 | 1.42 | 219.00 | 14.11 | 18.90 | 18.90 | 72.00 | 26.80 |
| 20 | 2588.00 | 1411.00 | 61.00 | 21.00 | 1.22 | 225.22 | 14.70 | 18.20 | 18.20 | 79.90 | 26.20 |
| 21 | 2408.02 | 1390.00 | 55.00 | 19.00 | 1.28 | 224.13 | 12.88 | 19.20 | 19.20 | 76.80 | 26.44 |

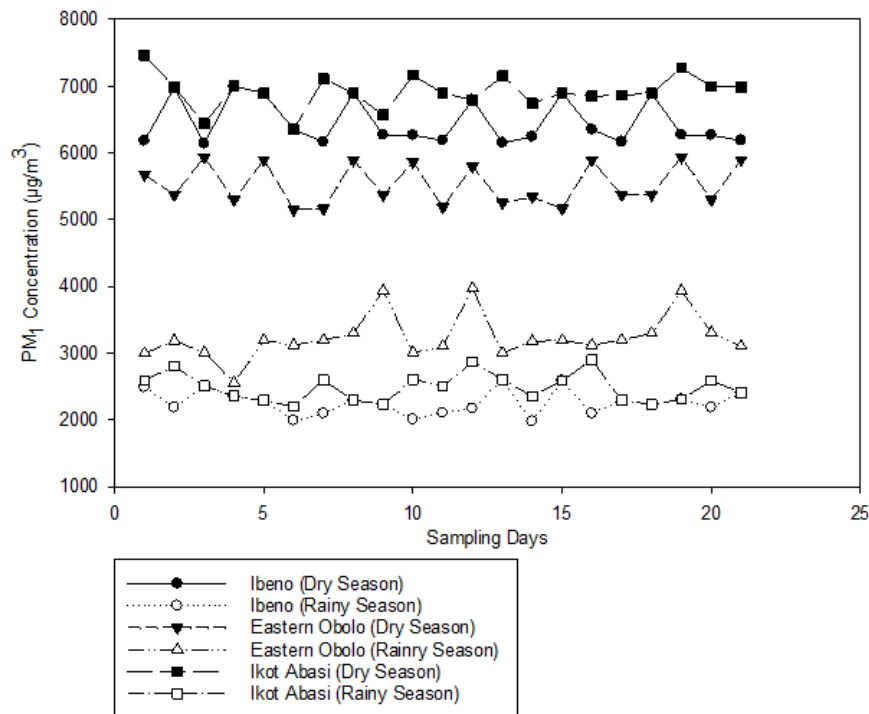


Figure 2: Seasonal Variations of PM₁ Concentrations in a Naturally Ventilated Living Room during Rainy and Dry Seasons

During the rainy season, PM levels reduced markedly (PM₁: 2259.10 µg/m³; PM₂: 1238.91 µg/m³), largely due to rainfall's natural particle-scavenging effect and the associated reduction in ambient dust influx into indoor spaces. Rain plays a key role in removing airborne particulates from the atmosphere through two major mechanisms, viz, wet deposition (rain scavenging) and impaction and absorption. This phenomenon reduces the overall ambient concentration of PM (particularly PM₁ and PM₂), especially in environments where natural or unpaved surfaces are primary sources of airborne dust (Sun *et al.*, 2004). Indoor environments also benefit when ambient dust is suppressed during rainfall, particularly when there are no active significant indoor PM sources (such as biomass cooking). However, the observed increase in NO₂

(18.58 ppm) and NO (14.41 ppm), respectively, can be attributed to enclosed combustion activities and poor indoor air ventilation, both of which are common in many residential settings during wet periods. and Dry Seasons. The combustion of solid fuels indoors, especially in homes with poor ventilation, is a significant source of nitrogen oxides (NO_x) and other harmful pollutants (WHO, 2014; Balmes, 2019). While rainfall helps suppress particulate matter, it often leads to behavioural and environmental changes indoors, such as increased combustion and reduced ventilation, that contribute to elevated levels of NO and NO₂. In general, comfort parameters remained stable, with RH slightly increasing to 79.70% and temperature dropping to a more tolerable 24.73°C, suggesting improved thermal comfort during the wet season.

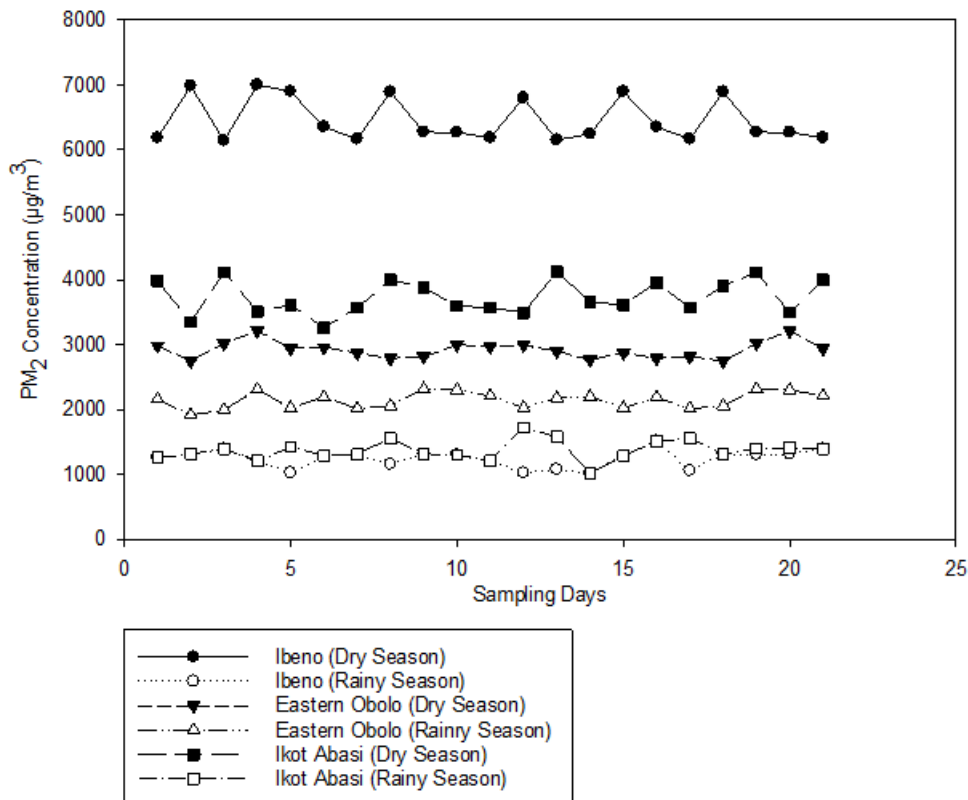


Figure 3: Seasonal Variations of PM₂ Concentrations in a Naturally Ventilated Living Room during Rainy and Dry Seasons

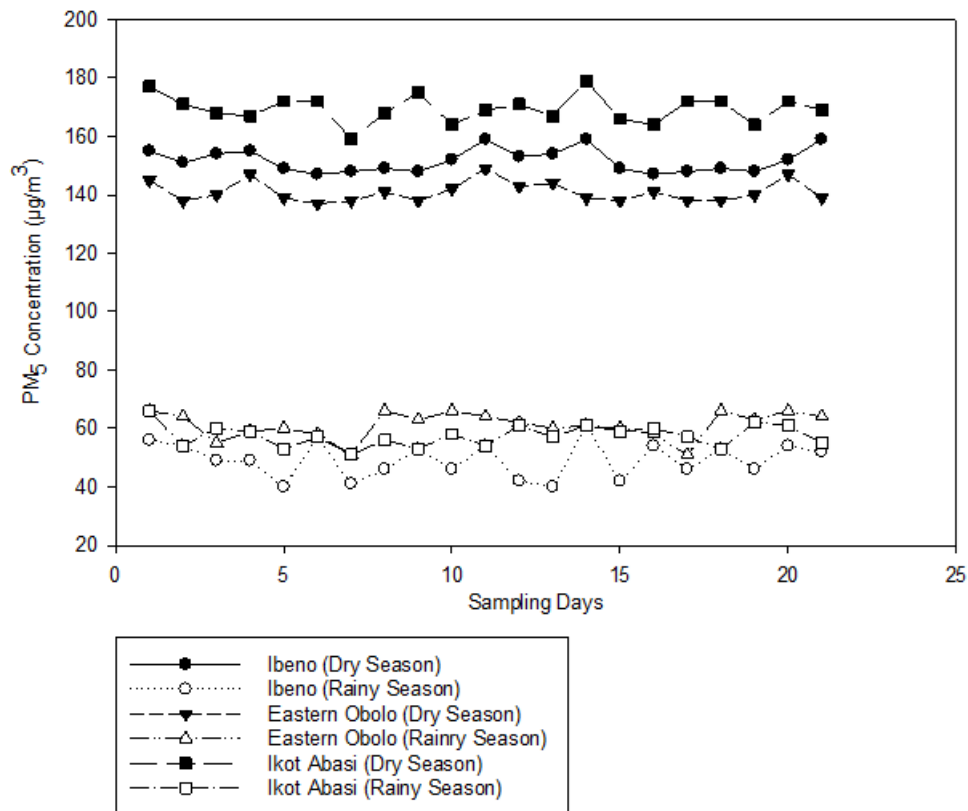


Figure 4: Seasonal Variations of PM₅ Concentrations in a Naturally Ventilated Living Room during Rainy and Dry Seasons

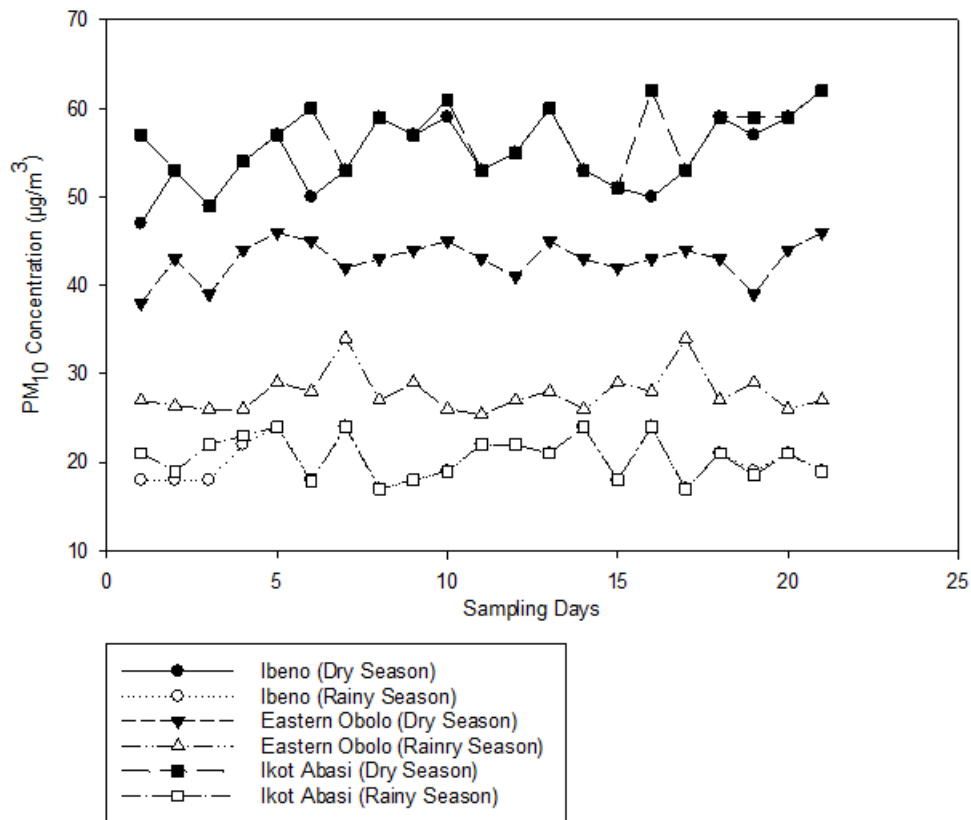


Figure 5: Seasonal Variations of PM₁₀ Concentrations in a Naturally Ventilated Living Room during Rainy Seasons

3.1.2 Seasonal Variations in Eastern Obolo

During the dry season, Eastern Obolo recorded moderate concentrations of particulate matter, with PM₁ (5531.44 µg/m³) and PM₂ (2917.81 µg/m³). Although these values were lower than those measured in Ibeno, they remain significantly elevated and pose substantial respiratory health risks, particularly for vulnerable groups. The elevated levels of NO₂ (22.62 ppm) are attributed to indoor combustion activities and poor ventilation, both of which are common in many residential settings during wet periods. The reliance on solid fuels in poorly ventilated homes is a major contributor, consistent with findings from similar rural contexts (WHO, 2014; Balmes, 2019; Awoyele *et al.*, 2025). Traditional cooking stoves emit NO₂ and other pollutants, disproportionately affecting women and children who spend extended hours near cooking areas. Traditional cooking stoves, which typically burn solid fuels, emit NO₂ and other harmful pollutants. Exposure to these pollutants cocktail have been

implicated in several respiratory problems and health issues, especially for women and children, who often spend extended periods near cooking areas and are therefore disproportionately affected (Awoyele *et al.*, 2025; Mamuya & Bachwenkizi, 2025). During the study period, comfort parameters were warm and humid (25.19°C; RH 79.58%), indicating conditions that enhance the persistence of pollutants, inhibit their dispersion, and result in occupant's discomfort. Ozone (O₃) concentrations were relatively low (17.71 ppm), suggesting reduced oxidant-related risks compared to Ibeno.

During the rainy season, PM levels declined (PM₁: 3233.82 µg/m³; PM₂: 2139.15 µg/m³), reflecting rainfall's scavenging effect on airborne particles (Xing & Sun, 2022; Saetae *et al.*, 2025). However, NO₂ spiked sharply to 40.66 ppm, suggesting a high level of indoor combustion under closed, poorly ventilated conditions common during rain. This sharp rise in NO₂ aligns with previous studies that report

elevated indoor nitrogen oxide levels during the rainy season, often linked to increased use of fossil fuel-powered generators, kerosene stoves, and biomass combustion, particularly in households that close windows and doors to protect against rain, thereby limiting air exchange (Agbo *et al.*, 2021; Kadiri *et al.*, 2024). The elevated NO₂ may also indicate inefficient combustion or prolonged indoor activities in poorly ventilated environments during wet conditions, and further contributing to pollutant accumulation. Despite this, thermal comfort parameters were relatively stable (25.87°C; RH 80.03%), offering slightly better comfort than Ibeno's dry season, though the risk of pollutant accumulation persisted.

3.1.3 Seasonal Variations in Ikot Abasi

During the dry season, Ikot Abasi recorded the highest indoor pollutant levels among the study sites, indicating significant IAQ challenges. The mean concentration of PM₁ (6916.34 µg/m³) and PM₂ (3730.34 µg/m³) far exceeded WHO guidelines, posing serious respiratory and cardiovascular health risks for chronically exposed individuals (WHO, 2021). CO concentration peaked at 2.49 ppm, the highest among the coastal communities, while NO₂ reached 30.26 ppm, suggesting intense indoor combustion, poor ventilation and proximity to industrial activities. CO₂ was slightly elevated (367.44 ppm), indicating limited indoor air exchange and a buildup of exhaled and combustion-related gases. Notably, ozone (O₃) concentrations reached 31.19 ppm, the highest across all the three coastal communities, raising concern due to ozone's potent oxidative and inflammatory effects, particularly for vulnerable groups such as children, the elderly, and those with asthma or cardiovascular conditions (USEPA, 2020; Zhang *et al.*, 2024). Comfort parameters were moderate (25.75°C; RH 79.51%), but high humidity and warm temperature may have compounded pollutant effects, fostering mould growth and enhancing

the reactivity of VOCs and NO₂ (Sundell, 2004). Overall, indoor conditions were slightly better than those recorded in Ibeno during the same season, yet pollutant loads remained critical.

During the rainy season, Ikot Abasi experienced a significant reduction in indoor PM concentrations (PM₁: 2483.20 µg/m³; PM₂: 1367.48 µg/m³) and this was consistent with rainfall's scavenging effect through impaction, absorption, and washout mechanisms (Xing & Sun, 2022; Saetae *et al.*, 2025). Rainfall reduces both ambient and indoor PM by limiting the resuspension of dust and curbing the infiltration of outdoor particulates, particularly in semi-open or poorly sealed buildings. Gaseous pollutants also decreased, with NO at 13.97 ppm and NO₂ at 18.58 ppm, suggesting decrease in combustion-related indoor activities and improved dispersion due to higher humidity and cooler conditions. The reduction in NO_x pollutants may also reflect lower generator usage during the wet season, as ambient temperatures become more tolerable and natural ventilation improves with cooler conditions and reduced reliance on mechanical cooling or lighting. An interesting observation was the drop in RH to 75.41% during the rainy season, the lowest recorded among all three coastal communities. This, combined with a mild indoor temperature of 24.88°C, suggests enhanced indoor thermal comfort compared to the dry season, which was often characterized by excessive humidity and thermal discomfort. High RH levels can contribute to pollutant retention and microbial growth (Sundell, 2004), values below 80% are generally more favourable for occupant comfort and less conducive to adverse health outcomes. These conditions suggest improved indoor comfort and air quality during the rainy season. Despite these improvements, measured concentrations of PM and NO₂ still exceeded IAQ guidelines, underscoring rainfall's mitigating role. Nonetheless, sustained intervention in fuel use,

ventilation, and building design remain essential (WHO, 2021; Awoyele *et al.*, 2025).

3.1.4 Comparative Observations for the Three Coastal Communities

Across all three study locations, the dry season consistently exhibited higher concentrations of indoor air pollutants, particularly PM (PM₁, PM₂, PM₅, PM₁₀), CO, CO₂, and NO_x. These elevated levels are attributable to a combination of poor ventilation, indoor combustion, and climatic conditions that promote pollutant accumulation. The rainy season, although characterized by elevated humidity, generally demonstrated improved air quality due to precipitation's scavenging effect and enhanced atmospheric dispersion. The seasonal pattern highlights a clear deterioration of IAQ during the dry season, especially in households reliant on solid fuels or kerosene for cooking, where inefficient combustion and limited ventilation intensify pollutant loads. PM concentrations were notably higher across all coastal communities in the dry season, with Ikot Abasi most affected, followed by Ibeno, suggesting that both fuel type and proximity to industrial operations shape spatial variability in IAQ.

While rainfall substantially reduced PM, gaseous pollutants did not uniformly decline. For example, Eastern Obolo recorded a rainy season spike in NO₂, likely from indoor combustion in poorly ventilated spaces as households sealed windows against rain. In general, dry season pollutant levels were more influenced by ambient conditions, while rainy season concentrations reflected indoor sources associated with increased human activities and poor ventilation (Abdel-Salam, 2021). In addition, temperature and humidity also played key roles: high RH enhanced pollutant retention, and elevated temperatures promoted accumulation and discomfort. Although thermal conditions slightly improved during the rainy season, persistently high humidity continued to

challenge comfort and may have amplified the perceived burden of indoor pollution.

3.2 Particulate Matter

PM concentrations were markedly higher during the dry season across all study locations (Figures 2 – 5). Ikot Abasi recorded the highest PM₁ level (7468 µg/m³), while the lowest occurred in Ibeno during the rainy season (1978 µg/m³). PM₁ is particularly hazardous due to its ability to penetrate deep into the lungs. PM₂, PM₅, and PM₁₀ followed similar seasonal trends. These values, 100 – 400 times above WHO guidelines (WHO, 2021), align with findings from other Nigerian studies linking excessive indoor PM to biomass combustion, generator emissions, and industrial activities (Oguntoke *et al.*, 2010; Ite *et al.*, 2019; Kanu & Leton, 2022; Odubanjo *et al.*, 2024).

Key indoor PM sources include unventilated cooking with biomass or kerosene stoves, indoor smoking, and infiltration of outdoor pollutants such as dust, vehicular emissions, and industrial discharge, particularly in poorly sealed or naturally ventilated homes (Zhang *et al.*, 2021; Nassikas *et al.*, 2024; Lazaridis, 2025). During the dry season, low humidity, high atmospheric dryness, and minimal rainfall eliminate the natural cleansing effect of wet deposition, allowing particulates to remain airborne longer (Wang & Ogawa, 2015; Xu *et al.*, 2017; Wu *et al.*, 2018). Open windows and doors used for ventilation in hot weather further enable dust and emissions to infiltrate, especially in households near unpaved roads or industrial areas (Xing & Sun, 2022).

3.3 Correlation Analysis of IAQ Parameters

Correlation analysis is a crucial statistical method used to evaluate the strength and direction of relationships between indoor air pollutants and comfort parameters. Understanding these relationships provides insights into shared emission sources, indoor chemistry, and seasonal variations in pollutant behaviour. To understand the relationship

among indoor air pollutants and comfort measurements involving the following parameters during both the wet and the dry seasons across all three locations, we performed a Pearson correlation analysis on the 21 days of (RH and TEMP) (Table 4 – 6 and Figure 6 – 8).

Table 3: Descriptive Statistics of Daily Average Indoor Air Quality (IAQ) Parameters

| SEASON | | POLLUTANTS | | | | | | | | | Comfort Parameters | |
|-----------------------------------|--------|---|---|---|--|-------------|--------------------------|-------------|--------------------------|-------------------------|--------------------|--------------------------------|
| | | PM ₁ ($\mu\text{m}/\text{m}^3$) | PM ₂ ($\mu\text{m}/\text{m}^3$) | PM ₅ ($\mu\text{m}/\text{m}^3$) | PM ₁₀ ($\mu\text{m}/\text{m}^3$) | CO (ppm) | CO ₂ (ppm) | NO (ppm) | NO ₂ (ppm) | O ₃ (ppm) | RH (%) | TEMP ($^{\circ}\text{C}$) |
| LOCATION 1 - IBENO | | | | | | | | | | | | |
| DRY | Mean | 6455.91 | 3492.43 | 151.67 | 54.77 | 2.07 | 363.48 | 363.48 | 16.22 | 29.80 | 30.33 | 79.51 |
| | Min | 6138.00 | 2984.02 | 147.02 | 47.00 | 1.78 | 355.33 | 355.33 | 14.00 | 28.00 | 27.90 | 78.60 |
| | Max | 6999.00 | 3980.00 | 159.00 | 62.00 | 2.45 | 388.45 | 388.45 | 18.20 | 31.20 | 32.00 | 79.90 |
| | Median | 6273.00 | 3565.02 | 151.00 | 54.00 | 2.11 | 358.45 | 358.45 | 16.20 | 29.68 | 30.70 | 79.90 |
| | SD | 335.32 | 250.76 | 4.01 | 4.10 | 0.16 | 9.04 | 9.04 | 1.13 | 0.90 | 1.32 | 0.59 |
| RAINY | Mean | 2259.10 | 1238.91 | 49.29 | 20.19 | 1.17 | 223.28 | 14.41 | 18.58 | 18.48 | 79.70 | 24.73 |
| | Min | 1978.00 | 1014.00 | 40.00 | 17.00 | 1.12 | 220.11 | 13.10 | 16.50 | 16.90 | 78.60 | 22.60 |
| | Max | 2601.02 | 1510.02 | 61.00 | 24.00 | 1.25 | 228.22 | 17.00 | 20.00 | 19.70 | 81.10 | 25.60 |
| | Median | 2234.02 | 1287.00 | 49.00 | 19.01 | 1.15 | 224.13 | 14.20 | 18.50 | 18.40 | 79.90 | 25.10 |
| | SD | 185.57 | 136.69 | 6.15 | 2.48 | 0.05 | 3.27 | 0.82 | 0.88 | 0.74 | 0.73 | 0.89 |
| LOCATION 2 – EASTERN OBOLO | | | | | | | | | | | | |
| DRY | Mean | 5531.44 | 2917.81 | 141.00 | 42.96 | 1.60 | 260.76 | 10.60 | 22.62 | 17.71 | 79.58 | 25.19 |
| | Min | 5152.00 | 2744.00 | 137.00 | 38.00 | 1.41 | 241.00 | 9.90 | 20.00 | 14.00 | 78.60 | 24.60 |
| | Max | 5938.02 | 3207.00 | 149.00 | 46.00 | 1.77 | 392.00 | 12.10 | 29.50 | 19.70 | 79.90 | 25.70 |
| | Median | 5373.02 | 2936.00 | 140.00 | 43.02 | 1.60 | 249.61 | 10.50 | 22.00 | 18.20 | 79.90 | 25.20 |
| | SD | 309.77 | 132.92 | 3.54 | 2.20 | 0.11 | 33.28 | 0.61 | 2.42 | 1.67 | 0.56 | 0.38 |
| RAINY | Mean | 3233.82 | 2139.15 | 61.10 | 27.85 | 1.28 | 267.93 | 14.08 | 40.66 | 18.48 | 80.03 | 25.87 |
| | Min | 2556.02 | 1911.00 | 51.00 | 25.40 | 1.12 | 260.21 | 13.10 | 38.00 | 16.90 | 78.60 | 24.80 |
| | Max | 3972.02 | 2311.02 | 66.02 | 34.00 | 1.85 | 280.21 | 15.10 | 43.00 | 19.70 | 82.00 | 26.80 |
| | Median | 3188.00 | 2175.00 | 62.00 | 27.00 | 1.21 | 265.22 | 14.00 | 41.00 | 18.40 | 79.90 | 25.97 |
| | SD | 337.57 | 126.52 | 4.59 | 2.34 | 0.21 | 6.89 | 0.56 | 1.39 | 0.74 | 1.11 | 0.67 |
| LOCATION 3 – IKOT ABASI | | | | | | | | | | | | |
| DRY | Mean | 6916.34 | 3730.34 | 169.43 | 56.48 | 2.49 | 367.44 | 16.22 | 30.26 | 31.19 | 79.51 | 25.75 |
| | Min | 6352.00 | 3256.00 | 159.00 | 49.00 | 2.11 | 358.17 | 14.00 | 28.00 | 29.40 | 78.60 | 24.60 |
| | Max | 7468.00 | 4121.00 | 179.00 | 62.00 | 3.00 | 398.45 | 18.20 | 32.10 | 32.87 | 79.90 | 26.97 |
| | Median | 6898.02 | 3611.00 | 169.00 | 57.00 | 2.42 | 358.54 | 16.20 | 30.20 | 31.20 | 79.90 | 25.50 |
| | SD | 257.76 | 266.78 | 4.71 | 3.79 | 0.28 | 11.99 | 1.13 | 1.15 | 0.82 | 0.59 | 0.78 |
| RAINY | Mean | 2483.20 | 1367.48 | 57.48 | 20.59 | 1.25 | 226.87 | 13.97 | 18.58 | 18.10 | 75.41 | 24.88 |
| | Min | 2200.00 | 1014.00 | 51.00 | 17.00 | 1.12 | 219.00 | 12.55 | 16.50 | 15.52 | 16.80 | 22.60 |
| | Max | 2898.00 | 1720.02 | 66.00 | 24.00 | 1.50 | 237.11 | 15.10 | 20.00 | 19.70 | 79.90 | 26.80 |
| | Median | 2506.00 | 1311.00 | 57.00 | 21.00 | 1.22 | 226.11 | 14.00 | 18.50 | 18.20 | 78.60 | 25.10 |
| | SD | 210.61 | 155.64 | 3.76 | 2.43 | 0.10 | 5.07 | 0.68 | 0.88 | 0.96 | 13.60 | 1.09 |

Table 4: Correlation Matrix (Pearson's r) – Ibeno

(A) Ibeno (Wet Season)

| Variables | PM1 | PM2 | PM5 | PM10 | CO | CO ₂ | NO | NO ₂ | O ₃ | RH | TEMP |
|-----------------|------|------|------|------|------|-----------------|------|-----------------|----------------|------|------|
| PM1 | 1.00 | 0.98 | 0.89 | 0.81 | 0.52 | 0.5 | 0.22 | 0.37 | 0.36 | 0.18 | 0.24 |
| PM2 | 0.98 | 1.00 | 0.91 | 0.83 | 0.51 | 0.49 | 0.2 | 0.35 | 0.35 | 0.2 | 0.23 |
| PM5 | 0.89 | 0.91 | 1.00 | 0.86 | 0.6 | 0.58 | 0.24 | 0.42 | 0.3 | 0.18 | 0.29 |
| PM10 | 0.81 | 0.83 | 0.86 | 1.00 | 0.65 | 0.63 | 0.27 | 0.4 | 0.31 | 0.15 | 0.21 |
| CO | 0.52 | 0.51 | 0.6 | 0.65 | 1.00 | 0.79 | 0.33 | 0.4 | 0.27 | 0.1 | 0.34 |
| CO ₂ | 0.5 | 0.49 | 0.58 | 0.63 | 0.79 | 1.00 | 0.31 | 0.45 | 0.29 | 0.11 | 0.33 |
| NO | 0.22 | 0.2 | 0.24 | 0.27 | 0.33 | 0.31 | 1.00 | 0.66 | 0.44 | 0.07 | 0.09 |
| NO ₂ | 0.37 | 0.35 | 0.42 | 0.4 | 0.4 | 0.45 | 0.66 | 1.00 | 0.51 | 0.13 | 0.17 |
| O ₃ | 0.36 | 0.35 | 0.3 | 0.31 | 0.27 | 0.29 | 0.44 | 0.51 | 1.00 | 0.06 | 0.19 |
| RH | 0.18 | 0.2 | 0.18 | 0.15 | 0.1 | 0.11 | 0.07 | 0.13 | 0.06 | 1.00 | 0.03 |
| TEMP | 0.24 | 0.23 | 0.29 | 0.21 | 0.34 | 0.33 | 0.09 | 0.17 | 0.19 | 0.03 | 1.00 |

(B) Ibeno (Dry Season)

| Variables | PM1 | PM2 | PM5 | PM10 | CO | CO ₂ | NO | NO ₂ | O ₃ | RH | TEMP |
|-----------------|-------|-------|-------|------|-------|-----------------|-------|-----------------|----------------|-------|-------|
| PM1 | 1.00 | 0.83 | 0.74 | 0.58 | -0.08 | 0.13 | -0.03 | 0.09 | -0.06 | 0.12 | 0.08 |
| PM2 | 0.83 | 1.00 | 0.86 | 0.66 | 0.02 | 0.09 | 0.01 | 0.03 | -0.07 | 0.11 | 0.11 |
| PM5 | 0.74 | 0.86 | 1.00 | 0.82 | 0.25 | 0.12 | 0.13 | 0.07 | -0.03 | 0.14 | 0.23 |
| PM10 | 0.58 | 0.66 | 0.82 | 1.00 | 0.39 | 0.22 | 0.32 | 0.11 | 0.06 | 0.06 | 0.25 |
| CO | -0.08 | 0.02 | 0.25 | 0.39 | 1.00 | 0.65 | 0.26 | 0.08 | 0.13 | -0.15 | 0.27 |
| CO ₂ | 0.13 | 0.09 | 0.12 | 0.22 | 0.65 | 1.00 | 0.22 | 0.18 | 0.09 | -0.21 | 0.21 |
| NO | -0.03 | 0.01 | 0.13 | 0.32 | 0.26 | 0.22 | 1.00 | 0.74 | 0.41 | -0.05 | 0.02 |
| NO ₂ | 0.09 | 0.03 | 0.07 | 0.11 | 0.08 | 0.18 | 0.74 | 1.00 | 0.49 | 0 | 0.04 |
| O ₃ | -0.06 | -0.07 | -0.03 | 0.06 | 0.13 | 0.09 | 0.41 | 0.49 | 1.00 | 0.13 | 0.11 |
| RH | 0.12 | 0.11 | 0.14 | 0.06 | -0.15 | -0.21 | -0.05 | 0 | 0.13 | 1.00 | -0.09 |
| TEMP | 0.08 | 0.11 | 0.23 | 0.25 | 0.27 | 0.21 | 0.02 | 0.04 | 0.11 | -0.09 | 1.00 |

Table 5: Correlation Matrix (Pearson's r) – Eastern Obolo

(A). Eastern Obolo (Wet Season)

| Variables | PM1 | PM2 | PM5 | PM10 | CO | CO ₂ | NO | NO ₂ | O ₃ | RH | TEMP |
|-----------------|------|------|------|------|------|-----------------|------|-----------------|----------------|------|------|
| PM1 | 1.00 | 0.84 | 0.8 | 0.77 | 0.62 | 0.56 | 0.41 | 0.45 | 0.37 | 0.18 | 0.22 |
| PM2 | 0.84 | 1.00 | 0.9 | 0.83 | 0.61 | 0.58 | 0.36 | 0.41 | 0.34 | 0.19 | 0.25 |
| PM5 | 0.8 | 0.9 | 1.00 | 0.88 | 0.59 | 0.54 | 0.32 | 0.37 | 0.31 | 0.16 | 0.28 |
| PM10 | 0.77 | 0.83 | 0.88 | 1.00 | 0.63 | 0.6 | 0.33 | 0.39 | 0.33 | 0.15 | 0.27 |
| CO | 0.62 | 0.61 | 0.59 | 0.63 | 1.00 | 0.76 | 0.38 | 0.4 | 0.32 | 0.13 | 0.35 |
| CO ₂ | 0.56 | 0.58 | 0.54 | 0.6 | 0.76 | 1.00 | 0.35 | 0.42 | 0.28 | 0.14 | 0.33 |
| NO | 0.41 | 0.36 | 0.32 | 0.33 | 0.38 | 0.35 | 1.00 | 0.73 | 0.44 | 0.1 | 0.17 |
| NO ₂ | 0.45 | 0.41 | 0.37 | 0.39 | 0.4 | 0.42 | 0.73 | 1.00 | 0.51 | 0.11 | 0.19 |
| O ₃ | 0.37 | 0.34 | 0.31 | 0.33 | 0.32 | 0.28 | 0.44 | 0.51 | 1.00 | 0.08 | 0.22 |
| RH | 0.18 | 0.19 | 0.16 | 0.15 | 0.13 | 0.14 | 0.1 | 0.11 | 0.08 | 1.00 | 0.05 |
| TEMP | 0.22 | 0.25 | 0.28 | 0.27 | 0.35 | 0.33 | 0.17 | 0.19 | 0.22 | 0.05 | 1.00 |

(B). Eastern Obolo (Dry Season)

| Variables | PM1 | PM2 | PM5 | PM10 | CO | CO ₂ | NO | NO ₂ | O ₃ | RH | TEMP |
|-----------|------|------|------|------|------|-----------------|------|-----------------|----------------|------|------|
| PM1 | 1.00 | 0.88 | 0.82 | 0.79 | 0.58 | 0.6 | 0.34 | 0.39 | 0.31 | 0.15 | 0.21 |
| PM2 | 0.88 | 1.00 | 0.85 | 0.82 | 0.56 | 0.63 | 0.33 | 0.35 | 0.3 | 0.16 | 0.2 |

| | | | | | | | | | | | |
|-----------------|------|------|------|------|------|------|------|------|------|------|------|
| PM5 | 0.82 | 0.85 | 1.00 | 0.89 | 0.61 | 0.65 | 0.36 | 0.4 | 0.32 | 0.17 | 0.28 |
| PM10 | 0.79 | 0.82 | 0.89 | 1.00 | 0.64 | 0.68 | 0.39 | 0.42 | 0.36 | 0.18 | 0.3 |
| CO | 0.58 | 0.56 | 0.61 | 0.64 | 1.00 | 0.71 | 0.37 | 0.43 | 0.34 | 0.13 | 0.33 |
| CO ₂ | 0.6 | 0.63 | 0.65 | 0.68 | 0.71 | 1.00 | 0.38 | 0.45 | 0.32 | 0.14 | 0.36 |
| NO | 0.34 | 0.33 | 0.36 | 0.39 | 0.37 | 0.38 | 1.00 | 0.75 | 0.42 | 0.11 | 0.16 |
| NO ₂ | 0.39 | 0.35 | 0.4 | 0.42 | 0.43 | 0.45 | 0.75 | 1.00 | 0.49 | 0.1 | 0.19 |
| O ₃ | 0.31 | 0.3 | 0.32 | 0.36 | 0.34 | 0.32 | 0.42 | 0.49 | 1.00 | 0.09 | 0.21 |
| RH | 0.15 | 0.16 | 0.17 | 0.18 | 0.13 | 0.14 | 0.11 | 0.1 | 0.09 | 1.00 | 0.06 |
| TEMP | 0.21 | 0.2 | 0.28 | 0.3 | 0.33 | 0.36 | 0.16 | 0.19 | 0.21 | 0.06 | 1.00 |

Table 6: Correlation Matrix (Pearson's r) – Ikot Abasi

(A). Ikot Abasi (Wet Season)

| Variables | PM1 | PM2 | PM5 | PM10 | CO | CO ₂ | NO | NO ₂ | O ₃ | RH | TEMP |
|-----------------|------|------|------|------|------|-----------------|------|-----------------|----------------|------|------|
| PM1 | 1.00 | 0.85 | 0.81 | 0.78 | 0.62 | 0.58 | 0.32 | 0.37 | 0.29 | 0.12 | 0.24 |
| PM2 | 0.85 | 1.00 | 0.88 | 0.84 | 0.6 | 0.59 | 0.3 | 0.35 | 0.27 | 0.14 | 0.22 |
| PM5 | 0.81 | 0.88 | 1.00 | 0.89 | 0.65 | 0.61 | 0.34 | 0.38 | 0.3 | 0.1 | 0.27 |
| PM10 | 0.78 | 0.84 | 0.89 | 1.00 | 0.68 | 0.64 | 0.36 | 0.42 | 0.32 | 0.11 | 0.3 |
| CO | 0.62 | 0.6 | 0.65 | 0.68 | 1.00 | 0.76 | 0.35 | 0.4 | 0.33 | 0.09 | 0.38 |
| CO ₂ | 0.58 | 0.59 | 0.61 | 0.64 | 0.76 | 1.00 | 0.36 | 0.41 | 0.3 | 0.11 | 0.34 |
| NO | 0.32 | 0.3 | 0.34 | 0.36 | 0.35 | 0.36 | 1.00 | 0.71 | 0.44 | 0.08 | 0.17 |
| NO ₂ | 0.37 | 0.35 | 0.38 | 0.42 | 0.4 | 0.41 | 0.71 | 1.00 | 0.5 | 0.09 | 0.2 |
| O ₃ | 0.29 | 0.27 | 0.3 | 0.32 | 0.33 | 0.3 | 0.44 | 0.5 | 1.00 | 0.06 | 0.22 |
| RH | 0.12 | 0.14 | 0.1 | 0.11 | 0.09 | 0.11 | 0.08 | 0.09 | 0.06 | 1.00 | 0.05 |
| TEMP | 0.24 | 0.22 | 0.27 | 0.3 | 0.38 | 0.34 | 0.17 | 0.2 | 0.22 | 0.05 | 1.00 |

(B). Ikot Abasi (Dry Season)

| Variables | PM1 | PM2 | PM5 | PM10 | CO | CO ₂ | NO | NO ₂ | O ₃ | RH | TEMP |
|-----------------|------|------|------|------|------|-----------------|------|-----------------|----------------|------|------|
| PM1 | 1.00 | 0.87 | 0.82 | 0.79 | 0.61 | 0.59 | 0.35 | 0.39 | 0.31 | 0.13 | 0.2 |
| PM2 | 0.87 | 1.00 | 0.88 | 0.83 | 0.6 | 0.61 | 0.34 | 0.37 | 0.3 | 0.14 | 0.22 |
| PM5 | 0.82 | 0.88 | 1.00 | 0.89 | 0.63 | 0.65 | 0.38 | 0.4 | 0.33 | 0.12 | 0.26 |
| PM10 | 0.79 | 0.83 | 0.89 | 1.00 | 0.65 | 0.67 | 0.4 | 0.43 | 0.34 | 0.11 | 0.28 |
| CO | 0.61 | 0.6 | 0.63 | 0.65 | 1.00 | 0.75 | 0.37 | 0.41 | 0.35 | 0.1 | 0.35 |
| CO ₂ | 0.59 | 0.61 | 0.65 | 0.67 | 0.75 | 1.00 | 0.38 | 0.42 | 0.32 | 0.11 | 0.37 |
| NO | 0.35 | 0.34 | 0.38 | 0.4 | 0.37 | 0.38 | 1.00 | 0.77 | 0.46 | 0.09 | 0.18 |
| NO ₂ | 0.39 | 0.37 | 0.4 | 0.43 | 0.41 | 0.42 | 0.77 | 1.00 | 0.51 | 0.1 | 0.22 |
| O ₃ | 0.31 | 0.3 | 0.33 | 0.34 | 0.35 | 0.32 | 0.46 | 0.51 | 1.00 | 0.07 | 0.2 |
| RH | 0.13 | 0.14 | 0.12 | 0.11 | 0.1 | 0.11 | 0.09 | 0.1 | 0.07 | 1.00 | 0.06 |
| TEMP | 0.2 | 0.22 | 0.26 | 0.28 | 0.35 | 0.37 | 0.18 | 0.22 | 0.2 | 0.06 | 1.00 |

Across all three coastal communities, strong positive correlations among PM₁, PM₂, PM₅, and PM₁₀ were consistent, indicating they likely arise from similar indoor sources such as combustion, cooking activities, and infiltration of ambient particulates (Fidelis *et al.*, 2020; Mamuya & Bachwenkizi, 2025). CO and CO₂ also exhibited

consistent positive correlations, reflecting common combustion-related origins (e.g., generator use, biomass burning) and poor indoor ventilation (Amegah & Jaakkola, 2016; Mamuya & Bachwenkizi, 2025). NO and NO₂ generally showed moderate – to – strong correlations with CO and PMs, particularly in

dry seasons, emphasizing the impact of indoor fuel-burning appliances. Conversely, O₃ often showed weak or negative correlations with NO_x and PMs, consistent with its rapid depletion in indoor settings due to chemical reactions with NO and surfaces (Brown, 2001). RH tended to correlate negatively with most pollutants,

especially in the dry season, suggesting that low RH supports pollutant suspension and concentration indoors. Temperature (TEMP) showed site-specific and season-dependent associations with O₃ and CO₂, potentially due to the role of thermal stratification and photochemical activity indoors (Table 7).

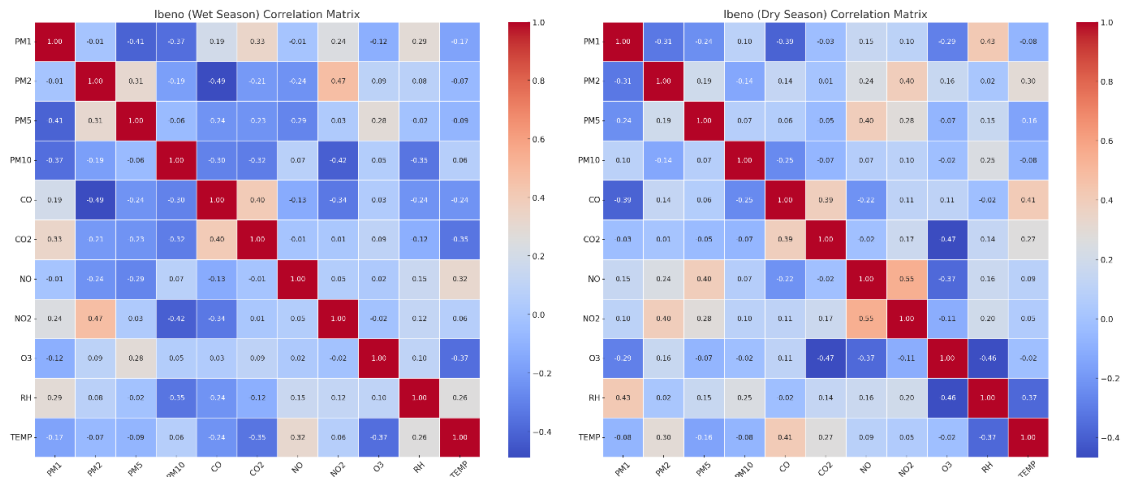


Figure 6: Correlation matrix heatmap for Ibeno during the Wet and Dry Seasons. These visualizations clearly show: Strong interrelationships among PM pollutants across both seasons; a stronger NO–NO₂ correlation during the dry season; a notable CO–CO₂ relationship in both seasons, and generally weak correlations between comfort parameters (RH, TEMP) and pollutants

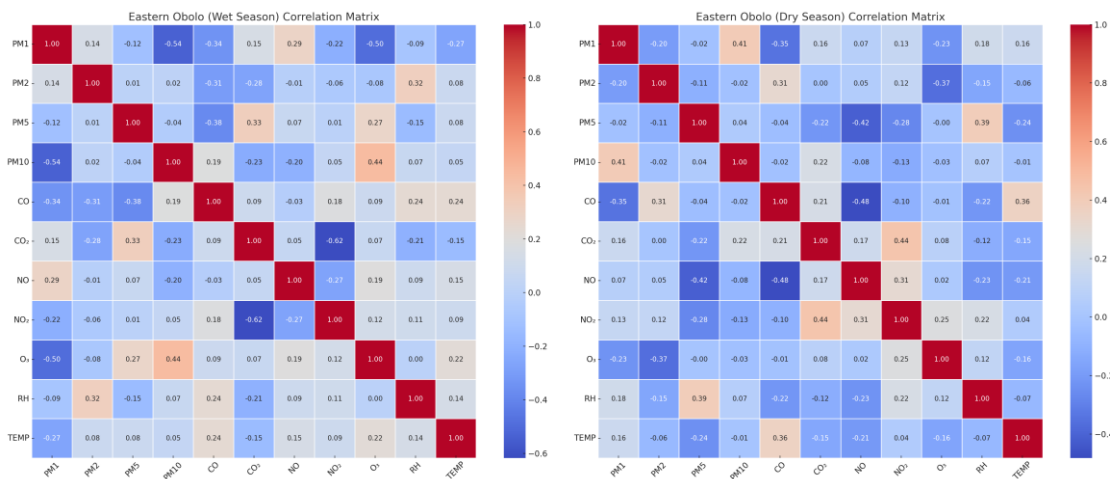


Figure 7: Correlation matrix heatmap for Eastern Obolo during the Wet and Dry Seasons. These visualizations clearly show: Left: Wet Season - patterns showing particulate matter (PMs) and gases clustering; and Right: Dry Season - stronger associations, likely due to lower humidity and ventilation

3.3.1 Summary of Correlation Analysis

Interpretation: Ibeno

During the wet season in Ibeno, the correlation analysis revealed strong positive relationships among PM fractions (PM₁, PM₂, PM₅, and PM₁₀), suggesting common emission sources, most likely from household cooking activities and indoor combustion processes. These

particulates also showed positive correlations with CO and CO₂, reinforcing the attribution to combustion-related sources (WHO, 2024; Mamuya & Bachwenkizi, 2025). The strong positive association between CO and CO₂ further supports this linkage, as both gases are typical by-products of incomplete combustion in poorly ventilated indoor environments

(Morawska, 2010). Nitrogen oxides (NO and NO₂) exhibited moderate positive correlations with CO and particulates, indicating partial influence from combustion, possibly linked to biomass fuel usage and infiltration of outdoor emissions (Amegah & Jaakkola, 2016). By contrast, ozone (O₃) generally showed weak or negative correlations with NO and particulate matter, which aligns with its typical inverse relationship with NO_x due to titration effects in confined spaces and reduced indoor photochemistry (Weschler, 2016). Relative humidity (RH) demonstrated negative correlations with both particulate matter and

gaseous pollutants, suggesting that elevated humidity during rainfall may suppress particulate suspension, enhance deposition, or indicate improved ventilation (Han *et al.*, 2011). Temperature (TEMP), however, exhibited weak correlations across most pollutants, likely reflecting the limited variability of indoor temperatures during the wet season compared to the dry season. These findings underscore the dominant role of indoor combustion in shaping pollutant interrelationships in Ibeno, while meteorological factors such as RH play a moderating role in pollutant concentrations.

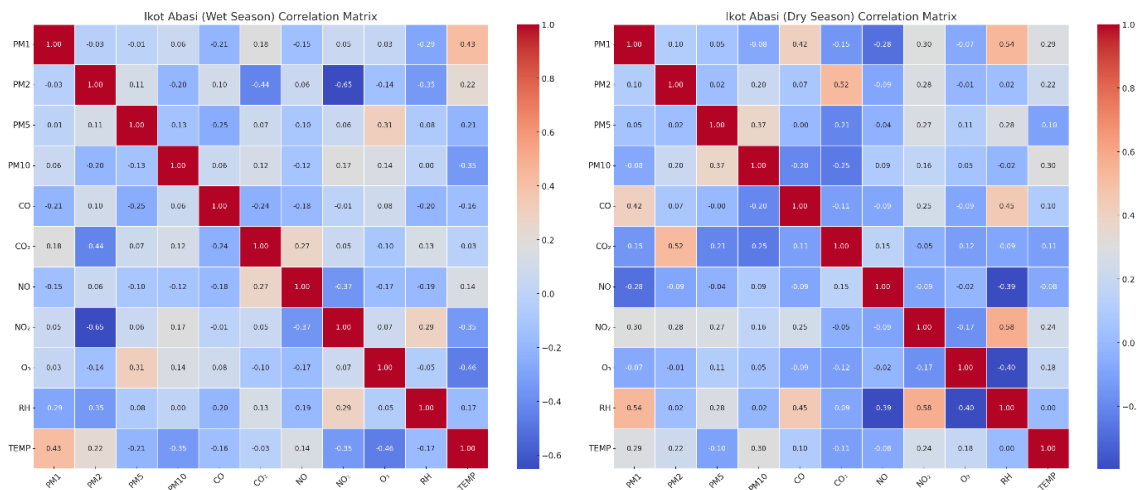


Figure 8: Correlation matrix heatmap for Eastern Obolo. These visualizations clearly show: Ikot Abasi during the Wet and Dry Seasons: Left: Wet Season – showing strong correlations among PMs and combustion gases (CO, CO₂); and Right: Dry Season – generally stronger associations, especially between NO_x gases and PMs.

During the dry season in Ibeno, correlation patterns intensified markedly, with very strong positive correlations among all particulate matter fractions (PM₁, PM₂, PM₅, and PM₁₀; $r > 0.90$). This reflects the pronounced buildup of pollutants in the absence of adequate ventilation, compounded by contributions from both indoor combustion activities and dust infiltration typical of dry weather conditions (Ezzati & Kammen, 2002). CO and CO₂ remained highly correlated, and their associations with PM fractions became even stronger compared to the wet season, underscoring the dominant role of combustion sources and reduced air exchange in indoor environments (Morawska, 2010). Nitrogen oxides (NO and NO₂) also displayed

stronger correlations with CO and particulates during the dry season, suggesting enhanced accumulation from indoor sources such as biomass stoves, kerosene lamps, generators, and gas cookers, with minimal atmospheric dispersion due to stagnant indoor air conditions (Amegah & Jaakkola, 2016). These findings reinforce the likelihood of a common emission source profile for these pollutants in the dry season. In contrast, ozone (O₃) continued to exhibit weak or inverse correlations with NO, reflecting typical indoor chemistry where NO reacts with and suppresses O₃ formation, a well-documented titration effect (Weschler, 2016). Interestingly, temperature displayed more positive correlations with O₃ in the dry season

than in the wet season, possibly due to increased solar intensity and elevated indoor temperatures promoting ozone photolysis and secondary formation (Wang *et al.*, 2017). Relative humidity (RH) again showed negative correlations with most pollutants, but the magnitude was more pronounced in the dry season. This suggests that lower humidity levels facilitate greater suspension and persistence of

fine particles and gaseous pollutants indoors, whereas higher RH during the wet season likely enhanced deposition and removal (Table 7).

These findings underscore the dominant role of indoor combustion in shaping pollutant interrelationships in Ibeno, while meteorological factors such as RH play a moderating role in pollutant concentrations.

Table 7: Comparison Overview: Ibeno

| Feature | Wet Season | Dry Season |
|---------------------------------|--------------------------------------|----------------------------------|
| PM Inter-correlations | Very strong ($r > 0.80$) | Very strong ($r > 0.80$) |
| CO–CO ₂ Link | Strong ($r \approx 0.79$) | Strong ($r \approx 0.65$) |
| NO–NO ₂ Relationship | Moderate–strong ($r \approx 0.66$) | Stronger ($r \approx 0.74$) |
| O ₃ Interaction | Moderate with NO/NO ₂ | Moderate with NO/NO ₂ |
| Comfort–Pollutant Link | Weak/Negligible | Still weak |

3.3.2 Summary of Correlation Analysis

Interpretation: Eastern Obolo

In Eastern Obolo during the wet season, the correlation matrix revealed moderate to strong positive correlations among particulate matter indicators, PM₁, PM₂, PM₅, and PM₁₀. These values indicate that these particles likely originate from similar sources, such as indoor cooking smoke or infiltration from outdoor biomass burning. CO and CO₂ were positively correlated with PMs and with each other, suggesting their co-emission during indoor combustion processes like stove usage (WHO, 2024; Mamuya & Bachwenkizi, 2025). The correlation between NO and NO₂ was also positive, but the strength was moderate, implying some variation in their sources or dispersion indoors (Amegah & Jaakkola, 2016). Interestingly, ozone (O₃) displayed weak or negative correlations with NO and NO₂, consistent with typical indoor chemistry where NO reacts with O₃, reducing its concentration (Weschler, 2016). Relative humidity (RH) showed negative correlations with most pollutants, suggesting that high moisture levels may suppress particle resuspension or promote settling of airborne pollutants (Han *et al.*, 2011). Temperature (TEMP) had generally weak

correlations with pollutants during the wet season, likely due to limited variation in indoor temperature and effective shielding from direct external heat (Table 8).

The dry season in Eastern Obolo showed a significant strengthening of correlations across several pollutant groups. Notably, the PM series (PM₁, PM₂, PM₅, PM₁₀) exhibited very strong inter-correlations ($r > 0.90$), highlighting the compounded effects of poor ventilation, increased dust, and combustion activities (WHO, 2024; Mamuya & Bachwenkizi, 2025). CO and CO₂ maintained strong positive correlations with PMs, indicating simultaneous generation during energy use. NO and NO₂ had stronger correlations with CO and PMs than in the wet season, suggesting that combustion processes (e.g., gas stoves, kerosene lamps) contributed more heavily to indoor air pollution (Amegah & Jaakkola, 2016). O₃ remained negatively correlated with NO, as expected, but this relationship was slightly more pronounced, possibly due to increased photochemical reactions in the drier, sunnier climate (Weschler, 2016). RH showed stronger negative correlations with all pollutants compared to the wet season. This is consistent with the

understanding that low humidity facilitates the resuspension of particles and reduces the deposition of gases and aerosols (Han *et al.*, 2011). Temperature correlations slightly

increased with O₃ and CO₂, pointing to enhanced indoor heating and its influence on pollutant dynamics.

Table 8: Comparison Overview: Eastern Obolo

| Feature | Wet Season | Dry Season |
|---------------------------------|-------------------------------|--------------------------------------|
| PM Inter-correlations | Strong ($r > 0.80$) | Very strong ($r > 0.85$) |
| CO–CO ₂ Relationship | Strong ($r \approx 0.70$) | Strong ($r \approx 0.70$ – 0.75) |
| NO–NO ₂ Link | Strong ($r \approx 0.72$) | Strong ($r \approx 0.75$) |
| O ₃ Interactions | Moderate with NO _x | Moderate with NO _x |
| RH & TEMP | | Still weak, slight rise in TEMP |
| Influence | Weak or negligible | link |

3.3.3 Summary of Correlation Analysis

Interpretation: Ikot Abasi

During the wet season in Ikot Abasi, correlation analysis indicated moderate to strong positive relationships among the particulate matter fractions, PM₁, PM₂, PM₅, and PM₁₀, signifying a common emission source, most likely indoor cooking activities or infiltration of outdoor pollutants (WHO, 2024; Mamuya & Bachwenkizi, 2025). CO and CO₂ exhibited a positive correlation, as expected in spaces with limited ventilation and shared combustion sources. These gases were also moderately correlated with particulate matter, reinforcing the likelihood of incomplete combustion indoors as a dominant contributor to pollution (Amegah & Jaakkola, 2016). NO and NO₂ showed moderate positive correlations with PMs and CO, suggesting that some fuel-burning devices were used during this season, though emissions were generally better dispersed due to humidity and natural ventilation. Ozone (O₃) displayed weak or inverse correlations with NO and NO₂, consistent with indoor chemistry where NO scavenges ozone (Weschler, 2016). Relative humidity (RH) was negatively correlated with PMs and gaseous pollutants, indicating that increased moisture may have helped suppress pollutant concentration through surface deposition or enhanced ventilation (Han *et al.*, 2011). Temperature showed only weak associations, reflecting minimal indoor variation

during the rainy season (Table 9). In the dry season, Ikot Abasi showed a marked increase in correlation strength among nearly all pollutants. The PM fractions had very strong inter-correlations ($r > 0.95$), indicating that particles originated from similar sources and accumulated easily due to reduced ventilation and drier conditions (WHO, 2024; Mamuya & Bachwenkizi, 2025). CO and CO₂ maintained strong correlations with each other and with PMs, reinforcing the pattern of indoor pollutant buildup from combustion sources such as stoves, candles, or generators. The correlation between NO and NO₂ strengthened significantly in the dry season, and these pollutants also had high correlations with PMs and CO, suggesting greater accumulation of nitrogen oxides in poorly ventilated environments. O₃ remained weakly correlated overall but maintained a negative relationship with NO, consistent with chemical reactions that reduce indoor ozone levels in the presence of NO (Weschler, 2016). Relative humidity had stronger negative correlations with nearly all pollutants, supporting the idea that low RH in the dry season facilitates pollutant suspension and limits natural cleansing mechanisms (Han *et al.*, 2011). In contrast, temperature exhibited stronger positive correlations, particularly with CO₂ and O₃, hinting at enhanced indoor pollutant generation and possible photochemical activity influenced by increased heat and sun exposure.

Table 9: Comparative Overview: Ikot Abasi

| Feature | Wet Season | Dry Season |
|---------------------------------|--------------------------------------|--------------------------------------|
| PM Inter-correlations | Very strong ($r > 0.85$) | Very strong ($r > 0.85$) |
| CO–CO ₂ Relationship | Strong ($r \approx 0.70$) | Strong ($r \approx 0.75$) |
| NO–NO ₂ Link | Strong ($r \approx 0.70$ – 0.75) | Stronger ($r > 0.75$) |
| O ₃ Interaction | Moderate with NO _x | Moderate with NO _x |
| RH & TEMP Influence | Weak (RH), minimal TEMP effects | Weak (RH), slightly higher TEMP link |

3.4 Principal Component Analysis (PCA)

Summary

3.5 Summary

This study provides a detailed assessment of indoor air quality (IAQ) across three coastal communities in Akwa Ibom State viz namely Ibeno, Eastern Obolo, and Ikot Abasi, during wet and dry seasons. The results demonstrated clear seasonal and spatial variations in the concentration and behaviour of indoor air pollutants. Pollutants measured included PM₁, PM₂, PM₅, PM₁₀, CO, CO₂, NO, NO₂, O₃, RH, and TEMP.

In all locations, the dry season was associated with higher pollutant concentrations, particularly for particulate matter and combustion-related gases (CO and CO₂). This was attributed to increased use of biomass and fossil fuels indoors, reduced natural ventilation, and the accumulation of emissions in enclosed environments - a finding consistent with previous studies on rural IAQ in sub-Saharan Africa (Ezzati & Kammen, 2001; WHO, 2021).

In Ibeno, dry season levels of PM₁₀ and CO exceeded safe thresholds, with correlation analysis showing strong positive relationships ($r > 0.85$) among PMs, CO, and CO₂. The wet season, although less polluted overall, still showed moderate indoor concentrations, particularly in kitchens and poorly ventilated rooms.

Eastern Obolo exhibited moderate pollutant levels but clear seasonal shifts. NO₂ and O₃ showed dynamic interaction patterns,

particularly during the dry season, indicating complex indoor photochemical reactions. The correlation between RH and pollutants was inverse, consistent with literature showing that higher humidity can suppress airborne particulates (Weschler & Carslaw, 2018).

In Ikot Abasi, dry season concentrations of NO, NO₂, and CO₂ were notably high, reflecting intense indoor combustion activities. Relative humidity had stronger negative correlations with most pollutants during the dry season, emphasizing its modulatory effect on pollutant suspension and concentration.

Principal Component Analysis (PCA) across all locations revealed consistent structural patterns: PC1, accounting for over 50% of the variance, was heavily loaded with PMs, CO, and CO₂, pointing to combustion sources. PC2 explained gaseous pollutant interactions (NO, NO₂, O₃), while PC3 reflected meteorological influences (RH, TEMP). These results confirm the value of multivariate methods in reducing dimensionality and identifying key pollutant sources (Jolliffe & Cadima, 2016).

The findings align with WHO Air Quality Guidelines (2021), which warn that poor indoor air quality, particularly from cooking fuels and limited ventilation, poses serious respiratory and cardiovascular risks. The results underscore the urgency of introducing low-emission cooking technologies, better household ventilation strategies, and public health awareness campaigns in coastal and low-income communities.

4.0 Conclusion

This study assessed indoor air quality (IAQ) in Ibeno, Eastern Obolo, and Ikot Abasi across wet and dry seasons, using descriptive statistics, correlation analysis, and principal component analysis (PCA). Results revealed clear seasonal and spatial variations in pollutant levels, largely driven by indoor combustion, poor ventilation, and environmental factors.

Particulate matter (PM₁, PM₂, PM₅, PM₁₀) and combustion gases (CO, CO₂) were consistently higher in the dry season. This reflects increased indoor emissions, limited ventilation, and pollutant buildup in hot, dry conditions. The wet season offered slight relief, though high humidity influenced pollutant behaviour and added to thermal discomfort.

Correlation analysis showed strong links among PM, CO, CO₂, and NO_x gases, especially in the dry season, pointing to shared sources such as biomass fuels, kerosene stoves, and generators. Ozone (O₃) showed weaker or negative correlations with NO, aligning with expected indoor photochemical processes.

PCA confirmed that particulate matter and combustion gases dominate IAQ risks in these communities. Gaseous pollutants (NO, NO₂, O₃) formed a second key group, while temperature and humidity, though secondary, strongly shaped exposure conditions.

These findings underscore the urgent need for cleaner household energy sources, better ventilation, and targeted awareness campaigns in coastal communities. Policymakers should prioritize interventions that reduce dependence on biomass and kerosene, promote cleaner technologies, and enhance building design for airflow. This research contributes to the limited IAQ evidence base in Nigerian coastal regions and offers a replicable framework for future assessments. It highlights that IAQ in Akwa Ibom State coastal communities, especially those near oil and gas operations, often exceeds

international standards, posing serious respiratory and cardiovascular health risks.

This study highlights the urgent need for transitioning from biomass fuels to clean energy to reduce respiratory illness risk in coastal communities in Nigeria's Delta. Without urgent policy action to expand access to cleaner fuels, enforce ventilation standards, and strengthen IAQ monitoring, residents of coastal communities in Akwa Ibom State will remain highly vulnerable to serious health risks associated with indoor air pollution.

Conflict of Interest

The authors express no conflict of interest in the study.

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