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SPATIO-SEASONAL VARIABILITY AND SOURCE INFERENCE OF $PM_{2.5}$ IN ABUJA, NIGERIA: IMPLICATIONS FOR URBAN AIR QUALITY POLICY

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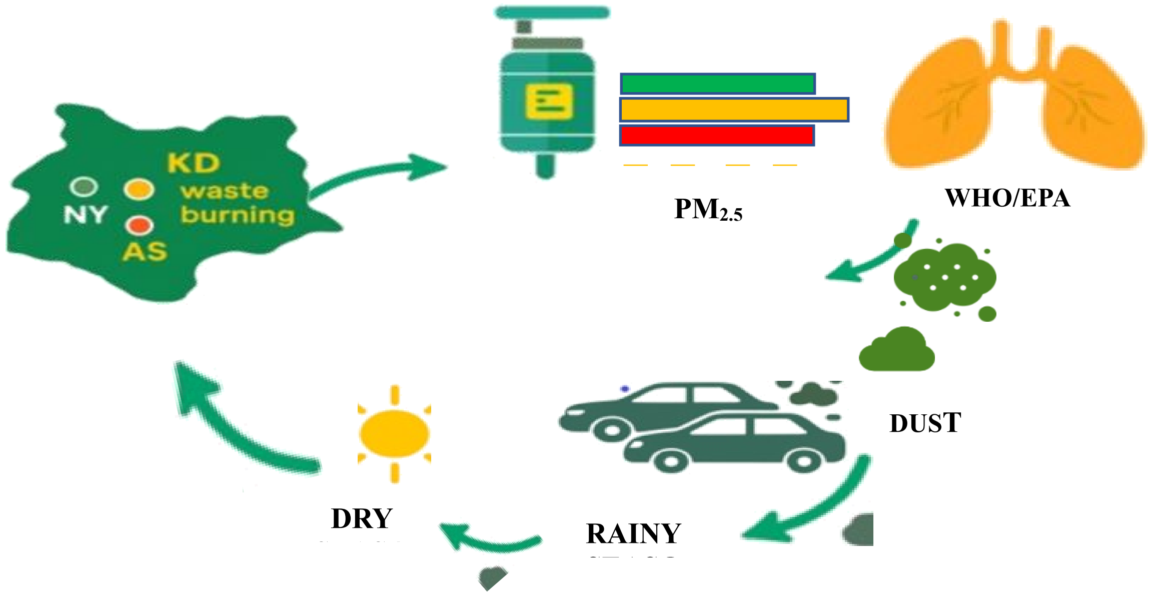
Abstract

Particulate matter ($PM_{2.5}$) poses a critical global public health risk. Urban centers in developing countries, like Abuja, Nigeria, frequently experience air quality levels that exceed international guidelines, yet data remains sparse. This study conducted a spatio-temporal assessment of $PM_{2.5}$ concentrations across three distinct urban locales in Abuja—Karu Abattoir (KD), Nyanya Park (NY), and Asokoro (AS) to capture variability from anthropogenic and traffic influences. 24-hour samples were collected using a [Insert Sampler Model, e.g., BGI PQ100 low-volume gravimetric sampler] during the distinct dry and rainy seasons. $PM_{2.5}$ mass was determined gravimetrically. Concurrent meteorological data were analyzed using Pearson correlation to identify key drivers of pollution dispersion and accumulation. $PM_{2.5}$ concentrations exhibited significant seasonal and spatial heterogeneity. Dry season levels (50.34 – 87.07 µg/m³) consistently surpassed WHO (15 µg/m³), US EPA (35 µg/m³), and EU (25 µg/m³) standards by a factor of 3.3-5.8, with Nyanya Park, a high-traffic zone, recording the highest burden. Air Quality Index (AQI) categorizations ranged from "Unhealthy for Sensitive Groups" to "Unhealthy." Meteorological analysis revealed that low wind speed and high atmospheric pressure during the dry season facilitated severe pollutant accumulation. While wet season precipitation provided some scavenging, it was insufficient to reduce concentrations to safe levels. Abuja experiences a severe and seasonally exacerbated $PM_{2.5}$ pollution problem, positioning it among the most polluted urban centers globally. The findings underscore an urgent public health priority and necessitate immediate, targeted policy interventions, including enhanced continuous monitoring, traffic management, and public awareness campaigns.

Keywords: *Gravimetric Analysis; Sub-Saharan Africa; Particulate Matter; Air Quality Index (AQI); Meteorological Parameters.*

Graphical Abstract

Spatio- seasonal $PM_{2.5}$ Variability & Source Inference in Abuja



1.0 INTRODUCTION

Polymer Air quality plays a critical role in human health, particularly within environments where vulnerable populations are concentrated. $PM_{2.5}$, a fine particulate pollutant with a diameter ≤2.5 µm, is known for its ability to penetrate deep into the respiratory system, leading to serious health implications. Although the global health impacts of $PM_{2.5}$ are widely acknowledged in regions such as the United States, China, India, Brazil, South Korea, and the European Union [1]. Studies from Europe and Asia have consistently demonstrated the presence of airborne pollutants in healthcare environments [5], with short- and long-term exposure to $PM_{2.5}$ being linked to asthma, cardiovascular disease, and premature death [6].

Results from the Global Burden of Disease (GBD) Study 2017 emphasize air pollution, especially $PM_{2.5}$, as a major contributor to global morbidity and mortality. Numerous studies, including those by [2], have established links between long-term exposure to air pollution and cardiovascular diseases, while [3] detailed the biological mechanisms through which particulate matter induces oxidative stress and inflammation. Meta-analyses, such as those by [8], have confirmed strong correlations between PM exposure and cardiopulmonary mortality, while [9] found links between long-term PM_{10} exposure and lung cancer. [10].

Further established $PM_{2.5}$ as having a more substantial impact on cardiovascular health than PM_{10}, emphasizing the importance of fine particle monitoring in health-centric spaces. Environmental toxicology literature, including work by [6] and [7], highlights the harmful neurological and systemic effects of pollutants such as heavy metals and pesticides, reinforcing the need to evaluate toxicity potential in indoor air environments. Moreover, understanding PM ratios such as $PM_{2.5}/PM_{10}$ and black carbon to total PM has been instrumental in source apportionment studies [9]. Such indicators aid in distinguishing between pollution from vehicular emissions, biomass burning, or industrial sources, thereby guiding targeted intervention.

The Lancet Commission on Pollution and Health [4] further underscores air pollution as a global health crisis demanding urgent action. Despite this robust body of evidence, there remains a lack of empirical data regarding $PM_{2.5}$ exposure in some environments in Nigeria. This study addresses that void by evaluating $PM_{2.5}$ concentrations in abattoir, Motor Park and residential areas and comparing the results with national and international air quality standards. It also seeks to highlight the paradox of compromised air quality within spaces where individuals should be protected. This study presents a detailed investigation into the concentration and potential health risks of particulate matter ($PM_{2.5}$) in three locations within Abuja, Nigeria. Through systematic sampling and risk assessment, the study aimed at identifying and addressing environmental conditions that may pose health threats to people within this vicinity.

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2.0 MATERIALS AND METHOD

2.1. Study Area: Federal Capital Territory (FCT), Abuja

The Federal Capital Territory (FCT), also known as Abuja (Fig. 1), was created on December 12, 1991, and serves as Nigeria's capital and eighth most populous city. Located in the center of the country, it replaced Lagos, Nigeria's most populated city. According to the 2006 census by the National Population Commission, the city of Abuja had a population of 776,298. The United Nations reported that Abuja grew by 139.7% between 2000 and 2010, making it the fastest-growing city in the world at the time. As of 2015, the city was still experiencing an annual growth of at least 35%, retaining its position as the fastest-growing city on the African continent. As of 2016, the Abuja metropolitan area was estimated to have six million people, making it the second most populous metro area in Nigeria after Lagos. Like other Nigerian states, the FCT is endowed with various mineral resources.

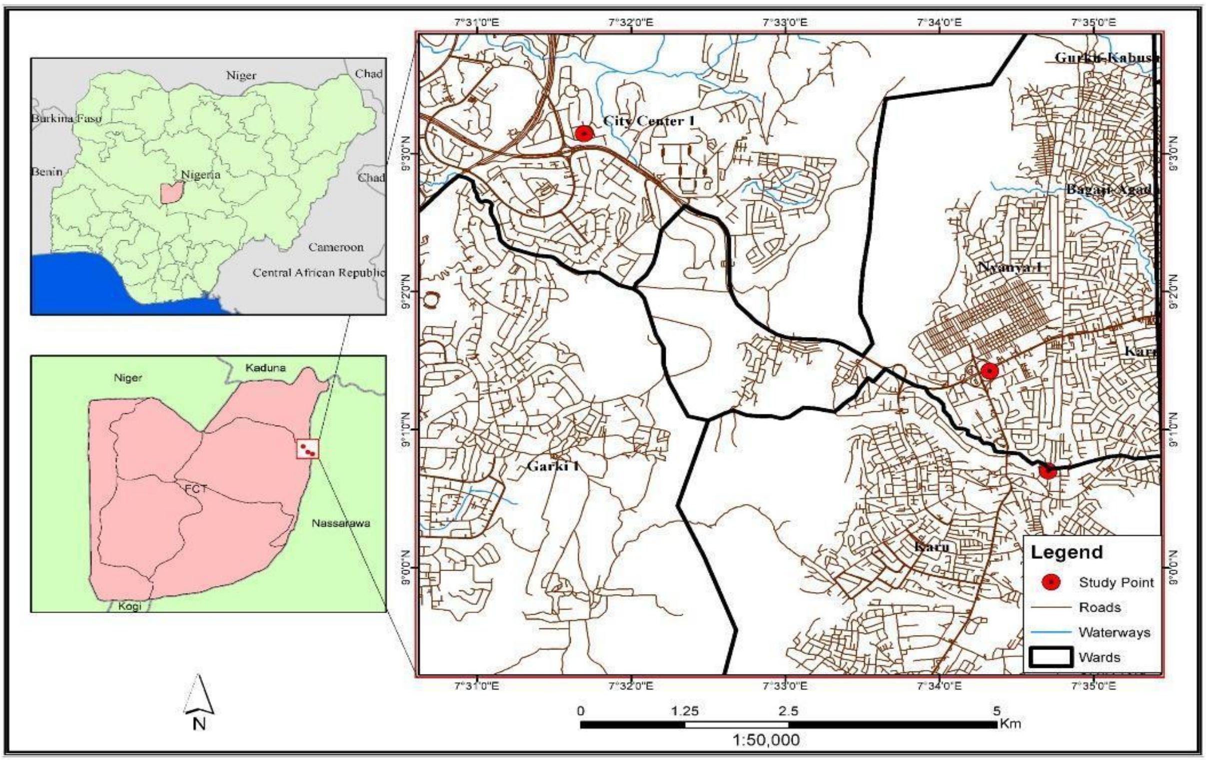

Fig. 1. Geographical map of Federal Capital Territory, Abuja, Nigeria.

2.2 Sampling Site Selection and Strategy

Three distinct sampling locations (Asokoro, Nyanya Park, and Karu Abbatoir) were selected as sampling points within the Abuja Municipal Area Council. The choice of these sites was guided by their high anthropogenic activity profiles, potential pollutant sources, and relevance to public health. Nyanya Park was selected for its heavy vehicular traffic and commuter density; Asokoro Hub was chosen due to its concentration of commercial activities and generator reliance; while Karu Abattoir was included because of its high organic waste output and potential for zoonotic and effluent-related contamination. (Asokoro, Nyanya Park, and Karu Abbatoir) were selected as sampling points within the Abuja Municipal Area Council. Sampling took place for 8h (8 am to 4 pm) during the rainy season (July to September) and dry seasons (December to February) for each location. Meteorological parameters including temperature, wind speed, precipitation, relative humidity, visibility, and atmospheric pressure were monitored at the three sampling sites during the study period. The geographical coordinates (longitude and latitude) of each site were determined using a GPS device respectively (Longitude 7.569865, Latitude 9.024072), KD (Longitude 7.579527, Latitude 9.011330), and AS (Longitude 7.528050, Latitude 9.051940). Sampling was conducted for 8h (8 am to 4 pm) during the rainy season (July to September) and dry seasons (December to February) for each location, each daily sampling event lasted for 8 hours (from 8:00 am to 4:00 pm), resulting in a total of fourty-five samples collected.

2.3 Particulate Matter (PM) Collection Procedure

Particulate Matter (PM) was collected at 1m height from the ground using a Nano- sampler APM 3600. The sampler was connected to a vacuum pump via an air tube. Sets of 55 mm quartz filter papers were prepared for the sampler's multiple stages (stages 1-4, backup filter, and inertial filter). The PM was

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collected by connecting the sampler to a vacuum pump and an air tube. Sets of 55 mm quartz filter papers (1, 2, 3, 4 stages, backup filters, and inertial filters) were placed in the stages in preparation for sampling as shown in figure 2, 3 and 4.

Fig. 2. Sampling At Asokoro

Fig. 3. Sampling at Karu Abatoir

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Fig. 4. Sampling at Nyanya park

The filter was pretreated by baking in an oven at 500 °C for 6 h to remove organic contaminants. Post heating, the filters were kept in a desiccator for 24 h. The filter was weighed before and after sampling to determine the weights of the particulates using a single pan top loading digital balance (Denver, Model TB -2 150) with a precision of ±1 µg. The flow rate meter was set at 40 L/min while the pressure was set to -0.02MPa, and the pump opened for the commencement of sampling. After 8 h of operation, the flow rate and pressure w ere checked and noted. The filters were removed from the stages, folded to a semicircle, wrapped in aluminum foils to avoid photo degradation, kept in a zip-lock bag and saved in the refrigerator below 4°C to prevent volatilization of PAHs of lower molecular weight prior to analyses. Additionally, filter was prepared for blanks and handled the same way as the samples. [12] Results of air quality analysis of $PM_{2.5}$ were evaluated using the air quality index (AQI). The index was calculated based on the average concentration, following the updated WHO Guidelines of 2021 as the standard. The results, as summarized in Table 2, indicate that for KD, NY, and AS, none of the sampling days during the dry season recorded Air Quality Index (AQI) values within the 50–100 range, which is classified as satisfactory. Instead, all observations fell within the 101–200 range, corresponding to moderate levels of $PM_{2.5}$ pollution.

3.0 RESULTS AND DISCUSSION

3.1 Mass concentration of $PM_{2.5}$ of the study area

The statistical results of atmospheric $PM_{2.5}$ concentrations in Karu abbatoir (KD), Nyanya (NY), Asokoro (AS), for dry and wet season are summarized on table 4.1 for mean concentrations and standard deviation, for the dry and rainy seasons respectively. PM levels are highest in NY, moderate in KD, and lowest in AS, for both seasons, the values differ significantly across locations, and dry season values are significantly higher than rainy season at each location (*p < 0.05*).

Table 1: $PM_{2.5}$ Concentration During Rainy and Dry Season

Location	Dry Season	Rainy Season	t-value
KD	69.73 ± 2.25	50.45 ± 2.21	6.11*
NY	87.07 ± 3.29	70.77 ± 3.43	3.43*
AS	50.34 ± 0.84	38.64 ± 2.26	4.84*

Mean (± Standard error of 10 replications) on the same row with different superscripts are significantly different ($p < 0.05$); *Significantly different at 5 % level, KD = Karu Abatoir, NY = Nyanya Park and AS = Asokoro.

3.1.1 Mass Concentration of $PM_{2.5}$ Abuja, Federal Capital Territory, Nigeria

The high PM concentration in the atmospheric samples obtained during the dry season could have been as a result of harsh weather conditions such as high temperatures or temperature inversions, increased vehicular emissions, open waste burning [11], low atmospheric humidity, dust suspension, urban heat and air stagnation experienced during the dry season while the wet deposition phenomenon of the wet season coupled with the lower occurrences of the earlier listed factors during the wet season helps wash away atmospheric particulate matter during the wet season. These, are thus, key factors which contributed to the observed seasonal variations in the concentrations of this PM across the sampling locations of this study. Additionally, the increased rate of construction activities, singeing of animals hides, and the influence of the northeast trade winds during the dry season also contribute to higher PM concentrations in this period [12].

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The respective mean concentrations of $PM_{2.5}$ in the sampling sites during the dry season were 69.73, 87.07 and 50.45 µg/m^3 for Karu (KD), Nyanya Park (NY) and Asokoro (AS) respectively. For the wet season, 50.45, 72.77 and 38.64 µg/m^3 was obtained for Karu (KD), Nyanya Park (NY) and Asokoro (AS) respectively. These indicate that the dry season values across all sampling locations were significantly (at $p<0.05$) higher than those of the wet season. The result for $PM_{2.5}$ recorded in this study in both seasons higher than the 12.00 – 85.00 µg/m^3 range reported by [13] for $PM_{2.5}$ samples obtained in aerosols from Historical and Modern Areas of Jeddah, Saudi Arabia; 17.2 µg/m^3 reported by [14] for $PM_{2.5}$ from an urban location in Kenitra, Morocco; 49.62 µg/m^3 and 49.62 µg/m^3 reported by [15] for particulate matters obtained in selected areas of Abuja and Benin City, Nigeria. The results recorded in this study were, lower than the 131 µg/m^3 $PM_{2.5}$ by [16] from industrial community in Ewekoro Ogun State, Nigeria, except for KD dry season sample that was observed to be 140.52 µg/m^3. The results obtained were lower than the 182.15 µg/m^3 reported by [17] for samples obtained from Western Coast, India; the 179 µg/m^3 reported by [18] for particulate matter ($PM_{2.5}$) in samples from Wuhan, China; the 398 µg/m^3 obtained by [19] for samples from Delhi India. They are also lower than the 167 µg/m^3 for $PM_{2.5}$ obtained from the coastal city of northern Poland [20]. The higher concentrations of particulate matter in India and many other developed countries compared to cities like Abuja in Nigeria can be attributed to several factors such as; increased industrialisation, dust, volcanoes and wildfires, higher levels of vehicular emissions, higher population densities, different climatic conditions, and urbanisation [21]. Moreover, the low mean $PM_{2.5}$ mass concentrations measured in all the .samples during the wet season in this study can be attributed to the washing effect of rainfall on particulates in the atmosphere [22]. The trends in the concentrations of $PM_{2.5}$ in both dry and wet seasons in this study is in line with the findings of [23] who found higher levels of particulate matter during the dry season than during the wet season. These seasonal variations which may not be limited to major cities alone, and which gave higher values for samples obtained during the dry season than those of the wet season could have been due to a combination of factors, including seasonal variations in emission, transportation, and deposition processes [23]. The consistently higher concentrations of particulate matter (PM) observed during the dry season compared to the wet season have significant environmental and public health consequences. These seasonal differences are well-documented across sub-Saharan Africa and align with established atmospheric processes and anthropogenic activity patterns [34].

During the dry season, several factors converge to elevate PM levels. First, the absence of rainfall reduces wet deposition, thereby prolonging the atmospheric residence time of particulates [37]. Second, the harmattan phenomenon transports Saharan dust across West Africa, substantially increasing fine and coarse particle loads in the lower troposphere. In addition, resuspension of dust from unpaved roads and open soil surfaces further exacerbates particulate concentrations in peri-urban and rural areas [36].

By contrast, in the wet season, frequent rainfall events enhance scavenging of aerosols and dust through wet deposition processes, effectively reducing ambient PM concentrations [35]. The differences in atmospheric chemistry and meteorological conditions between the seasons underscore the critical role of natural processes in shaping air quality dynamics.

Anthropogenic activity also plays a major role. Biomass burning, a common practice during the dry season for agricultural land clearing, is a major source of fine particulates, carbonaceous aerosols, and trace gases [39]. Likewise, reliance on diesel and petrol generators during periods of high electricity demand contributes significantly to PM emissions, especially in urban and peri-urban Nigeria [40]. In the wet season, these sources persist but their impacts are mitigated by rainfall-driven pollutant removal.

The health implications of these seasonal variations are profound. Epidemiological studies consistently associate elevated PM levels with increased hospital admissions for respiratory and cardiovascular conditions during the dry season [38]. Vulnerable groups—including children, the elderly, and those with pre-existing conditions—face heightened risks of asthma exacerbations, bronchitis, and cardiovascular morbidity. This seasonal health burden is not confined to major cities; rural and peri-urban communities, often overlooked in regulatory frameworks, are equally exposed to dust resuspension and biomass-burning emissions [36].

From a policy perspective, these findings highlight the importance of season-specific interventions. Strengthened public advisories, monitoring systems, and pollution control measures should be prioritized during the dry season, when the risks are highest. Moreover, integrating rural and peri-urban regions into national air quality monitoring programs is essential, given the evidence of elevated PM levels beyond major urban centers [39].

Overall, the higher dry-season PM levels reflect the complex interplay of emission, transportation, and deposition processes. Addressing these seasonal disparities requires integrative approaches that couple emission reductions with climate-sensitive policies and adaptive health strategies [37].

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3.2 The air quality Index of the selected sampling locations

The air quality index (AQI) is a tool widely used to evaluate and rate the ambient air quality of a specific area or region [24]. Furthermore, the wet season samples did not have values within the 0-50 range for a "good" air quality as given by [25]. In all the sites considered for both the dry and wet seasons, the AQIs were above 50 indicating different degrees of poor air quality, the AQI calculated based on US EPA standard. These could have been the result of high emissions from different sources like burning of tyres, vehicular exhausts emission, burning of hydrocarbons from generators, and biomass burning used in singeing of cow and goat hides near the sampling sites particularly the Karu Abattoir.

Table 2: Mean (± standard deviation) Air Quality Index (AQI) and statistical comparison between seasons at each location.

Location	Dry Season	Rainy Season
KD	158.0 ± 0.03	137.0 ± 0.04
NY	167.0 ± 0.04	160.0 ± 0.04
AS	138.0 ± 0.02	108.0 ± 0.03

KEYS; KD = Karu Abattoir, NY = Nyanya Park, AS = Asokoro

Table 2 reveals the spatial differences in seasonal AQIs of the samples. While KD and NY showed no significant changes in the air quality between dry and raining seasons (χ^2 = 1.495 and 0.249, respectively), AS recorded a statistically significant difference (χ^2 = 4.84, $p < 0.05$), in its $PM_{2.5}$ content highlighting probably the role of precipitation and meteorological processes in pollutant distribution. These results support the premise that seasonal meteorological effects on air quality are location-specific, being more prominent in regions with lower persistent emissions.

According to [26], the air quality index (AQI) consists of six categories: Good, Satisfactory, Moderately Polluted, Poor, Very Poor, and Severe. These categories are determined based on the ambient concentrations of various air pollutants and their potential health impacts, known as health breakpoints. Each category represents a range of pollution levels and their associated health risks, guiding the public on the air quality and necessary precautions. The PM considered in this study was PM2.5 and had been found in reasonable quantities in the sampling sites and could be classified as moderately polluted environment for all the sampling locations in both seasons.

3.3 Comparison of mean concentrations (μgm^{-3}) of $PM_{2.5}$ obtained in this study with other studies

Table 3 compares the results of this study with the air quality values reported in selected literature. The result obtained ranged from 50.34±0.84 (AS) to 87.07±3.29 μg/m^3 (NY) for the dry season samples while for raining season, the values ranged from 38.64±2.26 (AS) and 72.77±3.43 μg/m^3 (NY). These ranges are quite different from the 68.66 μg/m^3 and 182.15 μg/m^3 range of $PM_{2.5}$ reported for urban and semi-urban locations in India [17].

3.4 Comparison of mean concentrations (μgm^{-3}) of $PM_{2.5}$ obtained in this study with other studies

Table 3 summarises the comparison between the findings of this study and the air quality values reported in selected literature. The result obtained ranged from 50.34±0.84 (AS) to 87.07±3.29 μg/m^3 (NY) for the dry season samples while for raining season the values ranged from 38.64±2.26 (AS) and 72.77±3.43 μg/m^3 (NY). These ranges are quite different from the 66.29 μg/m^3 and 182.15 μg/m^3 range of $PM_{2.5}$ reported for sub-urban locations in the western coast of India by [17].

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Table 3: Comparison of mean $PM_{2.5}$ concentrations (µg/m³) from this study with values reported in literature and relevant air quality standards.

Location	Area Type	Sampling Period	Method	$PM_{2.5}$ (µg/m³)	Reference
This Study					
Asokoro (AS), Nigeria	Urban	8-hr mean	**Quartz fibre filters**	50.34 (Dry)	Present study
	Urban	8-hr mean		38.64 (Rainy)	
Kado (KD), Nigeria	Urban	8-hr mean		69.73 (Dry)	
	Urban	8-hr mean		50.45 (Rainy)	
Nyanya (NY), Nigeria	Urban	8-hr mean		87.07 (Dry)	
	Urban	8-hr mean		72.77 (Rainy)	
Other Studies					
Kenitra, Morocco	Urban	24-hr mean	Polycarbonate filters	17.2	[13]
Beijing, China	Urban	24-hr mean	Quartz fibre filters	4.3 - 289.6	[14]
Gdynia, Poland	Coastal	24-hr mean	Quartz micro fibre filters	1.72 - 16.7	[38]
Ewekoro, Nigeria	Industrial	--	PTFE filters	81.40 - 131	[7]
Dokki, Egypt	Urban	24-hr mean	Glass fibre filters	8.93 - 165	[36]
Al-Tebbi, Egypt	Urban	24-hr mean	Glass fibre filters	15.4 - 176	[36]
Jeddah, Saudi Arabia	Commercial	24-hr mean	Polycarbonate filters	12 - 85	[5]
Air Quality Standards					
WHO Guideline	--	24-hr mean	--	15	[46]
US EPA Standard	--	24-hr mean	--	35	[42]
EEA Standard	--	24-hr mean	--	25	[15]

Note: The sampling period for this study (8-hour mean) is not directly comparable to the 24-hour mean values from other studies and the air quality standards. This was considered when interpreting the data

3.4.1 Comparison of mean concentrations of $PM_{2.5}$ in the city of Abuja with those obtained from studies reported in literature and relevant air quality standard

This elevated PM concentration is likely due to the use of tyres for burning of cow and goat hide. However, results in this study for all the three-sampling site is higher than those recorded by [16] in Ogun state Nigeria, [14] in Kenitra, Morocco, [13] Jedda, Saudi Arabia, though the results is lower than the results by [28] in Al-Tebbi, Cairo Egypt [20] in Gdyndia, Poland, [27] in Beijing, China. Furthermore, the results are higher than the ambient air quality standards for $PM_{2.5}$ set at 40 µg/m³ annually and 60 µg/m³ hourly (NAAQS, 2009). In this study, $PM_{2.5}$ concentrations were found to be more than twice the annual average concentration of WHO (15µg/m³), specified by the United State Environmental Protection Agency (35 µg/m³). When compared with the World Health Organization (WHO) air quality guidelines, the concentrations exceeded the recommended levels by nearly ten times in all areas, the findings in Table 3 confirm that particulate matter concentrations were substantially elevated in the study areas when compared with other studies, emphasizing the combined influence of meteorological and anthropogenic factors.

3.5 Meteorological Parameters

Table 4. Represents the summary of the meteorological data obtained during the sampling period in this study. There are distinct seasonal variations in the atmospheric temperature of the sampling points which were significant at $p \leq 0.05$. Values obtained ranged from 22.60±0.60 (NY) to 23.40±0.40 ºC (AS) in the raining season while those of the dry season ranged from 32.20±0.37 (NY, AS) to 32.80±0.53 ºC (KD). On the other hand, the differences between the wind speed of NY and KD for the two seasons were not significantly different (at $p>0.05$). All other meteorological parameters considered in this study showed significant differences on seasonal basis. These discrepancies could be due to the differences in the influence of

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human activities on the sampling points particularly during the dry season The observed patterns align with findings from India and Uganda [37]; [7], West Africa [6], and Southeast Asia [6] confirming the broader consistency of tropical meteorology. For instance, temperature seasonality was similar to Indian and East Asian records, while rainfall and humidity cycles mirrored those reported in Pakistan [34] and Jakarta [6].

Implications for $PM_{2.5}$ dynamics are multifaceted. Higher daytime temperatures, such as those in the dry season, can enhance chemical reactions and particle mobility, leading to elevated $PM_{2.5}$ levels, consistent with studies in Ghana ([28]). Conversely, the cooler, more humid rainy season facilitated wet deposition, reducing particle concentrations, corroborating results from Ghana ([45]). While relative humidity in this study showed a strong seasonal increase, its influence on $PM_{2.5}$ remains complex. As observed elsewhere, low humidity can encourage hygroscopic particle growth, elevating $PM_{2.5}$ levels, while high humidity can promote particle deposition and cleaner air.

Wind speed exerted mixed effects: moderate dry-season winds may aid dispersion but also resuspend dust, while suppressed rainy-season winds limit pollutant dilution, reinforcing observations from Kampala and Jinja, where wind speed and gusts showed location-dependent correlations with $PM_{2.5}$. Visibility patterns in this dataset also support its role as a proxy for air pollution, as reduced visibility coincided with humid rainy-season conditions, echoing findings in Jakarta [6].

Table 4. Meteorological parameters (mean ± SE) during the sampling period at three locations (Kaduna, Nyeri, Ashanti)

Parameter	Season	KD	NY	AS
Temperature (°C)	Dry	32.80 ± 0.53	32.20 ± 0.37	32.20 ± 0.80
	Rainy	23.00 ± 0.32	22.60 ± 0.60	23.40 ± 0.40
	t-value (Dry vs Rainy)	t = 14.77*	t = 13.58*	t = 9.84*
Windspeed (km/h)	Dry	6.20 ± 0.80	7.00 ± 0.45	7.60 ± 0.75
	Rainy	5.60 ± 4.93	5.40 ± 1.21	5.20 ± 0.20
	t-value (Dry vs Rainy)	t = 0.49NS	t = 1.24NS	t = 3.10*
Precipitation (mm)	Dry	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	Rainy	8.20 ± 4.81	5.52 ± 4.01	4.78 ± 1.76
	t-value (Dry vs Rainy)	t = 1.71^{NS}	t = 1.38^{NS}	t = 2.72*
Relative Humidity (%)	Dry	33.40 ± 4.55	44.00 ± 2.74	45.20 ± 4.26
	Rainy	89.60 ± 1.29	92.40 ± 2.18	92.60 ± 1.57
	t-value (Dry vs Rainy)	t = 11.90*	t = 13.82*	t = 10.33*
Maximum Visibility (km)	Dry	10.00 ± 0.00	10.00 ± 0.00	10.00 ± 0.00
	Rainy	8.60 ± 0.25c	8.00 ± 0.63ab	7.00 ± 0.45a
	t-value (Dry vs Rainy)	t = 5.72*	t = 3.16*	t = 6.71*
Pressure (kPa)	Dry	1008.40 ± 0.51	1008.80 ± 0.37	1009.40 ± 0.40
	Rainy	1012.80 ± 0.37	1014.20 ± 0.75	1013.47 ± 0.25
	t-value (Dry vs Rainy)	t = 6.96*	t = 6.55*	t = 8.53*

KD: Karu Abbatoir Nigeria; NY: Nyanya Park; AS: Asokoro. * Indicates a significant difference between seasons within a location ($p \leq 0.05$); NS = non-significant ($p > 0.05$). For visibility in the rainy season, mean values with different superscript letters across locations (a, b, c) are significantly different ($p \leq 0.05$).

3.5.1 Metrological Factors

Meteorological conditions play a pivotal role in modulating ambient concentrations of fine particulate matter ($PM_{2.5}$). The interaction of atmospheric variables such as temperature, pressure, relative humidity, wind speed, visibility, and precipitation not only influence the dispersion and transport of pollutants but also drives secondary aerosol formation via complex physico-chemical pathways [9]. Understanding these dynamics is critical for accurately assessing $PM_{2.5}$ exposure risk and developing evidenced mitigation strategies. High temperatures across the sites (32.5–33.25 °C) indicate a thermally active environment that enhances photochemical reactions ozone in dry season ($NO_2 + h\nu \rightarrow NO + O$, $O + O_2 \rightarrow O_3$),

This study demonstrated distinct seasonal meteorological variations across KD, NY, and AS stations, with higher temperatures (32–33 °C), lower humidity (33–45%), and greater wind activity in the dry season, compared to cooler (22–23 °C), more humid (89–93%), and less windy conditions during the rainy season. Precipitation was absent in the dry months but averaged 4.8–8.2 mm/day in the rainy season, while visibility and pressure also showed significant seasonal contrasts.

Taken together, the KD, NY, and AS datasets reinforce the conclusion that meteorological drivers exert significant though partial control over $PM_{2.5}$

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variability. Meteorological conditions explain only part of $PM_{2.5}$ variation (7–50%), highlighting the essential role of anthropogenic sources such as traffic, biomass burning, and industrial emissions. Nonetheless, this study underscores the critical interplay between climate and air quality, with implications for spatiotemporal pollution management in tropical regions. High temperatures during the dry season enhance dust suspension and promote the formation of secondary organic aerosols (SOA), whereas moderate conditions exert a comparatively lesser influence. Temperature (wet) → less volatilization. The combination of high temperatures, low humidity, and stagnant conditions creates favourable conditions for pollutant accumulation and secondary aerosol formation through gas-phase oxidation pathways [29] lower temperatures (~22–23.5 °C) and markedly elevated relative humidity (90.25–93 %), indicative of localized cooling and moisture enrichment. Such conditions are conducive to aqueous-phase chemical reactions that facilitate the formation of secondary inorganic aerosols (SIAs), primarily sulfates and nitrates, within $PM_{2.5}$. High RH favors aqueous-phase reactions, hygroscopic growth ($PM_{2.5}$ swelling), and secondary inorganic aerosol (e.g., NH_4NO_3 formation), RH > 80 % (KD ~90 %; NY ~93 %; AS ~92 %) → supports: Aqueous SO_2 oxidation → sulfate aerosol (H_2SO_4 → $(NH_4)_2SO_4$), Hygroscopic growth → increases PM2.5 mass + light scattering (reduces visibility), KD, NY, AS → High RH → expect higher secondary sulfate + nitrate contribution, Enhance sulfate, nitrate, ammonium aerosols (SIA) High RH +High Temp SOA + SIA coexistence; challenge to apportion, Low Wind + High Pressure $PM_{2.5}$ accumulation, especially secondary particles, Low wind speed (<6 km/h) and high atmospheric pressure conditions are associated with $PM_{2.5}$ accumulation due to reduced atmospheric dispersion. Wind Speed was lower at sampling sites (5–6.25 km/h). Chemical implications, Lower dispersion potential → Increased residence time of precursor gases (SO_2, NO_x, NH_3, VOCs), facilitating secondary particle formation, Supports accumulation of both primary particles (combustion soot, dust) and aged secondary aerosols. PM accumulation enhances secondary reaction, low wind +high pressure results to $PM_{2.5}$ accumulation, especially secondary particles [32]. Precipitation (PPT) Observed rainfall (4.13–8.55 mm) at sampling sites introduces wet scavenging processes, Below-cloud scavenging (impaction of rain droplets with $PM_{2.5}$) → Reduces particle concentration, Cloud processing enhances in-cloud SO_2 oxidation → further sulfate production before rainout. However, light rainfall (<10 mm/day), as observed here, can also promote aerosol recirculation by cleaning only coarse PM while fine $PM_{2.5}$ persists [30].

4.0 CONCLUSION

This study provides a comprehensive assessment of $PM_{2.5}$ concentration and its interaction with meteorological variables in selected sites in Abuja, Nigeria. The results confirm that $PM_{2.5}$ levels were substantially higher during the dry season compared to the rainy season, with concentrations far exceeding USEPA, EEA AND WHO air quality guidelines. Among the studied locations, Nyanya exhibited the highest $PM_{2.5}$ burden, attributable to high traffic density, biomass burning, and abattoir activities. Meteorological analysis revealed a strong seasonal influence, with high temperatures, low wind speeds, and elevated atmospheric pressure during the dry season facilitating pollutant accumulation and secondary aerosol formation. Conversely, rainy season conditions although beneficial in reducing particulate loads, were often insufficient for complete pollutant washout, particularly when rainfall was light or intermittent. Correlation analysis further indicated the intricate, and at times counterintuitive, relationships between meteorological parameters and $PM_{2.5}$ levels, highlighting the need for site-specific and season-specific mitigation strategies. In conclusion, air quality across all locations in Abuja remains a serious concern, especially during the dry season. The AQI ratings consistently classified these areas as "moderately polluted," with potential adverse health effects for vulnerable populations. The study underscores the critical need for regulatory action, including stricter emission controls, urban planning reforms, and meteorology-informed air quality forecasting systems. These findings serve as an evidence base for environmental health policymaking and provide direction for future research on air pollution exposure and health risk assessments in Nigerian cities.

Conflict of Interest

The authors declare no conflicts of interest related to this work.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Authors' Contributions

Feyisetan, O. A., Ndamitso, M. M., Salau, R. B., Salihu, S. O., Mustapha, S., Abulude, F. O., & Mathew, J. T. contributed to the literature search, data organization, and manuscript drafting. all authors revised the manuscript for intellectual content, developed the conceptual framework, validated data, supervised the study, and coordinated the writing process. All authors approved the final version.

Authors' Declaration

The authors certify that this research is original, has not been published previously, and is not under

consideration by any other journal. We assume full responsibility for the integrity of the data and the accuracy of the reported findings and will accept all liability for any claims about the content.

Ethical Declarations – Human/Animal Studies
Not applicable.

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