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Investigation of particulate matter Air Quality Index (AQI) and risk assessment in some locations in Nigeria

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Abstract

Air pollution issues specifically with Particulate Matter (PM), have turned out to be a critical and pressing concern, posing grave threats to human health, the ecosystem, and the environment which tragically resulted in millions of premature deaths worldwide. The study investigated the ambient air mass concentration of PM_1, $PM_{2.5}$, and PM_{10} in Lagos, Abuja, Osogbo, Anyigba, and Benin City in Nigeria from 1^{st} of May, 2021 to 30^{th} of April, 2023. Air Quality Index (AQI) due to $PM_{2.5}$ and PM_{10} were evaluated for all the locations with the rationale for establishing characterization for health impact and risk of exposure assessment. Hourly measurement of PM concentrations was collected from the Purple Air Real-Time Air Quality Sensors Network for all selected locations. The results revealed an increase in the daily average spatial variation of PM concentration across studied locations in order of Anyigba, Osogbo, Lagos, Abuja, and Benin City. The average daily AQI due to $PM_{2.5}$ and PM_{10} for Lagos, Abuja, Anyigba, Osogbo, and Benin City are 98.07 and 36.95, 108.77and 43.22, 47.66 and 14.35, 85.02 and 32.29 and 114.26 and 46.35 respectively. For the risk of exposure assessments, locations are at varying levels of risk of PM $_{2.5}$ exposure, Benin city was identified with the highest level of risk having some days with AQI ranging from unhealthy to very unhealthy even to Hazardous. PM_{10} air quality in all locations portends little or no risk of exposure to the public. Across all the studied locations, a distinct seasonal difference was observed, characterized by higher monthly average AQI during the dry season compared to the rainy season.

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Keywords: Particulate Matter (PM), Air Quality Index (AQI), Exposure assessment, Seasonal variation, Ambient air pollution, Spatial variation

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1. Introduction

Air pollution is a pressing global concern that significantly impacts public health and the environment worldwide. Air pollution is introduced into air substances regarded as pollutants that are harmful to various aspects of life on earth and the natural environment [1]. Clean air is an essential requisite for human survival and general well-being; however, the presence of air pollution has constituted a notable danger to human wellness and environmental health globally. The issues relating to air pollution are of major concern worldwide, irrespective of the nation's level of development. These prevalent issues have detrimental effects on life on Earth and the environment [2, 3]. According to the World Health Organization (WHO), there are approximately 4.2 million deaths due to diseases caused by ambient air pollution [4]. Air pollutants are known to be either natural or man-made substances that exist as solids, liquids, or

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gases. They have been reported to have detrimental impacts on both human health and ecosystems. A pollutant can be of natural origin or man-made origin. Some of the crucial air pollutants include suspended particulate matter (such as Total Suspended Particle, $PM_{2.5}$, PM_{10}), Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), Ozone (O_3), Carbon Monoxide (CO), Lead (Pb), Volatile Organic Compounds (VOCs). Others are Greenhouse gases (including carbon dioxide, methane, nitrous oxide, and fluorinated gases) and Chlorofluorocarbons (CFCs). Criteria air pollutants, on the other hand, are a specific category of air pollutants that are used to establish both acceptable levels of exposure and also to determine ambient air quality standards. As outlined by the United States Environmental Protection Agency (US-EPA), the six criteria pollutants are PM, O_3, CO, SO_2, NO_2, and Pb.

Particulate matter, a major air pollutant, has been acknowledged for its greater health impacts than other gaseous pollutants [5]. It could exist as a combination of solid particles or liquid droplets of multiple chemicals. They are categorized according to their sizes, PM_{10} is inhalable, with diameters lesser than or equal to 10 µm while $PM_{2.5}$ is regarded as fine inhalable particles, having diameters lesser than or equal to 2.5 µm. PM sources include construction sites, fields, smokestacks or fires, and others. Mostly, the formation of PM in the atmosphere results from complex reactions of chemicals such as NOx and SO_2. Exposure to $PM_{2.5}$ and PM_{10} has been reported in numerous scientific studies as a leading cause of premature death among patients with heart or lung disease. Other respiratory problems associated with PM exposure include aggravated asthma, coughing or difficulty in breathing, irregular heartbeat e.t.c [6–8]. Exposure to particle pollution has increased the likelihood of affecting those in the sensitive group such as children, older adults, and heart or lung disease patients. The permissible threshold level of PM has received a downward adjustment by WHO in the year 2021 from 10 $\mu g/m^3$ to 5 $\mu g/m^3$ for $PM_{2.5}$ and from 20 $\mu g/m^3$ to 15 $\mu g/m^3$ For PM_{10} as a result of its intense effects on health globally [7].

The Air Quality Index (AQI), a measurement tool developed by the U.S. Environmental Protection Agency (US-EPA) is a system used for air characterization and to specifically warn the public when air pollution is dangerous through a simple and uniform way of reporting daily air quality conditions. The aim of computing the AQI is to assign a numerical value that reflects measured concentrations of individual air pollutants. In their study, Kanchan *et al.* [9] outlined several key criteria that should be considered during the design of an effective Air Quality Index (AQI). These criteria aim to ensure that the AQI is user-friendly, capable of serving as an alert system, encompasses major air pollutants, accommodates additional pollutants, aligns with National Ambient Air Quality standards, and relies on valid air quality data obtained from representative monitoring stations within the community. Researchers from all around the world have sometimes studied variations in PM pollution concentrations, AQI based on PM concentrations, and exposure risk assessment in varying capacities and locations. Lala *et al.* [10] tracked $PM_{2.5}$ and PM_{10} levels in Nigerian metropolitan regions (Benin City and Abuja), estimated the associated AQI and, assessed the health risks connected with PM exposure. They found that $PM_{2.5}$ and PM_{10} levels frequently surpassed WHO limits in the study areas. Furthermore, the estimates of the AQI revealed poor to unhealthy levels of PM, posing high health risks to local populations. The authors draw the conclusion that in order to ameliorate the alarming state of the air quality in these Nigerian localities, more drastic actions are required. A study in Hawassa, Ethiopia by Abebech *et al.* [11] found significant seasonal and site-specific fluctuations in pollutant levels, with $PM_{2.5}$ and PM_{10} often exceeding acceptable thresholds, posing non-carcinogenic and carcinogenic health risks to the local population. The authors emphasize the need for more comprehensive air quality monitoring and urgent action to address this critical public health issue in Hawassa. Ajit *et al.* [12] have assessed the urban air quality and pollution exposure in the capital cities of East Africa, finding hazardously elevated levels of $PM_{2.5}$ and PM_{10} concentrations, with Kampala exhibiting the poorest air quality. The study identified traffic as a major contributor to urban air pollution, exposing both commuters and nearby buildings to poor air quality. Subhanullah *et al.* [13] in their research conducted in Pakistan found that several major cities have extremely high concentrations of $PM_{2.5}$ and PM_{10}, far exceeding national air quality standards. The researchers linked these elevated particulate matter levels to serious health issues like asthma, cancer, and respiratory problems among the local population. The study identified vehicle emissions, industrial pollutants, and waste burning as the main contributors to the high PM concentrations, underscoring the need for urgent action to address this critical environmental and public health concern. The significance of this study lies in its ability to provide critical insights into the air quality status, exposure risks, and the need for targeted policies to mitigate PM pollution in Nigeria. This information is crucial for appreciating the seriousness of the air pollution problem and its impact on public health, and for guiding effective air quality management strategies in the country

2. Methodology

2.1. Research area

This study was carried out in five locations in Nigeria, namely Lagos, Abuja, Benin City, Osogbo, and Anyigba. Nigeria is a nation in the African continent. It is bounded to the north by the Sahara Desert and to the south by the Atlantic Ocean. It is located between latitudes 4° N and 14° N and longitudes 4° E and 14° E [14]. The climate is characterized by a well-established pattern in Nigeria, where the rainy season typically extends from April to October, and the dry season generally occurs from November to March.

Lagos (Latitude 6.53° N and Longitude 3.50° E) is the largest city in Nigeria, located along the southwestern coast. It serves as the economic and commercial hub of the country, with a high population density and significant industrial activities. The city is characterized by a diverse range of sources contributing to air pollution, including vehicular emissions, industrial processes, and residential energy use.

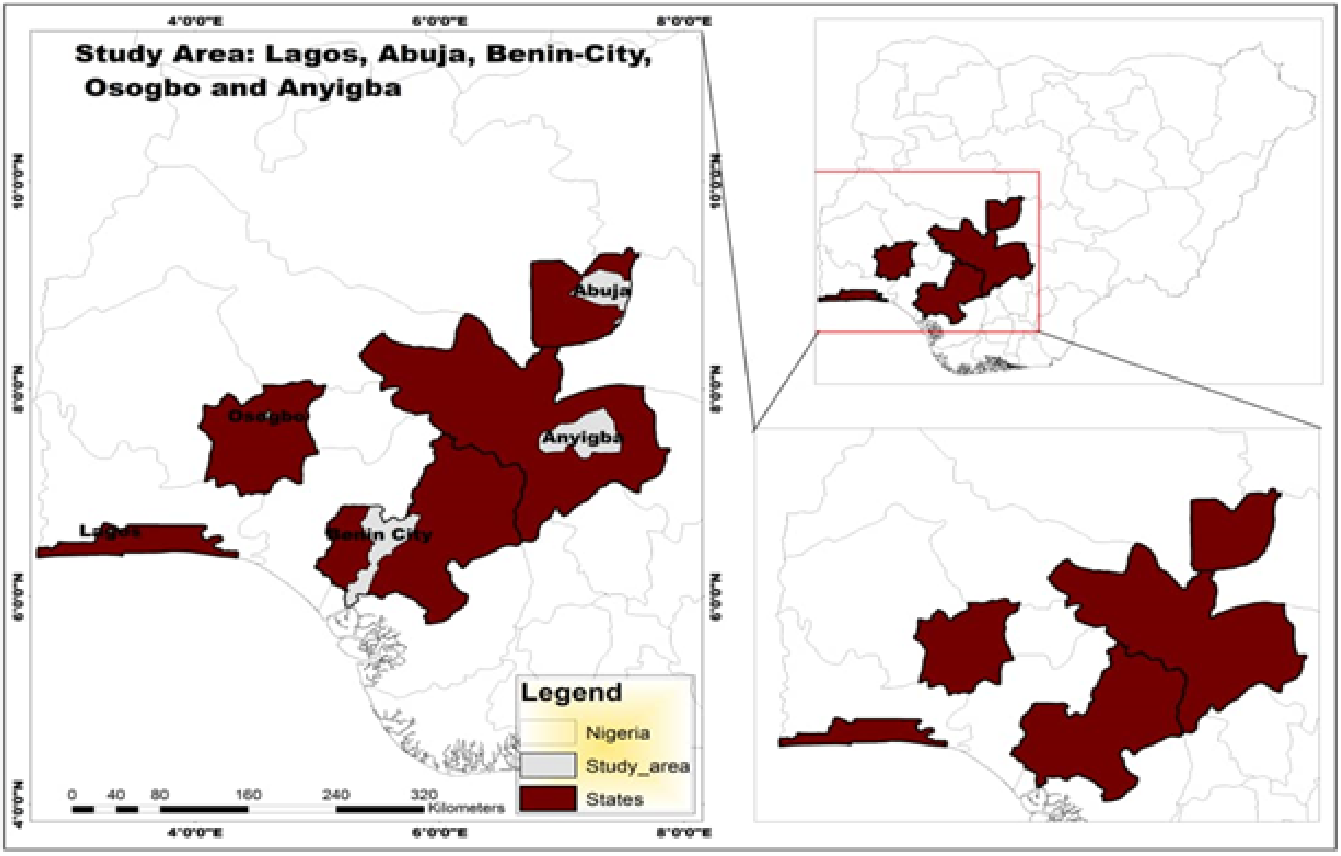

Figure 1. Map showing the states and study area in Nigeria.

Abuja (Latitude 9.06° N and Longitude 7.50° E) is the capital city of Nigeria, situated in the central part of the country. It is known for its administrative and political significance, hosting government offices, diplomatic missions, and international organizations. Abuja experiences rapid urbanization and population growth, leading to increased vehicular traffic and construction activities. Industrial zones and power generation facilities also contribute to air pollution in the city.

Benin City (Latitude 6.33° N and Longitude 5.61° E) is located in the southern region of Nigeria, in the Edo State. It is a major cultural and historical center with a significant population. The city experiences a mix of urban and rural areas, with various pollution sources including vehicular emissions, commercial activities, and biomass burning. Industrial activities, such as oil and gas exploration, also contribute to the air pollution in Benin City [15].

Osogbo (7.78° N and Longitude 4.54° E) is the capital city of Osun State, located in southwestern Nigeria. It is a growing urban center with a mix of residential, commercial, and industrial areas. The city experiences traffic congestion, which contributes to increased vehicular emissions. Industrial activities, such as manufacturing and processing, and the use of biomass for energy and cooking purposes, are additional sources of air pollution in Osogbo. Osogbo is characterized by a predominant agricultural activity such as fishing, poultry, and cultivation of vegetables, yam, and maize

Anyigba (Latitude 7.49° N and Longitude 7.17° E) is a town located in Kogi State, in central Nigeria. It is primarily an agricultural area with a mix of rural and semi-urban characteristics. The town experiences a combination of pollution sources, including biomass burning for cooking and heating, agricultural activities, and vehicular emissions. Anyigba may also be influenced by regional air pollution transport from nearby industrialized areas. Anyigba is located within the southern Guinea savanna and the vegetation can be described as tropical woodland savanna [16].

2.2. *Method of data collection*

Hourly data of Particulate Matter concentrations for the study period of 1st May 2021 to 30th April 2023 for the selected locations (Lagos, Abuja, Anyigba, Osogbo, and Benin City), located in Nigeria were collected from the Purple Air Real-Time Air Quality Sensors Network through PM sensors installed by the Center for Atmospheric Research (CAR), a world-class research and development center under the National Space Research and Development Agency (NASRDA), (https: //carnasrda.com/particulate/). CAR-NASRDA has PM sensors capable of providing real-time data for PM_1, $PM_{2.5}$, PM_{10}, temperature, pressure, and relative humidity installed in some locations in Nigeria [10]. The real-time daily average for Particulate Matter

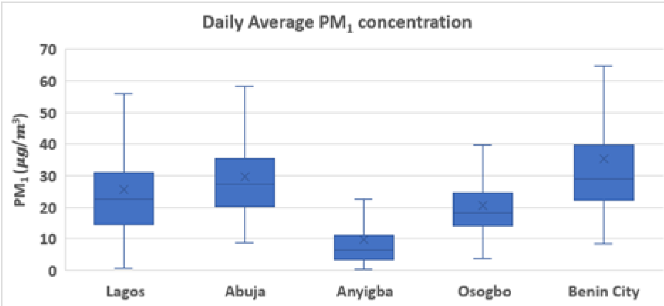

Figure 2. Boxplots representing a daily average of PM_1 concentrations for all locations.

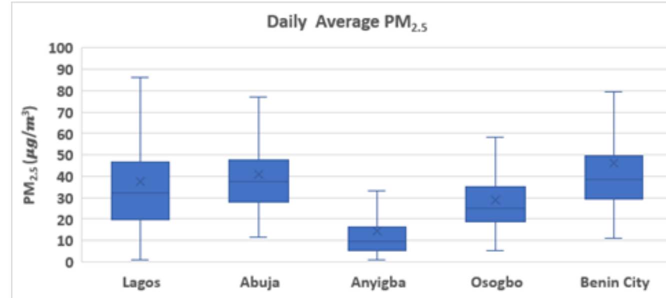

Figure 3. Boxplots representing a daily average of $PM_{2.5}$ concentrations for all locations.

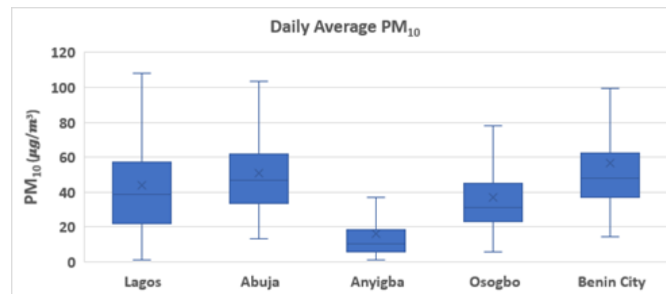

Figure 4. Boxplots representing a daily average of PM_{10} concentrations for all locations.

concentrations was evaluated for establishing the Air Quality Index (AQI) at daily and monthly scales and also for the AQI characterization and exposure risk assessment.

3. Descriptive Statistics

After the cleaning and quality auditing were carried out on the raw data, descriptive statistics were conducted on the dataset of each location to establish the patterns and distributions of PM concentrations. The descriptive statistics included measures such as mean, median, 25^{th} percentile, 75^{th} percentile, minimum, and maximum values. Boxplots were employed for graphical visualization of the distribution of PM concentration across all locations. Concentrations of PM in the study locations were compared against the air quality standards set by the Federal Ministry of Environment (FMEnV) at the national level, as well as international standards established by World Health Organization (WHO) and the National Ambient Air Quality Standard (NAAQS) [7, 17, 18]. Specifically, the 24-hour average PM concentrations were evaluated for compliance with the standard.

3.1. Air Quality Index (AQI)

The Air Quality Index (AQI) stands for a quantitative tool that allows for the easy reporting of air pollution data, that provides valuable information on the cleanliness or pollution levels of the air [19]. To determine the AQI due to $PM_{2.5}$ and PM_{10} for all locations, the 24-hour average concentration values alongside breakpoint concentration ranges specified for $PM_{2.5}$ and PM_{10} by the United States Environmental Protection Agency in 2006 as shown in Table 1 were used. Equation 1 was used to calculate the AQI for a particular pollutant, as presented below:

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} (Cp - BP_{Lo}) + I_{Lo}, \quad (1)$$

where I_p = The index for pollutant P, C_p=The rounded concentration of pollutants P, BP_{Hi}=The breakpoint that is greater than or equal to C_p, BP_{Lo}=The breakpoint that is less than or equal to C_p, I_{Hi}=The AQI value corresponding to BP_{Hi}, I_{Lo}=The AQI value corresponding to BP_{Lo}.

Table 2 represents an overview of major classifications of AQI, the levels of health concerns, along with corresponding color codes and possible health impact/risk assessment.

4. Results and discussion

4.1. Daily average of PM concentrations for all locations

Figures 2, 3, and 4 are the boxplots for the daily average of PM_1, $PM_{2.5}$, and PM_{10} for all the study locations. Higher variations in mass concentrations of all PM of different aerodynamic sizes were observed in Lagos, Abuja, and Benin City than what were observed in the other two locations (Osogbo and Anyigba). The mean values for PM_1, $PM_{2.5}$, and PM_{10} in these three locations with higher variations in the mass concentrations are comparable and higher than the corresponding mean values in Osogbo and Anyigba. This is just an indication that the average levels of PM_1, $PM_{2.5}$, and PM_{10} tend to be elevated in Lagos, Abuja, and Benin City compared to Osogbo and Anyigba which provides insights into the potential health risks associated with PM exposure in these locations. Some of the essential factors that can contribute significantly to higher PM pollution in these cities could be due to processes that are associated with high levels of anthropogenic activities, including vehicular emission, industrial emission, residential emission, and agricultural activities. Among all the studied locations, Anyigba was found to have the lowest level of PM pollution while Benin City displayed the highest level of PM pollution, the observed difference in PM pollution for these two cities could be due to Anyigba's smaller population, less industrial activities, fewer pollution sources that will result in lower concentrations of PM pollution in the air when compared to what is obtainable in Benin City. The high mass concentrations of PM, especially more dangerous $PM_{2.5}$ in Benin City could

Table 1. The US-EPA's breakpoint concentrations and AQI for $PM_{2.5}$ and PM_{10}.

AQI Values	Level of Health Concern	$PM_{2.5}$ (µg/m^3)	PM_{10} (µg/m^3)
0 – 50	Good	00.0-15.4	0.0- 54
51-100	Moderate	15.5-40.4	55-154
101-150	Unhealthy for sensitive people	40.5-65.4	155-254
151- 200	Unhealthy	65.5-150.4	255-354
201-300	Very Unhealthy	150.5-250.4	235-424
301-400	Hazardous	250.5-350.4	425-504
401-500	Hazardous	350.5-500.4	505-604

Source: Adapted from [20]

Table 2. Color codes AQI characterization for health impact and exposure's risk assessment.

AQI	Level of Health Concerns	Color code	Health Impact/Risk Assessment
0 – 50	Good	Green	The quality of the air is deemed acceptable, and there is minimal to no risk from air pollution
51 – 100	Moderate	Yellow	The quality of the air is acceptable, although, many people who are usually sensitive to air pollution may be at minor risk for health problems
101 – 150	Unhealthy for sensitive group	Orange	Sensitive group members may have negative health effects. It is unlikely that the general population will be impacted.
151 – 200	Unhealthy	Red	Everyone may start to feel the consequences on their health; however, people who fall into sensitive groups may feel the effects more severely
201 – 300	Very unhealthy	Purple	Health warning: More serious health problems could affect everyone
301 – 500	Hazardous	Maroon	An emergency health alert is in effect. There is a greater chance that everyone will be impacted

Table 3. Daily average PM concentration statistics for all locations.

Parameters	Statistics	Lagos	Abuja	Benin-city	Osogbo	Anyigba
$PM_1(\mu g/m^3)$	Min.	0.60	8.71	8.52	3.64	0.47
	Max.	55.84	58.16	64.70	39.79	22.57
	Mean	25.51	29.69	35.51	20.71	9.72
$PM_{2.5}(\mu g/m^3)$	Min.	0.94	11.66	11.02	5.10	0.82
	Max.	86.42	76.90	79.25	58.39	33.28
	Mean	37.39	40.81	46.19	28.88	14.36
$PM_{10}(\mu g/m^3)$	Min.	1.03	13.01	14.29	5.74	0.90
	Max.	108.06	103.37	99.43	77.86	37.25
	Mean	43.88	50.77	56.43	36.68	16.11

not also be unconnected to the activities of various illegal refineries located within the region [10].

The results of the daily average concentration of $PM_{2.5}$ for the locations also revealed that, in most cases, there was an exceedance of the National and International standards. Abuja and Benin City exceeded the 40 $\mu g/m^3$ National limits of Nigeria Federal Ministry of Environment (FMEnV) by 2% and 15.48% respectively, while other locations were within the limit. All the locations except Anyigba with a daily average concentration of 14.36 $\mu g/m^3$, failed to comply with 15$\mu g/m^3$ of the 24-hour average limits of the World Health Organization (WHO). Lagos, Abuja, Osogbo, and Benin City exceeded the WHO limit by 149.27%,172.00%,92.53.00%, and 207.93% respectively. For the limit of 35 $\mu g/m^3$ recommended for the 24-hour average air quality guideline by the National Ambient Air Quality Standard (NAAQS), Osogbo and Abuja were within the limit while Lagos, Abuja, and Benin City exceeded the limit by 6.83%,16.57%, and 31.97% respectively. These results of high concentrations of $PM_{2.5}$ pollution surpassing both national and international standards are indications of poor air quality in most of the cities in Nigeria. Lala *et al.* [10] documented comparable outcomes for Benin City and Abuja. Similar findings were also noted in other African countries [21, 22]. In contrast, better results were obtained in terms of PM_{10} daily average concentrations of all the locations in comparison with 24-hour National and International Standards. All the locations have

Table 4. The comparison of average daily mean concentrations of $PM_{2.5}$ and PM_{10}, with the 24-hour average national and international standard.

		$PM_{2.5}$ ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)
FMEnV	STANDARD	40	150
	Lagos	37.39	43.88
	Abuja	40.80	50.77
	Benin – City	46.19	56.43
	Osogbo	28.88	36.68
	Anyigha	14.36	16.11
WHO	STANDARD	15	45
	Lagos	37.39	43.88
	Abuja	40.80	50.77
	Benin – City	46.19	56.43
	Osogbo	28.88	36.68
	Anyigha	14.36	16.11
NAAQS	STANDARD	35	150
	Lagos	37.39	43.88
	Abuja	40.80	50.77
	Benin – City	46.19	56.43
	Osogbo	28.88	36.68
	Anyigha	14.36	16.11

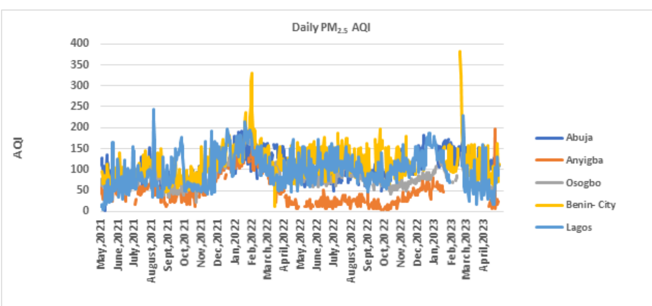

Figure 5. Time series plots for daily AQI Due to PM $_{2.5}$ for all the locations.

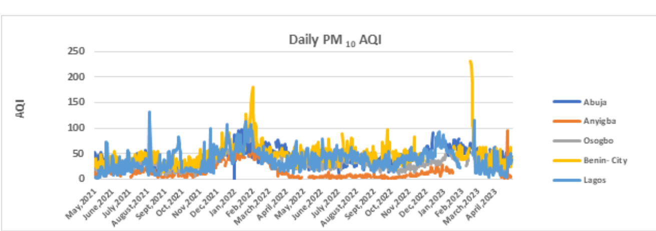

Figure 6. Time series plots for daily AQI Due to PM $_{10}$ for all the location.

daily average concentrations below 150 $\mu g/m^3$ benchmark concentration for PM_{10} 24-hour average by FMEnV and NAAQS. Abuja (50.77 $\mu g/m^3$) and Benin City (56.43 $\mu g/m^3$) on the other hand, also exceeded the more stringent 45 $\mu g/m^3$ PM_{10} 24-hour average by WHO.

4.2. Daily AQI due to PM $_{2.5}$ and PM $_{10}$ for all the locations

The AQI was evaluated from the daily average concentration values with the use of the US-EPA guidelines as the standard. Equation 1 with US-EPA's breakpoints for $PM_{2.5}$ and PM_{10} of Table 1 were used for the computation. Figure 5 and Figure 6 represent the time series plots for $PM_{2.5}$ AQI and PM_{10} AQI for all the locations respectively. The figures reveal the same trend of variations in AQI due to $PM_{2.5}$ and PM_{10} in that the series of minima and the maxima AQI for $PM_{2.5}$ and PM_{10} for each location was reached at the same time of the day similar to the findings of Lala *et al.* [10]. This occurrence could be a result of common fundamental factors determining the pollution levels in all the study locations that could be attributed to factors such as daily patterns of human activities, atmospheric conditions, or pollution sources that exhibit a regular temporal trend. The occurrence of high AQI values was noticed in all the locations during the months between November and March of each year for both PM $_{2.5}$ and PM_{10} measurements. This reveals a pattern indicating better air quality during the rainy season compared to the dry season in all the locations, this is an indication of better air quality in the rainy season than a dry season in all the locations. Additional research carried out by earlier researchers at the global level supports the present results on seasonal variations in the concentration of PM. The results of Chauhan *et al.* [23] are consistent with the current investigation on the seasonal fluctuation of PM. However, the lower values AQI of PM during the months of the rainy season could be traceable to the process of precipitation scavenging or wet removal whereby rain delivers and deposits pollutants, especially particulate matter to the ground and thus washing them down the drain, reducing the mass concentrations of PM thus, making the quality of air becomes drastically better. There

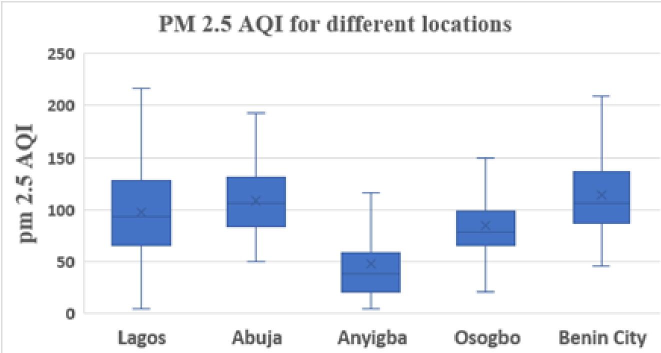

Figure 7. Boxplots representing the daily average PM $_{2.5}$ AQI in all locations.

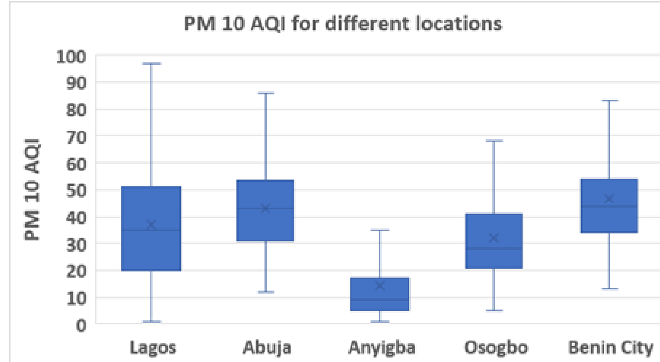

Figure 8. Boxplots representing the daily average PM $_{10}$ AQI in all locations.

could be several reasons for a typical spike in the average daily AQI in some locations, such as a day in August 2021 for Lagos and days in February 2022 and March 2023 for Benin City, as shown in Figures 5 and 6 for $PM_{2.5}$ and PM_{10} AQI plots respectively. An upsurge in the AQI may be caused by a sudden rise in pollution emissions from nearby sources like power plants and industrial sites, or it may be the result of traffic congestion. Several meteorological factors, including temperature inversions, low wind speeds, and stagnant air, can have a substantial impact on air pollution levels by trapping $PM_{2.5}$ and PM_{10} near the ground and preventing their dispersal. A greater $PM_{2.5}$ and PM_{10} concentrations with an increased AQI as well may follow from this. There's also a chance that natural occurrences like dust storms, volcanic eruptions, or wildfires will discharge a lot of PM into the atmosphere. Such events have the potential to dramatically affect the location's PM concentration level and produce an abrupt peak in the AQI if they happen close to the ground level.

The highest AQI recorded for the period of the study for $PM_{2.5}$ and PM_{10} were 372 and 223 respectively and was for the Benin City location, this AQI of 372 is hazardous for all categories of people with health effects. For such an elevated AQI observed, it is strongly advised that individuals with respiratory or heart diseases, the elderly, and children avoid engaging in any outdoor activities. In addition, it is also recommended for the general population as a whole to limit prolonged exertions and minimize physical activity.

4.3. Daily average AQI for all the locations

Figures 7 and 8 are the boxplots for the daily average of $PM_{2.5}$ AQI and PM_{10} AQI obtained for two years for the study respectively. The average maximum, average minimum, and average daily mean AQI due to $PM_{2.5}$ and $PM_{10}$for Lagos, Abuja, Anyigba, Osogbo, and Benin City are presented in Table 5. Based on $PM_{2.5}$, It is evident from the boxplot of Figure 7 that Abuja and Benin City reflect the higher average daily mean AQI values as compared to other locations. Particularly, Abuja has an average daily mean AQI of 109, while Benin City has an average daily mean AQI of 114. The air quality in Abuja and Benin City is classified as "unhealthy for sensitive groups". This categorization indicates that some groups in the population, especially those that are more vulnerable or have pre-existing health conditions such as people with respiratory conditions, may experience adverse effects from pollution levels present in these locations. In Lagos and Osogbo, the average daily mean AQI values were 98 and, 85 respectively, These AQI values fall within the "moderate" air quality category, implying that air quality in these two locations is generally acceptable, this pollution level due to $PM_{2.5}$ in these locations is unlikely to have a significant impact on the general public. However, sensitive individuals to air pollution, even without pre-existing respiratory or heart conditions, may experience adverse health effects. Lastly, Anyigba's average daily mean QAI of 48 was the least among all the five locations. This value places Anyigba in the category of "good" air quality. With this classification, it shows that Anyigba experiences minimal risk of $PM_{2.5}$ pollution with little or no significant health effect on the general public. According to the boxplot presented in Figure 8 and Table 5, the AQI based on PM_{10} in all the locations of Lagos, Abuja, Benin City, Osogbo, and Anyigba generally falls within the "good" range (0 – 50). This indicates that the level of PM_{10} pollution is relatively low and suggests good air quality generally. Despite these PM_{10} favorable AQI readings, individuals with respiratory sensitivities should still be mindful of their surroundings and take necessary precautions, especially in areas where air pollution is known to be higher. Wambebe *et al.* [24] reported similar results for PM_{10} base AQI for various locations in Abuja, Nigeria.

4.4. Daily $PM_{2.5}$ and PM_{10} AQI for exposure risk assessment in all locations

Figures 9 and 10 represent charts for $PM_{2.5}$ and PM_{10} AQI daily exposure risk assessments with color code notations in all locations. Remarkable variations can be observed across the different locations. In Figure 9, for $PM_{2.5}$ AQI, Anyigba emerges as the location with the highest number of days, representing 58.1% (310 days in total), falling within the "good" category, indicating relatively clean air quality (Table 6). Benin City exhibits the highest levels of pollution with a notable number of days falling within the "unhealthy," "very unhealthy," and "hazardous" categories. Specifically, Benin City experiences 116 days (18.1%) categorized as "unhealthy," 5 days (0.8%) as

Table 5. Daily average PM AQI statistics for all locations.

Parameters	Statistics	Lagos	Abuja	Benin-city	Osogbo	Anyigba
$PM_{2.5}$(AQI)	Min.	4	50	46	21	4
	Max.	217	193	209	150	116
	Mean	98.07	108.77	114.22	85.02	47.66
PM_{10}(AQI)	Min.	1	12	13	5	1
	Max.	97	86	54	83	35
	Mean	36.95	43.22	46.75	32.29	14.32

Table 6. Percentage characterization of daily $PM_{2.5}$ and PM_{10} AQI for risk assessment in all locations.

	Lagos		Abuja		Osogbo		Anyigba		Benin-City	
	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}
Good	12	85	0.3	67	2.3	79.2	58.1	96.6	0.8	61.5
Moderate	53	14	45.7	35.3	77.9	15.5	31.6	3.4	40	33
Unhealthy for Sensitive Group	53	14	45.7	35.3	77.9	15.5	31.6	3.4	40	33
Unhealthy	7		17.8		4.9		1.5		18.1	0.5
Very Unhealthy	1								0.8	0.3
Hazardous									0.9	

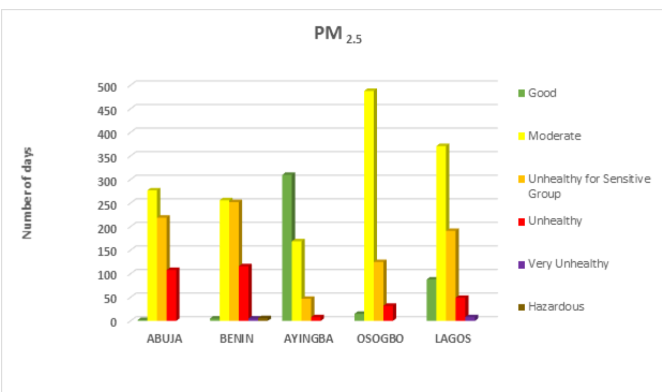

Figure 9. Daily $PM_{2.5}$ AQI for exposure risk assessment in all locations.

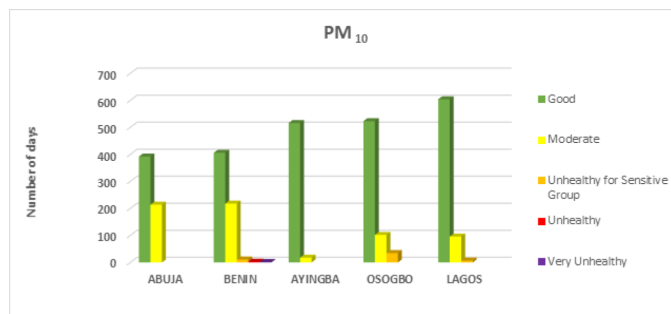

Figure 10. Daily PM_{10} AQI for exposure risk assessment in all locations.

"very unhealthy," and 6 days (0.9%) as "hazardous." It should also be noted that Benin City is the only location with a few days characterized as "hazardous" in terms of $PM_{2.5}$ AQI. For the Abuja location, 2 days (0.3%), 227days (45.7%), 219 days (36.1%), and 108 days (17.8%) fall under "good", "moderate", "unhealthy for sensitive group" and "unhealthy" respectively. None of the days fell into the category "very unhealthy" and "hazardous". Similarly, for Osogbo, the distribution of days in terms of $PM_{2.5}$ pollution is as follows: 15 days (2.3%) in the "good" category, 488 days (77.9%) in the "moderate" category, 125 days (18.9%) in the "unhealthy for sensitive groups" category, and 32 days (4.9%) in the "unhealthy" category. As observed in Abuja, none of the days in Osogbo were classified as "very unhealthy" or "hazardous." PM_{10} air quality in all locations according to the study portends little or no risk of exposure for the people, the air quality can be said to be satisfactory in all the locations with a reasonable percentage of the days under good and moderate air quality as depicted in Figure 10. Nevertheless, a few cases of air quality that is unhealthy for the sensitive group were recorded for Osogbo and Lagos while Benin City still showcased a few days of unhealthy for the sensitive group, unhealthy and very unhealthy air quality.

4.5. $PM_{2.5}$ and PM_{10} average monthly AQI for exposure risk assessment in all locations

For the average monthly QAI in Figures 11 and 12, the horizontal lines colored green, yellow, orange, and red represent the threshold for each AQI characterization of "Good", "Moderate", "Unhealthy for sensitive people" and "Unhealthy" respectively. The common feature in the variation of the average monthly AQI in all locations was a pronounced seasonal variation. Rainy season months (April – October) revealed that $PM_{2.5}$ monthly average characterization of all locations fell within the "Good" and "Moderate" AQI category, but Lagos in April, June, and July and Benin City in July, August, and September had monthly average characterization of "Unhealthy for sensitive people". In the dry season months (Nov - March), all the months had at least three locations with either or both "Unhealthy for sensitive groups" and "Unhealthy" $PM_{2.5}$ monthly average characterization.

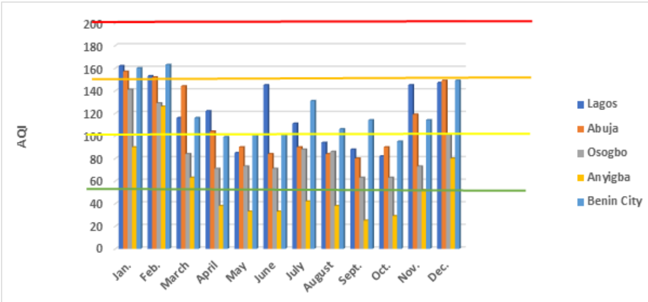

Figure 11. $PM_{2.5}$ and PM_{10} average monthly AQI for exposure risk assessment in all locations.

During the study period, Anyigba's monthly average $PM_{2.5}$ air quality can be considered acceptable as AQI consistently fell within the "good" and "moderate" categories except for the dry season month of February with the AQI of 126 which is unhealthy for sensitive people. This suggests that the levels of monthly average $PM_{2.5}$ pollution in Anyigba remained relatively low throughout the months. However, individuals who are particularly sensitive to air pollution should still exercise caution as there may be a slight health concern for them. On the other hand, even though Osogbo's location had none of the months falling within the "good" category, the location still experienced moderate air quality through most of the months. Only in January did Osogbo have an AQI that was classified as "unhealthy for sensitive groups." This indicates that the $PM_{2.5}$ pollution levels in Osogbo were generally moderate, posing a moderate level of risk to the public. Individuals in Osogbo need to be mindful of their exposure to air pollution, especially those who are more susceptible to its effects. In Abuja, the monthly average AQI reflected moderate levels from May to October. But, from November to April, a higher AQI level in the category of "unhealthy for sensitive groups" was recorded. The elevated AQI values from November to April constitute a potential health risk for sensitive individuals. It is important to note that the general public, which includes individuals without specific health vulnerabilities, is unlikely to experience any serious health effects from the observed AQI levels.

The average monthly AQI in Lagos and Benin City exhibited poor air quality conditions. In January and February, both locations experienced unhealthy air quality levels for the general population, with average monthly AQI values of 162 and 153 for Lagos, and 160 and 163 for Benin City respectively. In the remaining months, the air quality was categorized as moderate or unhealthy for sensitive groups. Unfortunately, there were no instances of "good" AQI recorded throughout the year in either of the locations. These results point to the need for adequate measures to address ways to improve the air quality in these locations.

Across all the studied locations, there was a consistent demonstration of higher monthly average AQI due to $PM_{2.5}$ during the dry season compared to the rainy season. These findings align with numerous studies conducted by researchers from different parts of the world [25–29]. The dry season is attributed

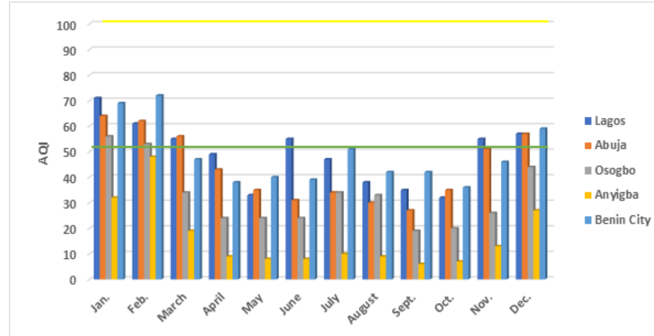

Figure 12. Average monthly PM_{10}AQI for exposure risk assessment in all locations.

to specific atmospheric conditions such as reduced rainfall, increased dust suspension, and limited dispersion of pollutants that can contribute to the building up of concentration of PM pollutants in the air.

The monthly average AQI due to PM_{10} depicts better air quality than that due to $PM_{2.5}$, most of the months for all locations have air quality within the good category Figure 1 AQI is less than 50. However, there are a few cases of higher AQI mainly in the dry season months (November, December, January, and February) which are still within the range of acceptable AQI of the "Moderate" category. Air quality due to exposure to PM_{10} in all the locations has proven to possess little or no risk of exposure to all categories of people in all seasons.

5. Conclusion

PM concentrations over a two-year study period were quantified in five Nigeria locations: Lagos, Abuja, Anyigba, Osogbo, and Benin City, and daily average AQI for all the locations were evaluated for Characterization and exposure risk assessment. The results showed that the daily average spatial variation of PM of different aerodynamic sizes considered increases in the order of Anyigba, Osogbo, Lagos, Abuja, and Benin Cities. The results of the daily average concentration of $PM_{2.5}$ for the locations revealed that, in most cases, there was exceedance from the National and International standards. Locations are at varying levels of risk of $PM_{2.5}$ exposure, Benin City was identified with the highest level of risk having some days with AQI ranging from unhealthy to very unhealthy even to Hazardous. PM_{10} air quality in all locations according to the study portends little or no risk of exposure for the people, the air quality can be said to be satisfactory in all the locations with a reasonable percentage of the days under good and moderate air quality.

Among the findings from the study was the significant presence of a distinct seasonal variation in the AQI values, with higher AQI levels observed during the dry season compared to the rainy season. In light of the important conclusions drawn from this study on PM-based air quality in Nigeria, policymakers and the government are anticipated to adopt a comprehensive strategy to deal with the urgent problem of PM pollution. Firstly, they should establish a long-term, nationwide air quality monitoring network that combines regulatory-grade stations and low-cost sensors to enhance data availability and quality across major urban centers. Second, the government should create and implement stronger regulations governing vehicle emissions, stimulate the use of cleaner technologies and fuels, and facilitate the switch to electric cars and other environmentally friendly forms of transportation. This would assist in greatly lowering PM pollution emissions from the transportation sector, which is a primary cause of Nigeria's problems with urban air quality. To further address the high levels of PM reported during the dry season, seasonal air quality management programs should be implemented. The initiatives have to concentrate on enhancing dust management tactics and increasing public knowledge of the risks linked to seasonal pollution patterns.

In conclusion, the government should establish public advisory and early warning systems to apprise the populace, especially the most susceptible groups, of instances of elevated pollution. By putting these policy recommendations into practice, the Nigerian government and policymakers can work towards enhancing air quality, reducing seasonal variations in pollution levels, and safeguarding the health and well-being of their citizens.

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