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Preliminary Geo-Statistical And Geo-Spatial Analysis Of Atmospheric Pollutants In Abuja, Federal Capital Territory, Nigeria

Johnbosco Emeka Umunnakwe[1*], Dr Richard Ebere Njoku[2], Dr Baywood Cecilia Nkechi[3], Dr Okwudili John Ugwu[4], Mr Okoroji Anthony Chibuzor[5]
[1*]Department of Environmental Management Federal University of Technology, Owerri, Imo State, Nigeria
johnbosco.umunnakwe@futo.edu.ng
[2]Department of Surveying & Geoinformatics Federal University of Technology, Owerri, Imo State, Nigeria
richard.njoku@futo.edu.ng
[3]Department of Surveying & Geoinformatics Federal University of Technology, Owerri, Imo State, Nigeria
nkechi.baywood@futo.edu.ng
[4]Department of Surveying and Geoinformatics Federal University of Technology, Owerri, Imo State, Nigeria
okwudili.ugwu@futo.edu.ng
[5]Department of Surveying and Geoinformatics Federal University of Technology, Owerri, Imo State, Nigeria
~~A~~ anthony.okoroji@futo.edu.ng

Abstract
A comprehensive geo-statistical and geo-spatial assessment of $PM_{2.5}$, PM_{10}, CO_2, CO, NO_2, VOCs and meteorological conditions was conducted during the wet and dry seasons, across major land-use categories in Abuja, Nigeria, with spatial surfaces and clusters modelled to identify pollutant hotspots across 21 sampling locations. Data was obtained through field sampling, satellite retrievals, meteorological datasets, and land-use/land-cover mapping. Results revealed $PM_{2.5}$, PM_{10} pollutants exhibited strong seasonal contrasts, with significantly higher dry-season levels in Galadimawa, Guzape and Kukwaba in high-traffic corridors, construction zones, and densely populated districts. Correlation analyses showed a strong positive association (71.6%) between dry and wet season for PM_{10} and $PM_{2.5}$, while climate data exhibited a weaker but significant positive correlation (43.6%). ANOVA results further established significant variability between and within seasonal groups indicating that air quality structured pollutant dispersion patterns are influenced by land-use intensity and meteorological conditions. The study demonstrates the deployment of geo-statistical modelling for evidence-based air-quality management in some parts of Abuja, highlighting seasonal differences and the need for continuous monitoring, data-driven urban planning, strengthened regulatory enforcement, and targeted mitigation measures to safeguard public health and promote sustainable urban air quality management.

Key Words: *Geo-statistics; Geospatial; Pollutants; Seasonal; Modelling; Analysis.*

INTRODUCTION

Air is one of the most fundamental components of the human environment and essential for human survival (Garg *et al.*, 2006). Over the past few decades, rapid urbanisation, industrial expansion, and technological advancement have transformed societies but also contributed to the deterioration of air quality, which has become one of the most critical global environmental and public health challenges (Otti *et al.*,2011). Urbanization in sub-Saharan Africa is accelerating at rates surpassing infrastructural and regulatory development (Eze & Nwankwo, 2021). Abuja, originally planned as a low-density administrative capital, has evolved into one of Nigeria's fastest-growing urban centres. This transformation has intensified atmospheric pollution through vehicular emissions, construction activities, generator use, industrial clusters, and biomass burning (Nwosu & Okonkwo, 2020). Understanding the spatial distribution and behavior of pollutants requires advanced analytical tools. Geo-statistical and geo-spatial techniques offer robust frameworks for identifying pollution patterns, modelling dispersion, and detecting spatial clusters (Pebesma, 2021). These methods address traditional monitoring limitations by generating continuous surfaces from discrete measurements and integrating meteorological and land-use variables.

This study develops a full geo-spatial and geo-statistical analysis of atmospheric pollutants in Abuja, providing a detailed assessment of their spatial variability, temporal behavior, and environmental implications. The results aim to support policymakers, environmental managers, and public health authorities in formulating targeted intervention. Above all, geo-statistical and geo-spatial analyses of key atmospheric pollutants in Abuja helps to determine spatial patterns, temporal dynamics, and their relationships with urban land-use and meteorological parameters (Akhter *et al.*,2018).

Description of the study area

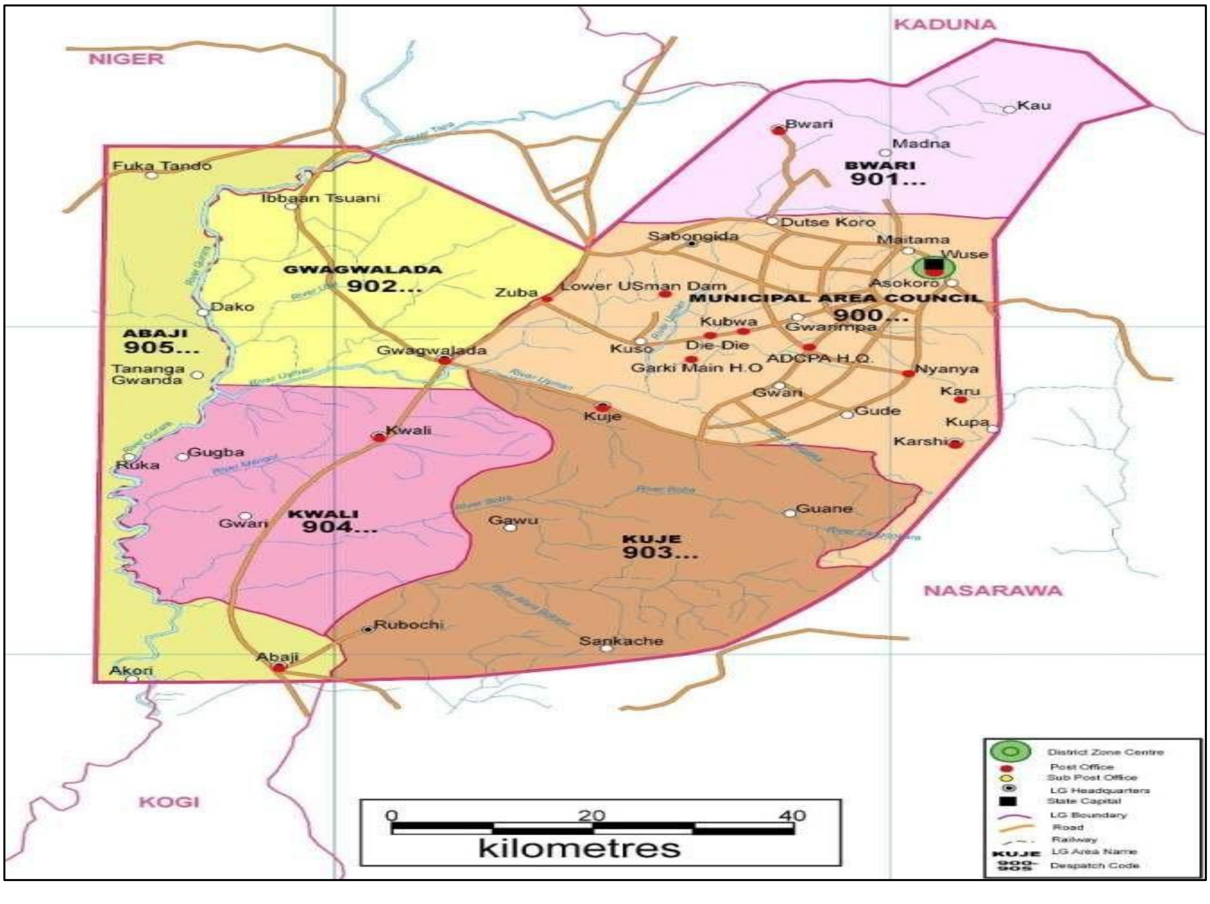
Abuja is the Federal Capital City of Nigeria and lies within the Federal Capital Territory (FCT). It is bounded by Kaduna State to the north, Nassarawa State to the east, Kogi State to the south, and Niger State to the west (Fig. 1). Geographically, Abuja is located approximately between 6°46′E to 7°37′E longitude and 8°21′N to 9°18′N latitude . It covers an area of approximately 8000 km and with a mean elevation of 476 m above sea level (Etuk *et al.*, 2022). The city's landscape is significantly influenced by notable geological features such as the Aso Rock, which shapes both the drainage network and the general topography. According to the most recent World Population Review, Abuja's population in 2025 is estimated at 4,209,940, reflecting rapid urbanisation and migration that have transformed it into one of Africa's fastest-growing capitals. (World Population Review, 2005).

Abuja experiences a tropical wet and dry climate, characterized by two distinct seasons. The rainy season typically begins in late March and lasts until October, while the dry season spans from October to March. Within the dry season, a short harmattan period occurs, usually between December and February, marked by dusty haze, dryness, reduced visibility, and intense cold at night due to the northeasterly trade winds blowing from the Sahara Desert (Wambebe & Duan, 2020). Rainfall in Abuja is moderate to heavy, with an annual total ranging between 1,100 mm and 1,600 mm, distributed across the rainy season (Ajibade & Wright, 1988).

The city records its highest temperatures, averaging about 34 °C, during the peak of the dry season, while the wet season, with its dense cloud cover, brings cooler conditions, with maximum temperatures dropping to about 24 °C (McCurry, 1985). Relative humidity also varies seasonally, often dropping significantly in the afternoons during the dry season, particularly at the height of the harmattan.

The subsurface geology of the study area consists of seven distinct aquiferous layers: (i) topsoil, (ii) lateritic sand, (iii) clayey sand, (iv) weathered basement rock, (v) weathered or fractured basement rock, (vi) fresh, non-fractured basement rock, and (vii) fresh fractured basement(Fig.2). Numerous fractures, both major and minor, occur within these layers at depths ranging from about 7 m to 36 m. These fractures predominantly trend in a northeast–southwest direction, aligning with the principal tectonic orientations of the Nigerian basement complex (Omada & Obayomi 2012; Agunleti &Arikawe 2014). The vegetation of Abuja is a mix of forest and savanna ecosystems**.** Forested areas are predominantly composed of woody plant species, while savanna regions consist of grasses interspersed with shrubs and scattered trees. (Idoko & Bisong, 2010) These ecological zones are shaped by climatic and geological factors.

Fig 1: Map of Abuja showing the six Area Councils (Ozioma, Ofobruku, & Okafor, 2017)



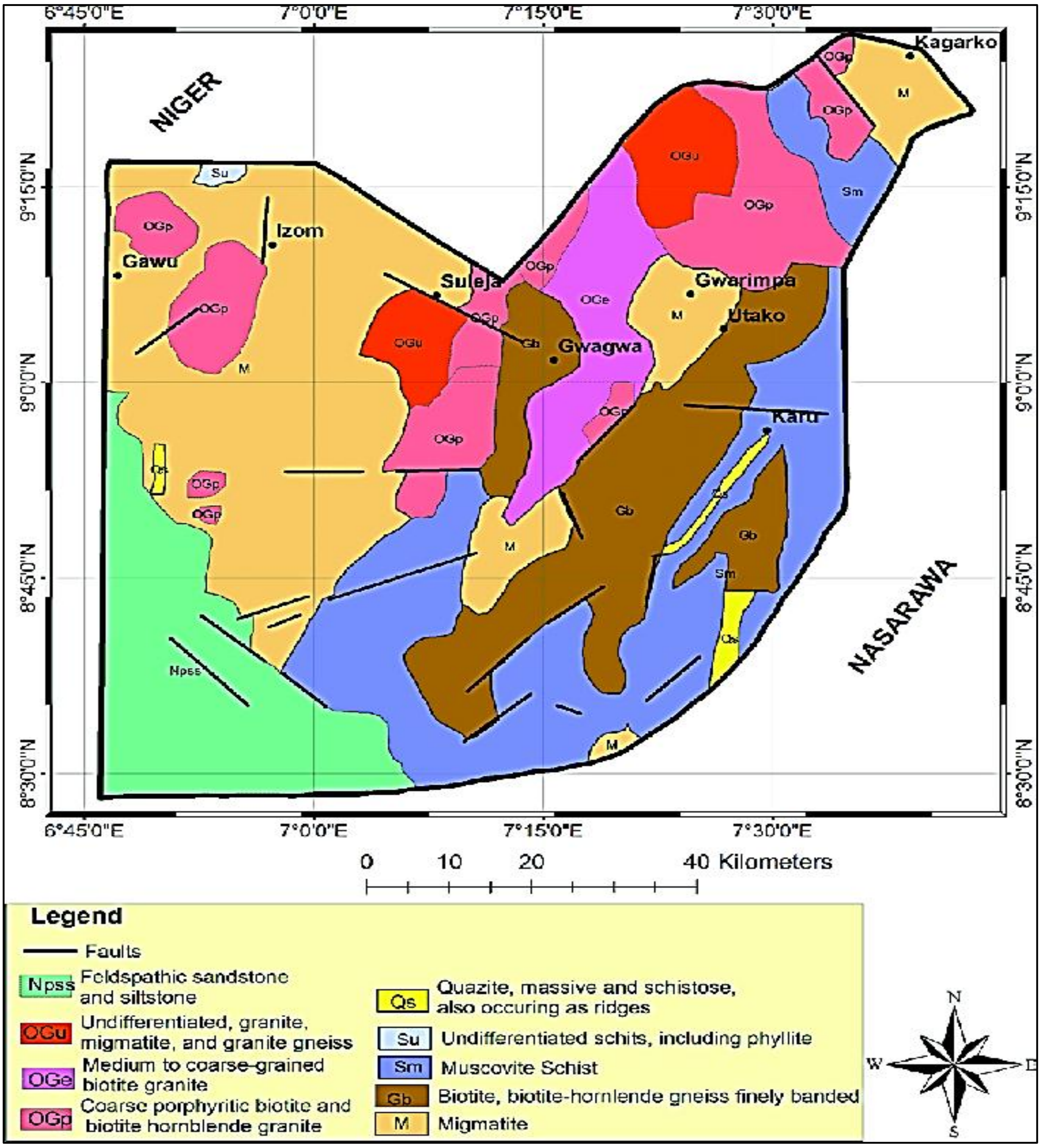


Fig 2: Geologic Map of The FCT. (Osotuyi, Falade, Adepelumi, & Onibiyo, 2020)

MATERIALS AND METHODS

A total of twenty sampling points and one control point were selected for the monitoring of air quality (Table 1). The monitoring locations within Abuja were selected based on their proximity to key sources of air pollution, such as busy roads, industrial zones, and residential areas. These sites provide valuable data on the variability of air quality across the city. An outline of the methodology is highlighted in the following areas: Study Area Description showing Abuja's geography, topography, climate, land-use patterns, population dynamics and Seasonal impacts (dry vs. wet season).The research design involved spatially-explicit observational design integrating field monitoring, satellite remote sensing, and GIS modeling .Stratified spatial sampling across residential, industrial, transport corridors, commercial hubs, and green zones was adopted to capture diurnal and seasonal variations as shown in the Fig. 3 below. Data Collection Procedures involved Field measurements for pollutants, Satellite proxies (e.g., MODIS AOD), Meteorological data (wind speed, temperature, humidity, planetary boundary layer height) and Land-use/land-cover maps from Landsat or Sentinel data. The study deployed Geo-statistical Techniques such as Exploratory spatial data analysis (ESDA), Spatial interpolation using Ordinary Kriging or Co-kriging and Spatial autocorrelation. The Geo-Spatial Techniques involved GIS mapping using ArcGIS/QGIS, Pollution surface modelling, Hotspot and cluster mapping and Land-use overlay analysis. Data Processing and Analysis Tools used for the analysis included ArcGIS, QGIS and Remote sensing processing with Google Earth Engine. Wind Rose Analysis for pollutant dispersion modeled prevailing wind directions and speeds. Air Quality Index (AQI) was computed using SIM-AIR (version 1.1) to categorize air pollution levels and their potential impacts.

Table 1: Description of the Sampling Points

S/N	District	Description	Lat	Long	Elevation	Characteristics
1	Maitama I	Close to Transcorp junction	9.07763	7.49663	514	High vehicular movement, petrol station
2	Maitama II	Nicon junction	9.09583	7.47725	514	High vehicular movement, petrol station, motor park
3	Wuse I	By NESREA office	9.04892	7.45792	472	Low vehicular movement, car park, office buildings, residential buildings
4	Wuse II	Beside Wuse Market	9.07053	7.46458	479	High vehicular and human movement, petrol station, Motor park, Market, temporary waste dump
5	Garki	By Murg plaza UTC	9.03817	7.4843	501	High vehicular movement, petrol station, Motor park, Printing hubs
6	Asokoro I	Close to AYA junction	9.04962	7.52663	550	High vehicular movement, petrol station, Motor park
7	Asokoro II	By Asokoro Village	9.01708	7.51642	510	High vehicular movement, keke, motorcycle and human traffic, Motor park
8	Guzape	Gilmor junction	9.02	7.49787	550	Moderate vehicular movement, keke, motorcycle and human traffic
9	Dawaki	By the bridge	9.12272	7.38445	503	Moderate vehicular movement, keke, motorcycle and human traffic
10	Lugbe	Lugbe car wash U-turn	8.98378	7.37628	418	High vehicular movement, keke, motorcycle and human traffic, market, Motor park, temporary waste dump
11	Gwarinpa	Opposite Tastia restaurant	9.10925	7.40408	480	High vehicular movement, keke, motorcycle and human traffic, market, Motor park
12	Kado	Kado mini roundabout	9.07913	7.41697	457	High vehicular movement, and human traffic
13	Utako	Close to Berger	9.0673	7.35097	466	High vehicular movement, keke, and human traffic, market, Motor park, temporary waste dump
14	Wuye	Wuye junction	9.05395	7.44413	460	Low vehicular movement, car park, office buildings, residential buildings
15	Kukwaba	By the city gate	9.03508	7.44838	478	High vehicular movement, petrol station
16	CBD	Close to NNPC towers	9.05462	7.48395	481	High vehicular movement, car park, office buildings, residential buildings, petrol station
17	Galadimawa	Galadimawa junction	9.00212	7.42388	550	High vehicular movement, keke, motorcycle and human traffic, market, Motor park, temporary waste dump
18	Gudu	By the Police station	9.00078	7.47128	559	High vehicular movement, Keke, motorcycle and human traffic, Lights/spare parts market, Motor Park, temporary waste dump
19	Mpape	After Mpape Markt	9.22583	7.84425	683	High vehicular movement, Keke, motorcycle and human traffic, market, motor park, temporary waste dump, granite mining activities
20	Dutse	Close to Dutse market	9.13595	7.36537	465	High vehicular movement, Keke, motorcycle and human traffic, market, Motor Park, temporary waste dump

In the context of monitoring air quality, several critical parameters were chosen for this study based on their relevance to both human health and environmental sustainability. These parameters, PM10, PM2.5, Volatile Organic Compounds (VOCs), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Sulfur dioxide (SO_2), and Nitrogen dioxide (NO_2), were selected due to their significant roles in atmospheric pollution and their impact on climate change, human health, and air quality management. Air quality parameters were measured using a variety of advanced instruments to ensure accurate and reliable data collection. The Temtop N2000 Series was utilized for monitoring particulate matter (PM2.5 and PM10), carbon dioxide (CO_2), temperature, and relative humidity (RH). The Extech VFM200 was employed to measure volatile organic compounds (VOCs), while the Dräger O_3 monitor was used to measure ground-level ozone (O_3). The Dräger X-am 5600 multi-gas monitor was used for measuring methane (CH_4), sulfur dioxide (SO_2), and carbon monoxide (CO). Additionally, Nextteq monitor was employed to monitor nitrogen dioxide (NO_2), a pollutant closely linked to combustion processes and traffic emissions. To measure atmospheric conditions, the BTmeter BT-100-APP Anemometer was used to measure wind speed and temperature. Air samples were collected at approximately 2 meters above ground level at various geo-referenced monitoring locations, including the control site. The analysis of air quality data in this study was conducted using a combination of geo-statistical and geo-spatial techniques to ensure comprehensive interpretation and to extract meaningful insights.

Statistical analysis involved descriptive statistics (mean, SD, range), Inferential tests (ANOVA or Kruskal-Wallis for spatial zone differences). Correlation and regression models linking pollutants to meteorological factors, Time-series analysis for seasonal trends and Validation metrics for geo-statistical models (RMSE, MAE, R^2).

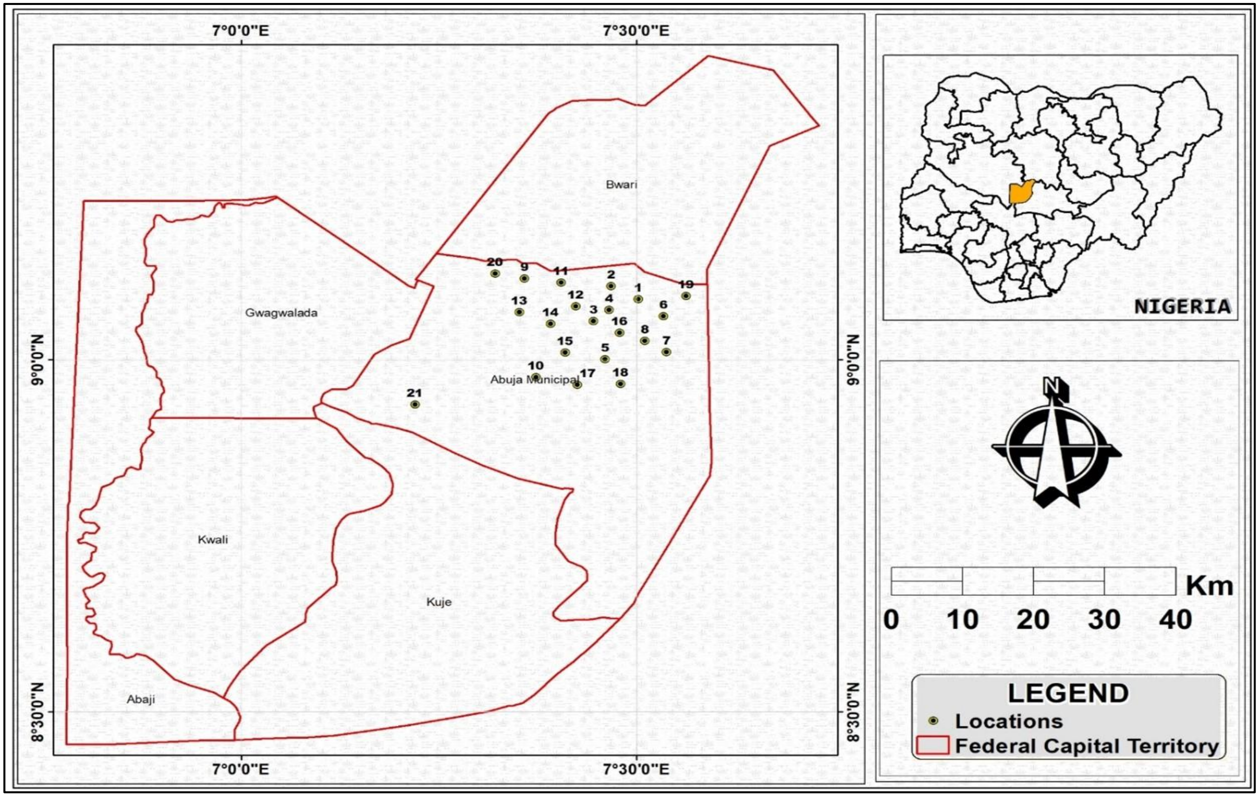


FIG 3. MAP OF FCT SHOWING AIR POLLUTION SAMPLING LOCATIONS

The air quality monitoring was conducted over a period of 6 days for morning, afternoon and evening, with data collection spread across both the dry and wet seasons. Specifically, 3 days of monitoring were carried out during the dry season, and 3 days during the wet season. Measurements were taken at 21 geo-referenced monitoring stations, with 7 pollutants measured at each station. This resulted in a comprehensive dataset across the 6 days of monitoring, providing valuable insights into the seasonal variation and spatial distribution of air pollutants.

RESULTS AND DISCUSSION

The summary of $PM_{2.5}$ concentration in the various sampling points ranged between 10.53 µg/m^3 in Galadimawa and maximum mean value of 15.80 µg/m^3 in Guzape (Table 2) ;while the wet season, $PM_{2.5}$ concentrations recorded significant spatial variability, with a minimum mean of 13.03 µg/m^3 in Galadimawa and a maximum mean of 44.57 µg/m^3 in Mpape. The mean levels of $PM_{2.5}$ for dry seasons are within the limits set out by the NAAQS . However, for the wet seasons the concentration in Galadimawa falls below the NAAQS annual limit of 25 μg/m^3, the Mpape value exceeds this annual limit, indicating potential long-term health risks if sustained over the year. The elevated PM$_{2.5}$ levels in Mpape may be influenced by local pollution sources such as quarrying and vehicular emissions from traffic. Also, Mpape recorded a mean wind speed of 2.5m/s, and Elevated wind speeds are associated with improved atmospheric mixing, thereby enhancing the dilution and dispersion processes of air pollutants (Huang *et al.*,2000). Elevated levels of PM$_{2.5}$ in Abuja can stem from sources including vehicle emissions, industrial processes, agricultural burning, and construction activities (Ogundele & Adie 2020; Kanee et al. 2020). The recorded PM$_{10}$ concentrations for the dry season ranged from a minimum mean value of 9.73 μg/m^3 in Kado to a maximum mean value of 21.13 μg/m^3 in Guzape**,** all of which remain well below Nigeria's NAAQS limits for PM$_{10}$ (150 μg/m^3 for 24 hours and 40 μg/m^3 annually). The elevated concentrations observed in Guzape suggest the presence of localised pollution sources such as construction activities, vehicular emissions, and dust resuspension from construction activities, which are prevalent in the area. Similar findings have been documented in previous studies, emphasizing the role of human activities like urban traffic, road construction activities, Open burning and industrial operations as key contributors to PM10 and PM$_{2.5}$ pollution in Nigerian cities (Efe, 2008; Giwa et al. 2019).

Table 2. Mean Values of PM$_{2.5}$ (μg/m^3) for Dry and Wet seasons

Dry Season PM 2.5 Concentration						**Wet (Rainy) Season PM 2.5 Concentration**				
District	Min	Max	Mean	SD	Variance	Min	Max	Mean	SD	Variance
Maitama I	10.00	15.94	12.03	2.74	7.48	12.6	20.20	16.233	3.112	9.68
Maitama II	10.50	12.50	11.67	0.85	0.72	17.8	30.53	23.60	5.24	27.49
Wuse I	9.01	18.61	13.83	3.92	15.36	14.1	23.90	18.87	4.01	16.04
Wuse II	11.02	13.20	12.30	0.94	0.89	16.3	23.25	20.73	3.14	9.87
Garki	10.01	18.40	13.81	3.28	10.75	14.1	23.43	18.52	3.81	14.54
Asokoro I	12.50	17.40	14.88	1.85	3.41	11.7	22.55	16.53	4.48	20.08
Asokoro II	16.02	19.34	17.80	1.32	1.68	13.4	38.42	22.62	11.22	125.95
Guzape	13.42	19.02	15.80	2.36	5.55	29.01	43.40	33.82	6.79	46.08
Dawaki	8.00	14.40	11.37	2.62	6.88	21.7	34.42	25.93	5.99	35.84
Lugbe	13.01	17.90	15.73	2.04	4.16	7.9	26.30	17.37	7.52	56.57
Gwarinpa	11.02	18.03	14.12	2.91	8.49	23.3	29.63	26.97	2.67	7.15
Kado	7.01	18.60	13.43	4.82	23.23	18.6	24.72	21.03	2.64	6.96
Utako	7.12	19.30	12.40	5.13	26.34	19.3	20.94	19.83	0.75	0.57
Wuye	8.13	17.40	13.53	4.01	16.12	25.24	27.40	25.93	1.04	1.08
Kukwaba	8.32	16.50	13.43	3.63	13.17	14.50	23.22	18.07	3.72	13.84
CBD	7.01	20.23	12.87	5.38	28.97	24.80	41.64	32.13	7.02	49.32
Galadimawa	4.40	17.22	10.53	5.24	27.45	7.53	17.20	13.03	4.08	16.62
Gudu	8.42	15.94	13.10	3.61	13.05	25.4	25.90	25.6	0.22	0.05
Mpape	12.34	14.21	13.03	0.82	0.670	26.6	54.40	44.57	12.71	161.54
Dutse	7.23	18.60	12.77	4.74	22.43	22.72	28.60	26.63	2.78	7.74
Control	13.2.5	19.31	15.63	2.46	6.04	13.24	24.70	18.97	4.69	22.04

Table 3: Summary of PM$_{10}$ Concentration (μg/m^3) for Dry and Wet Seasons

Dry Season PM$_{10}$ Concentration						**Wet (Rainy) Season PM$_{10}$ Concentration**				
District	Min	Max	Mean	SD	Variance	Min	Max	Mean	SD	Variance
Maitama I	11.34	14.62	12.87	1.473	2.169	19.74	33.06	25.767	5.492	30.162
Maitama II	13.03	27.90	18.53	6.66	44.35	28.153	47.94	36.9	8.23	67.76
Wuse I	10.41	22.52	16.23	5.11	26.04	22.4	42.53	30.37	8.72	76.02
Wuse II	12.43	18.23	15.53	2.63	6.78	26.21	38.24	33.6	5.28	27.92
Garki	11.30	19.33	15.57	3.44	11.83	22.40	36.46	29.37	5.72	32.67
Asokoro I	15.82	19.02	17.12	1.37	1.89	20.54	36.57	27.6	6.65	44.29
Asokoro II	12.91	20.45	17.27	3.12	9.74	22.26	62.93	38	17.82	317.49
Guzape	17.50	27.90	21.13	4.79	22.94	47.93	67.53	54.43	9.24	85.37

Dawaki	9.53	17.82	13.87	3.65	13.34	34.80	57.82	42.47	10.84	117.56
Lugbe	9.63	19.53	14.732	4.05	16.38	12.93	39.54	27.33	10.98	120.5
Gwarinpa	12.32	25.07	18.63	5.31	28.23	38.93	48.80	44.23	4.08	16.63
Kado	6.22	17.33	10.53	4.86	23.66	26.25	37.39	31.77	4.53	20.54
Utako	8.23	12.95	11.17	2.24	5.03	32.66	32.93	32.7	0.14	0.02
Wuye	9.92	25.42	19.04	7.16	51.31	42.63	45.44	43.53	1.32	1.74
Kukwaba	4.21	16.23	9.73	5.01	25.08	24.54	35.90	28.7	5.17	26.73
CBD	9.32	24.43	16.24	6.33	40.03	38.80	75.23	52.8	16	256.11
Galadimawa	9.32	14.1	11.47	1.99	3.95	11.52	29.30	21.63	7.47	55.85
Gudu	9.13	25.2	18.73	7.01	49.08	42.05	45.23	44.13	1.51	2.28
Mpape	12.10	19.23	15.03	2.91	8.47	43.55	92.10	71.9	20.67	427.28
Dutse	8.22	26.5	17.53	7.56	57.22	38.13	46.54	43.7	3.96	15.68
Control	11.02	16.2	13.17	2.21	4.88	23.40	36.24	30.63	5.36	28.73

The elevated PM_{10} levels in Mpape can be attributed to intensive human and industrial activities, such as quarrying, dust particles, and vehicular emissions, which are common in the area. Although short-term exposure may not immediately threaten public health, long-term exposure to concentrations above the NAAQS annual limit could contribute to respiratory and cardiovascular diseases, particularly among vulnerable populations. Elevated levels of $PM_{2.5}$ and PM_{10} during the wet season are often linked to specific activities and environmental conditions (Ndunda & Mungatana, 2020).

The maximum mean concentration of CO_2 during the dry season was recorded in CBD (607 ppm) while the minimum was recorded in the control point along airport road (527 ppm). This reflects a typical urban variation influenced by factors such as vehicular emissions, industrial activities, and construction (Etuk *et al.*,2022). For the wet season, the maximum mean value was recorded in CBD (527 ppm) and the minimum was (441 ppm) - Utako. These higher CO_2 values were found in the residential and commercial districts (Okobia *et al.*, 2017)

Table 4: Summary of CO_2 Concentration (ppm) for Dry and Wet Seasons

	Dry Season CO_2 Concentration					Wet (Rainy) Season CO_2 Concentration				
District	Min	Max	Mean	SD	Variance	Min	Max	Mean	SD	Variance
Maitama I	543.00	571.00	554.33	12.04	144.89	443.00	474.00	455.33	13.43	180.22
Maitama II	561.00	588.00	570.67	12.28	150.89	461,00	484.00	469.33	10.40	108.22
Wuse I	502.00	578.00	542.00	31.16	970.67	446,00	485.00	469.67	16.98	288.22
Wuse II	563.00	605.00	587.67	17.91	320.89	463.00	519.00	492.33	22.94	526.22
Garki	561.00	593.00	575.00	13.37	178.67	461.00	485.00	472.33	9.84	96.89
Asokoro I	550.00	638.00	583.33	38.96	1518.22	450.00	484.00	465.33	14.08	198.22
Asokoro II	557.00	593.00	577.33	15.06	226.89	457.00	482.00	465.33	11.79	138.89
Guzape	569.00	605.00	583.67	15.43	238.22	469.00	477.00	471.67	3.77	14.22
Dawaki	549.00	622.00	587.67	29.96	897.56	449.00	492.00	463.33	20.27	410.89
Lugbe	511.00	582.00	552.33	30.14	908.22	411.00	484.00	453.00	30.80	948.67
Gwarinpa	571.00	635.00	593.67	29.27	856.89	475.00	535.00	497.67	26.60	707.56
Kado	566.00	593.00	580.33	11.09	122.89	466.00	488.00	478.67	9.29	86.22
Utako	513.00	597.00	562.33	35.83	1283.56	413.00	497.00	441	39.60	15.68
Wuye	570.00	582.00	578.00	5.66	32.00	470.00	482.00	474	5.66	32.00
Kukwaba	560.00	588.00	576.33	11.90	141.56	460.00	481.00	470.67	8.58	73.56
CBD	571.00	673.00	607.00	46.73	2184	471.00	573.00	527	42.24	17.84
Galadimawa	561.00	573.00	568.33	5.25	27.56	461.00	474.00	469.33	5.91	34.89
Gudu	573.00	627.00	601.00	22.09	488.00	473.00	503.00	483	14.14	200.00
Mpape	508.00	606.00	567.33	42.59	1814.22	408.00	506.00	452.33	40.55	1644.22
Dutse	561.00	582.00	574.00	9.27	86.00	461.00	479.00	467	8.49	72.00
Control	460.00	562.00	527.00	47.39	22.46	459.00	462.00	460.33	1.250	15.60

Table 5, shows that the minimum mean value of CO concentration for dry season is BDL while the maximum mean value for CO concentration is 5.34 in Mpape, exceeding the 1-hour NAAQS acceptable threshold for short-term exposure limit of 0.01–0.06 ppm which can cause harmful effects, particularly for sensitive groups such as children, the elderly, and those with respiratory conditions. However, the concentration remains well below the 8-hour limit of 10–20 ppm, meaning that it complies with the long-term exposure standard (WHO,2022). The minimum mean concentration of CO for the wet season was recorded at the control along airport road, with a value of 0.03 ppm, and a maximum mean value of 3.40ppm recorded in Mpape. However, the concentration remains well below the 8-hour limit of 10–20 ppm, meaning that it complies with the long-term exposure standard. Possible reasons for high CO concentrations in Mpape may include vehicular emissions, quarrying activities, and poor traffic management within the area, all of which are common contributors to CO pollution in urban environments (Danek et al.,2022; Kavitha et al.,2023). Additionally, Mpape recorded a mean wind speed of 2.5m/s, and elevated wind speeds are associated with improved atmospheric mixing, thereby enhancing the dilution and dispersion processes of air pollutants (Huang et al., 2000; Ogundele & Adie,2020).

Table 5: Summary of CO Concentration (ppm) for Dry and Wet Seasons

Dry Season CO Concentration						Wet (Rainy) Season CO Concentration				
District	Min	Max	Mean	SD	Variance	Min	Max	Mean	SD	Variance
Maitama I	BDL	1.42	0.46	BDL	BDL	BDL	2.62	1.167	1.08	1.16
Maitama II	0.48	2.60	1.42	0.48	2.62	0.24	2.68	1.40	0.98	0.96
Wuse I	BDL	0.40	0.84	BDL	0.83	BDL	0.82	0.42	0.33	0.11
Wuse II	0.50	4.32	1.71	0.54	4.34	1.76	4.30	3.33	1.14	1.31
Garki	2.68	1.41	0.61	0.62	2.68	0.64	1.53	1.17	0.40	0.16
Asokoro I	1.66	3.43	3.10	1.66	3.41	2.32	3.44	2.93	0.46	0.22
Asokoro II	BDL	4.30	2.80	BDL	4.31	1.77	4.3	2.93	1.07	1.14
Guzape	BDL	0.51	BDL	BDL	0.51	BDL	0.51	0.17	0.24	0.06
Dawaki	5.76	3.41	2.20	2.24	5.76	1.24	3.42	2.27	0.93	0.81
Lugbe	BDL	2.14	1.32	BDL	2.12	BDL	2.10	1.13	0.87	0.75
Gwarinpa	BDL	2.51	3.42	BDL	3.41	0.33	3.44	2.07	1.30	1.73
Kado	BDL	1.40	1.62	BDL	1.64	BDL	1.63	1.00	0.71	0.51
Utako	BDL	2.92	2.312	BDL	2.92	BDL	2.92	1.73	1.25	1.56
Wuye	BDL	0.20	0.21	BDL	0.24	0.26	0.60	0.33	0.19	0.04
Kukwaba	BDL	2.12	1.32	BDL	2.12	BDL	2.12	1.13	0.87	0.75
CBD	BDL	2.81	0.23	BDL	2.80	BDL	2.80	1.00	1.28	1.63
Galadimawa	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Gudu	BDL	5.3	0.33	BDL	5.35	0.30	5.30	1.97	2.36	5.56
Mpape	4.25	2.1	5.34	2.1	5.30	2.12	5.32	3.40	1.37	1.89
Dutse	BDL	BDL	0.60	BDL	0.60	BDL	1.43	0.67	0.57	0.33
Control	BDL	BDL	0.15	BDL	0.14	BDL	0.14	0.03	0.05	BDL

The highest mean concentration of nitrogen dioxide (NO_2) recorded was in Wuse II during the dry season - 0.05 ppm. According to the Nigerian NAAQS, the ambient air quality standard for NO_2 is set at 0.04–0.06 ppm for a 1-hour averaging time (WHO,2021).

Table 6: Summary of NO_2 Concentration (ppm) for Dry and Wet Seasons

Dry Season NO_2 Concentration						Wet (Rainy) Season NO_2 Concentration				
District	Min	Max	Mean	SD	Variance	Min	Max	Mean	SD	Variance
Maitama I	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Maitama II	BDL	0.02	0.01	0.01	BDL	BDL	BDL	BDL	BDL	BDL
Wuse I	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Wuse II	BDL	0.15	0.05	0.07	BDL	BDL	BDL	BDL	BDL	BDL
Garki	BDL	0.06	0.02	0.03	BDL	BDL	BDL	BDL	BDL	BDL
Asokoro I	BDL	0.05	0.02	0.02	BDL	BDL	BDL	BDL	BDL	BDL
Asokoro II	BDL	0.02	0.01	0.01	BDL	BDL	BDL	BDL	BDL	BDL
Guzape	BDL	0.03	0.01	0.01	BDL	BDL	BDL	BDL	BDL	BDL
Dawaki	BDL	0.12	0.04	0.06	BDL	BDL	BDL	BDL	BDL	BDL
Lugbe	BDL	0.11	0.04	0.05	BDL	BDL	BDL	BDL	BDL	BDL
Gwarinpa	BDL	0.05	0.02	0.02	BDL	BDL	BDL	BDL	BDL	BDL

Kado	BDL	0.05	0.02	0.02	BDL	BDL	BDL	BDL	BDL	BDL
Utako	BDL	0.06	0.02	0.03	BDL	BDL	BDL	BDL	BDL	BDL
Wuye	BDL	0.02	0.01	0.01	BDL	BDL	BDL	BDL	BDL	BDL
Kukwaba	BDL	0.04	0.01	0.02	BDL	BDL	BDL	BDL	BDL	BDL
CBD	BDL	0.07	0.02	0.03	BDL	BDL	BDL	BDL	BDL	BDL
Galadimawa	BDL	0.04	0.01	0.02	BDL	BDL	BDL	BDL	BDL	BDL
Gudu	BDL	0.04	0.01	0.02	BDL	BDL	BDL	BDL	BDL	BDL
Mpape	BDL	0.10	0.03	0.05	BDL	BDL	BDL	BDL	BDL	BDL
Dutse	BDL	0.76	0.25	0.36	0.13	BDL	BDL	BDL	BDL	BDL
Control	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

The highest mean concentration of volatile organic compounds (VOCs) recorded during the dry season was 0.02ppm in Mpape and Utako while the minimum value was below detection limits (BDL). For the wet season, the highest mean concentration of VOC (0.01 ppm) was recorded in Mpape and Wuse volatile organic compounds (VOCs) recorded during the dry season to be 0.02ppm in Mpape and Utako while the minimum value was below detection limits (BDL). Key sources of VOC emissions include vehicular traffic, industrial activities, open waste burning, and fuel combustion (Ajayi et al., 2023; Oguntoke et al. 2014 and Awokola et al. 2020).

Table 7: Summary of VOC Concentration (ppm) for dry and wet seasons

Dry Season VOC Concentration						Wet Season VOC Concentration				
District	Min	Max	Mean	SD	Variance	Min	Max	Mean	SD	Variance
Maitama I	0.01	0.01	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Maitama II	BDL	BDL	BDL	BDL	BDL	BDL	0.01	BDL	BDL	BDL
Wuse I	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Wuse II	BDL	BDL	BDL	BDL	BDL	BDL	0.01	0.01	BDL	BDL
Garki	0.01	0.01	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Asokoro I	BDL	BDL	BDL	BDL	BDL	BDL	0.01	BDL	BDL	BDL
Asokoro II	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Guzape	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Dawaki	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Lugbe	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Gwarinpa	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Kado	0.01	0.01	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Utako	0.02	0.02	0.02	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Wuye	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Kukwaba	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
CBD	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Galadimawa	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Gudu	BDL	BDL	BDL	BDL	BDL	BDL	0.01	BDL	BDL	BDL
Mpape	0.02	0.02	0.02	BDL	BDL	BDL	0.01	0.01	BDL	BDL
Dutse	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Control	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

Geospatial Interpretation of Atmospheric Pollutants across the study area

Geospatial plots for analyzing the trends of $PM_{2.5}$, PM_{10} and other atmospheric pollutant concentrations to track their origin and spread are shown in the figures 4 -9 below. The spatial plot of PM $_{2.5}$ in the dry season measurement revealed that PM $_{2.5}$ concentration ranged between 6.5 6.5 $\mu g/m^3$ in the southwestern part of the study area around Utako to as high as 19.5 $\mu g/m^3$ in the southern and southeastern part of the study area close to Mpape.

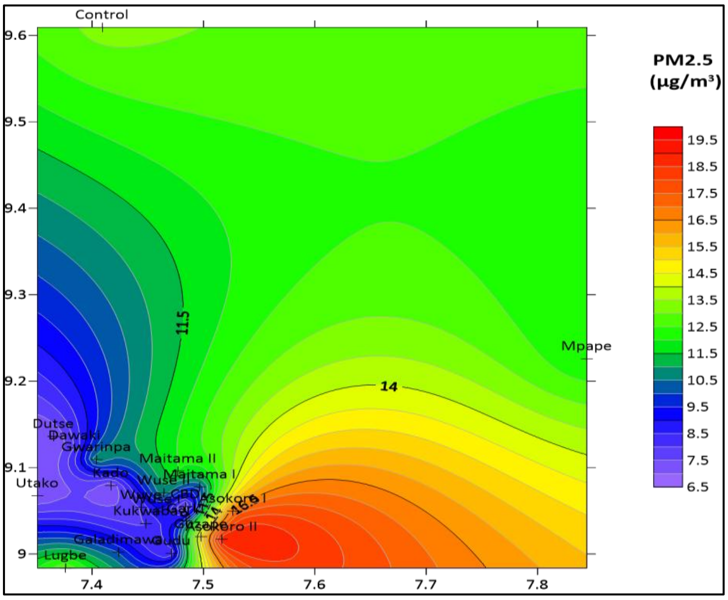


Fig 4: Spatial Plot of PM 2.5 For Dry Season Day 1

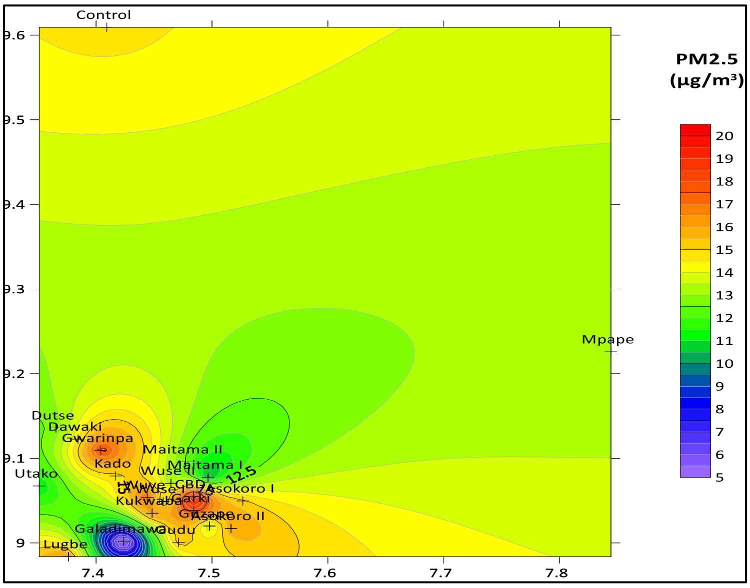


Fig 5: Spatial Plot of PM2.5 For Dry Season Day 2

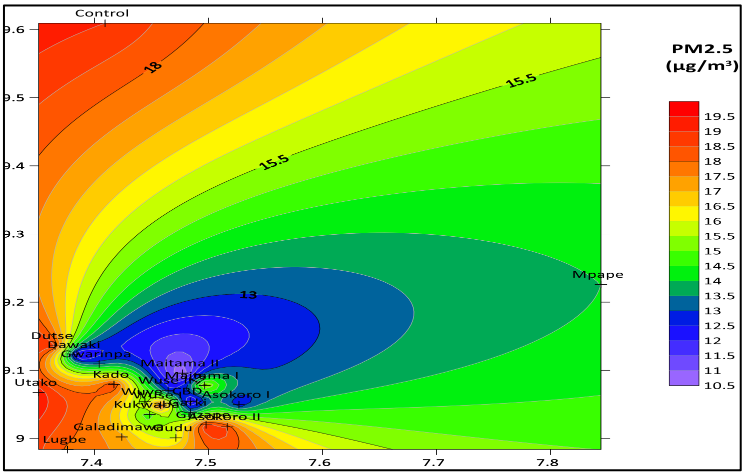


Fig 6: Spatial Plot of PM2.5 For Dry Season Day 3

The spatial plots of PM 10 across the study area revealed that the PM 10 concentrations were higher with an observed hotspot around Mpape. However, there seems to be a linear relationship between PM $_{2.5}$ and PM $_{10}$. All the spatial maps of the different pollutants followed the same trend indicating that the observed pollutant levels may be associated with daily non-point source events possibly related to traffic (Opara *et al.*,2016).

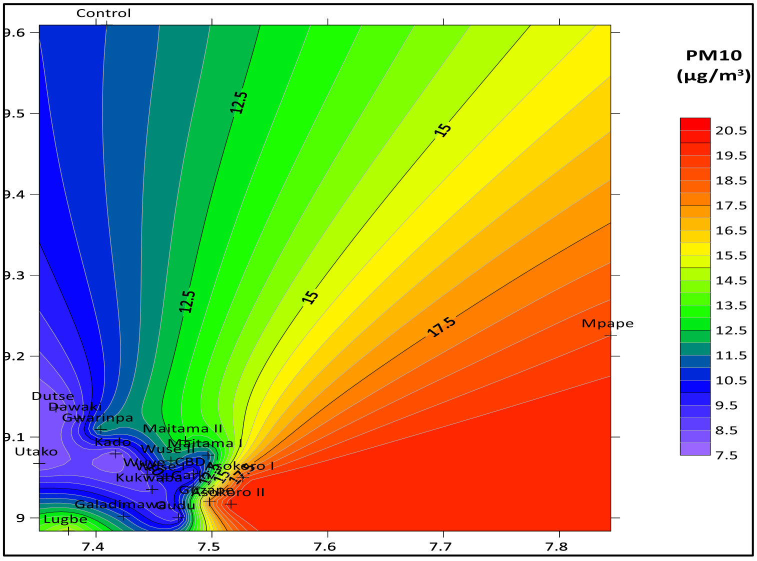


Fig 7: Contour Plot of PM10 for Dry Season Day 1

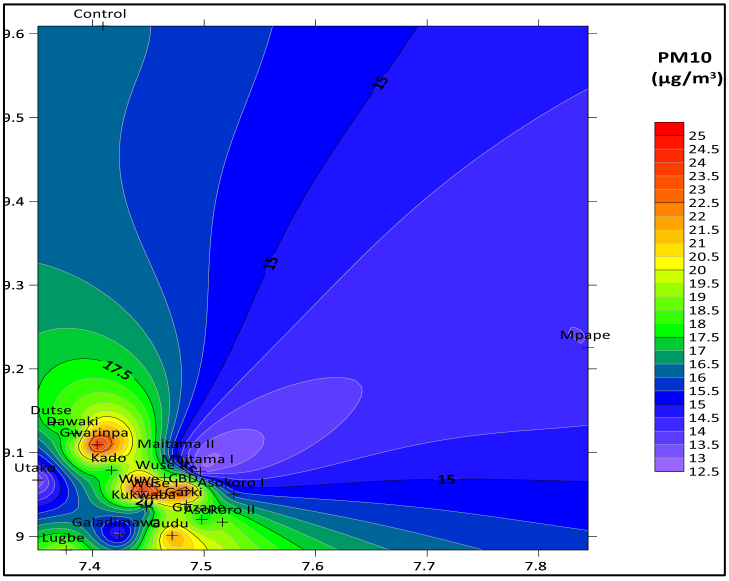


Fig 8: Contour Plot of PM10 For Dry Season Day 2

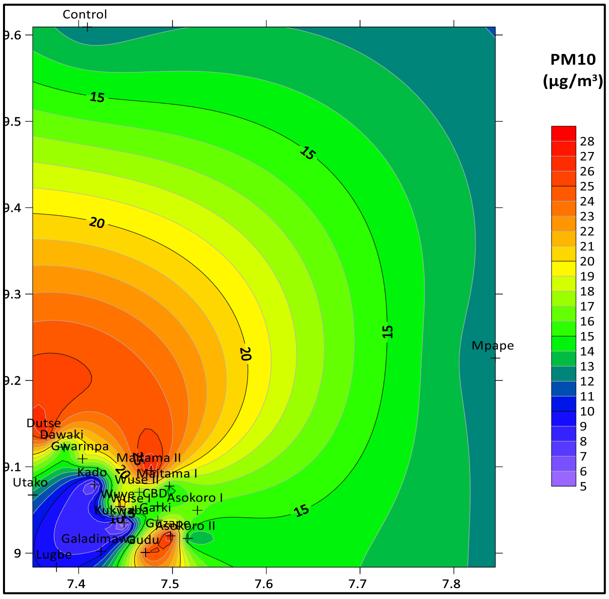


Fig 9: Contour Plot of PM10 For Dry Season Day 3

The spatial plots of $PM_{2.5}$ and PM_{10} consistently followed the same trend across the study area for wet season. However, the spatial maps for VOC, SO_2, NO_2 and Ozone did not follow any defined trend in the three days of measurement during the wet season. The spatial plot of $PM_{2.5}$ in day 1 rainy season measurement revealed that $PM_{2.5}$ ambient concentration varies as low as 7.0 μg/m^3 in the southwestern part of the study area around Lugbe to as high as 29.0 μg/m^3 around Gwarimpa Mpape and Dutse.

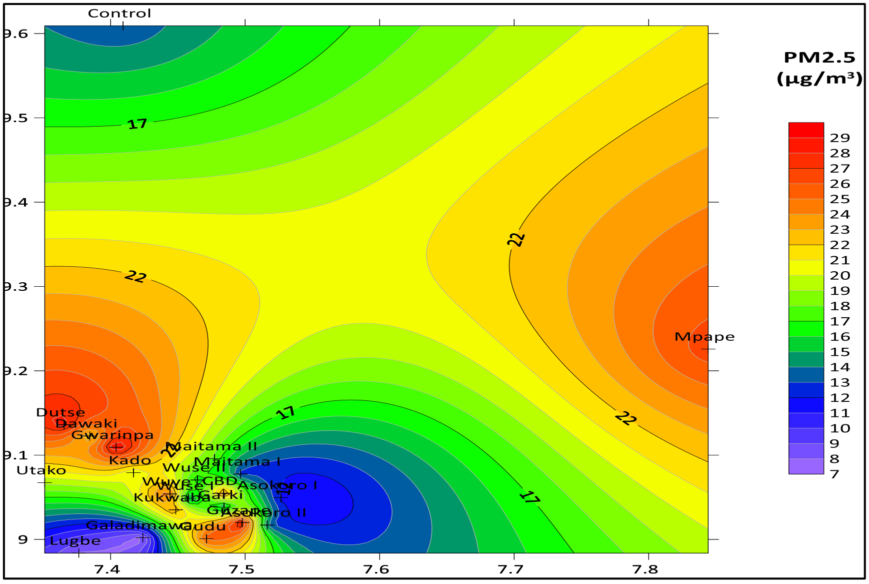


Fig 9: Contour Plot of Pm2.5 for Wet Season Day

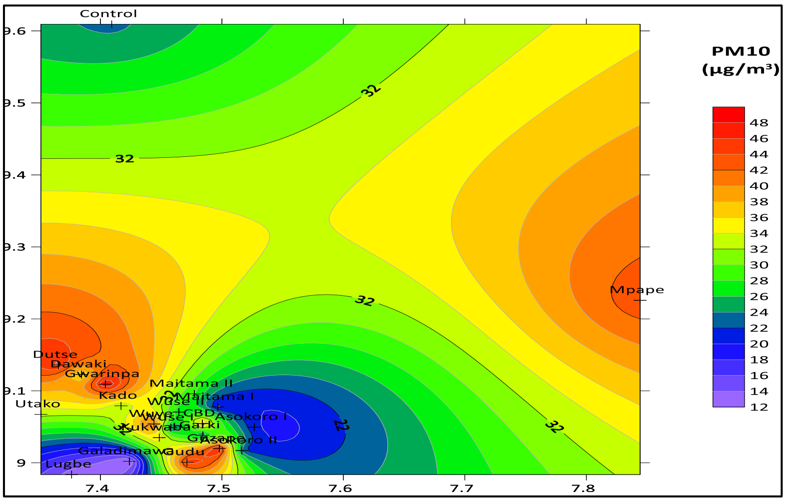
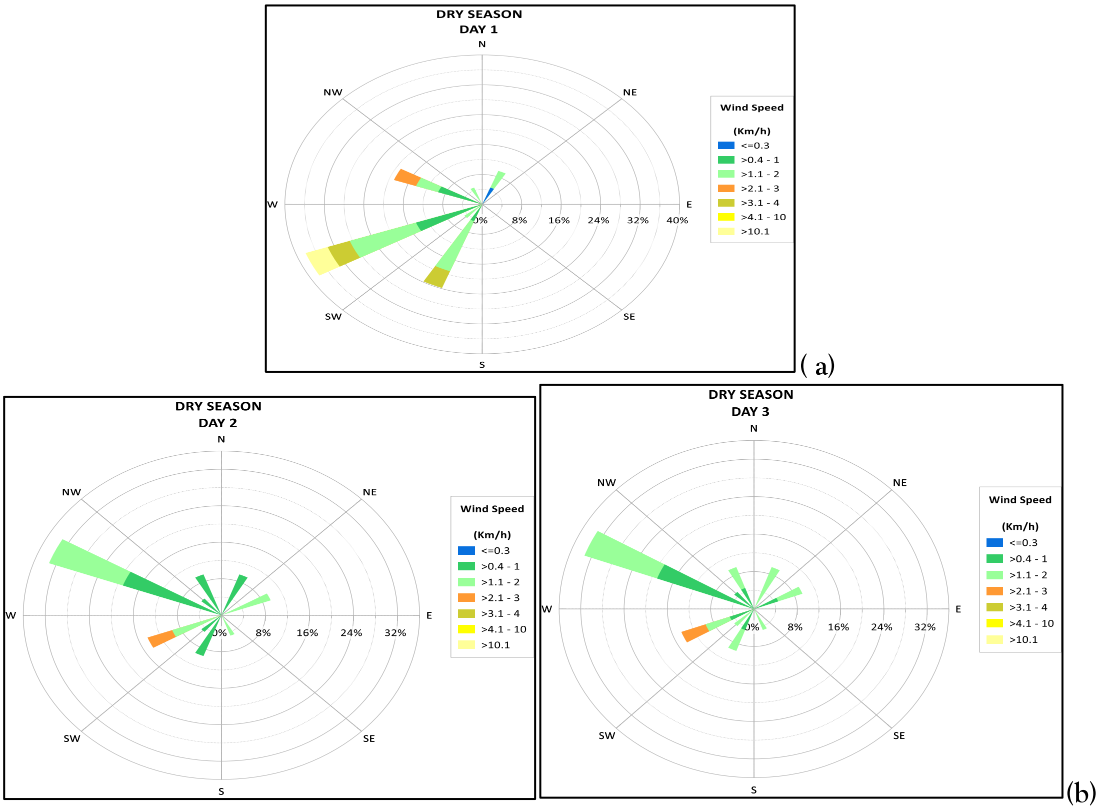


Fig 10: Contour Plot of PM 10 for Wet Season Day 1

The wind roses during the three days of field measurements during the dry and wet seasons were analyzed to describe the atmospheric dispersion patterns across the study area. The Wind rose diagram for dry season day 1 was predominantly Southwest with wind speeds ranging from calm to moderate. These dominant wind speeds and directions contributed significantly to the dispersion of the atmospheric pollutants (Fig.11). The wet season day 1 wind speed was predominantly Western and North Westerly, with wind speeds ranging from calm to moderate, with occasional stronger gusts. The light and variable winds from other directions contribute less to the overall wind pattern. The wet season day 2 study location experienced predominantly North Waste, and to a lesser extent South Waste, with wind speeds ranging from calm to moderate, with occasional stronger gusts. High-frequency NW winds could lead to the accumulation of airborne particulates in downwind regions, potentially impacting air quality and increased dispersion of urban pollutants during the wet season (Oguntoke and Yusuf 2008).

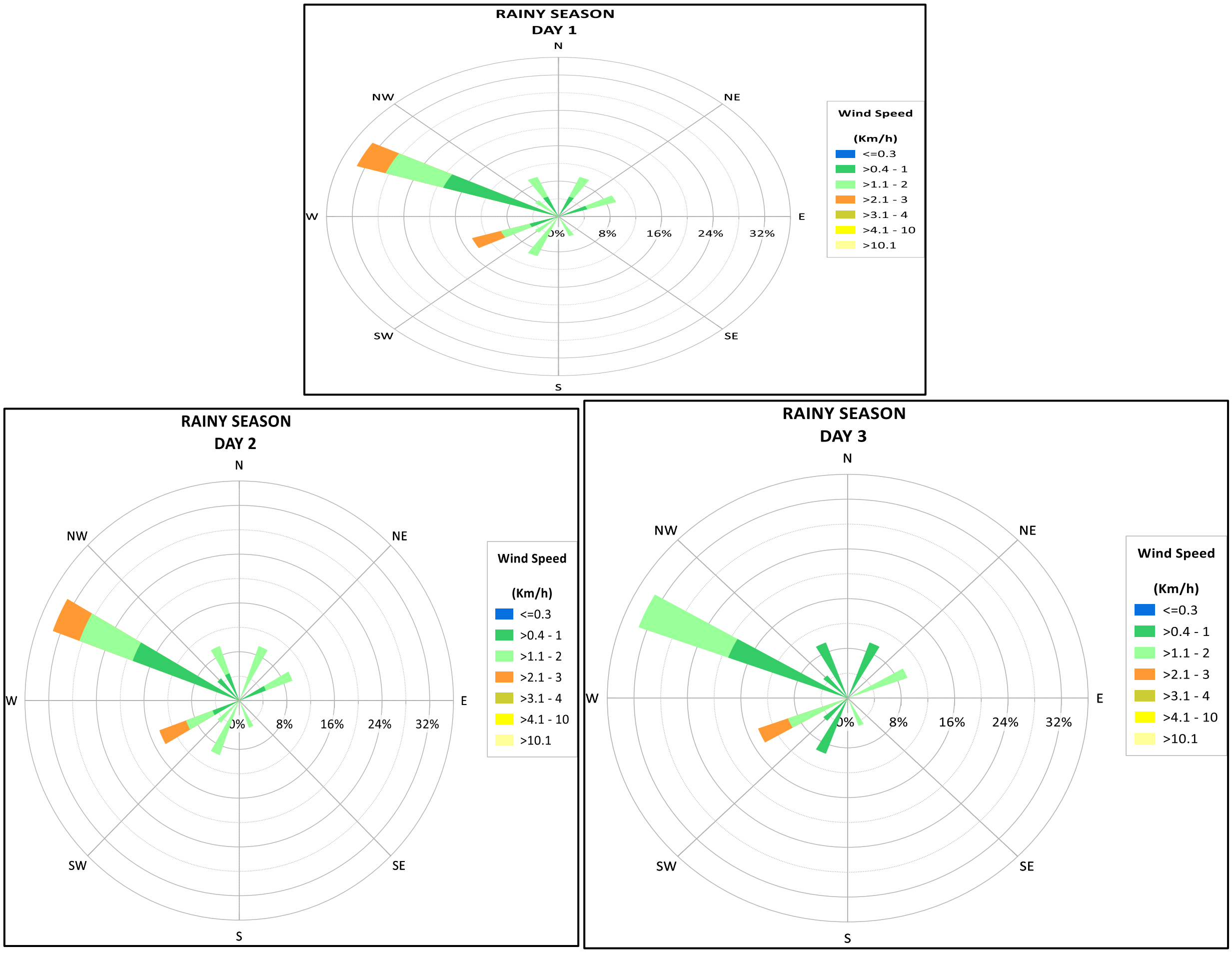


(a)

(b)

(c)

Fig 11: Wind Rose Diagram for Dry Season Showing The Pollutant Dispersion Pattern: (a) Day1 (b) Day 2 and (c) Day 3.



(b)

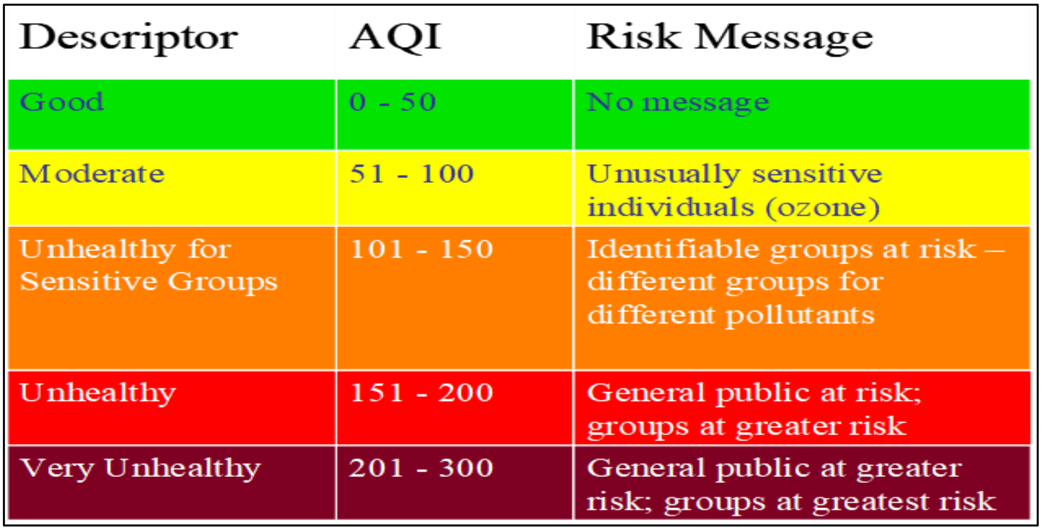
(c)

Fig 12: Wind Rose Diagram for Wet Season Showing the Pollutant Dispersion Pattern: (a) Day 1, (b) Day 2, and (C) Day 3

Air Quality Index (AQI) Determination of Abuja Sampled Areas

The Air Quality Index calculations across the study area were categorized good across the study area because the estimated AQI values fall within the range of 0-50, indicating good air quality with little or no risk to the public.

Table 8: AQI Categories and Health Effect



Descriptor	AQI	Risk Message
Good	0 - 50	No message
Moderate	51 - 100	Unusually sensitive individuals (ozone)
Unhealthy for Sensitive Groups	101 - 150	Identifiable groups at risk – different groups for different pollutants
Unhealthy	151 - 200	General public at risk; groups at greater risk
Very Unhealthy	201 - 300	General public at greater risk; groups at greatest risk

Table 9: AQ Index for Dry Season Day 1

DISTRICT	Individual AQI						Conditional Pollutant	Average AQI
	O3	PM2.5	PM10	CO	SO2	NOx		
Maitama I	0	32.46753	10.18519	0	0	0	PM2.5	21.32636
Maitama II	0	38.96104	12.03704	0.004606	0	0	PM2.5	17.00089
Wuse I	0	29.22078	9.259259	0	0	0	PM2.5	19.24002
Wuse II	0	35.71429	11.11111	0.004798	0	0	PM2.5	15.61006
Garki	0	32.46753	10.18519	0.025718	0	0	PM2.5	14.22615
Asokoro I	0	53.95181	17.59259	0.01593	0	0	PM2.5	23.85344
Asokoro II	0	57.88755	18.51852	0	0	0	PM2.5	38.20303
Guzape	0	48.7013	16.66667	0	0	0	PM2.5	32.68398
Dawaki	0	25.97403	8.333333	0.055274	0	0	PM2.5	11.45421
Lugbe	0	42.20779	13.88889	0	0	0	PM2.5	28.04834
Gwarinpa	0	35.71429	11.11111	0	0	0	PM2.5	23.4127
Kado	0	22.72727	7.407407	0	0	0	PM2.5	15.06734
Utako	0	22.72727	7.407407	0	0	0	PM2.5	15.06734
Wuye	0	25.97403	8.333333	0	0	0	PM2.5	17.15368
Kukwaba	0	25.97403	8.333333	0	0	0	PM2.5	17.15368
CBD	0	22.72727	8.333333	0	0	0	PM2.5	15.5303
Galadimawa	0	32.46753	10.18519	0	0	0	PM2.5	21.32636
Gudu	0	25.97403	8.333333	0	0.024992	0	PM2.5	11.44412
Mpape	0	38.96104	17.59259	0.040783	0	0	PM2.5	18.86481
Dutse	0	22.72727	7.407407	0	0	0	PM2.5	15.06734
Control	0	42.85714	10.18519	0	0	0	PM2.5	26.52116

Table 10: AQ Index for Wet Season Day 1

DISTRICT	Individual AQI						Conditional Pollutant	Average AQI
	O3	PM2.5	PM10	CO	SO2	NOx		
Maitama I	0	40.90909	18.24074	0.008636	0	0	PM2.5	19.71949
Maitama II	0	55.5261	26.01852	0.001919	0	0	PM2.5	27.18218
Wuse I	0	45.77922	20.74074	0	0	0	PM2.5	33.25998

Wuse II	0	52.5743	24.25926	0.037425	0	0	PM2.5	25.62366
Garki	0	45.77922	20.74074	0.014394	0	0	PM2.5	22.17812
Asokoro I	0	37.98701	18.98148	0.022071	0	0	PM2.5	18.99686
Asokoro II	0	43.50649	20.55556	0.016313	0	0	PM2.5	21.35945
Guzape	0	77.56627	44.35185	0	0	0	PM2.5	60.95906
Dawaki	0	63.2008	32.22222	0.011515	0	0	PM2.5	31.81151
Lugbe	0	25.64935	11.94444	0	0	0	PM2.5	18.7969
Gwarinpa	0	78.74699	45.18519	0.002879	0	0	PM2.5	41.31168
Kado	0	59.46185	29.44444	0	0	0	PM2.5	44.45315
Utako	0	58.47791	30.18519	0	0	0	PM2.5	44.33155
Wuye	0	70.08835	39.44444	0.005758	0	0	PM2.5	36.51285
Kukwaba	0	66.15261	33.24074	0	0	0	PM2.5	49.69668
CBD	0	69.3012	35.92593	0	0	0	PM2.5	52.61357
Galadimawa	0	24.35065	10.64815	0	0	0	PM2.5	17.4994
Gudu	0	70.67871	41.85185	0.002879	0	0	PM2.5	37.51115
Mpape	0	72.84337	40.27778	0.026869	0	0	PM2.5	37.71601
Dutse	0	76.77912	43.05556	0.013435	0	0	PM2.5	39.94937
Control	0	42.85714	21.66667	0	0	0	PM2.5	32.2619

Geostatistical Interpretation of Air Quality Data

The bivariate plots revealed a linear relationship with various degrees of strength between the various pollutants and climatic conditions which helps to understand how two variables are related in a predictable manner and can guide decisions or predictions about one variable based on the other.

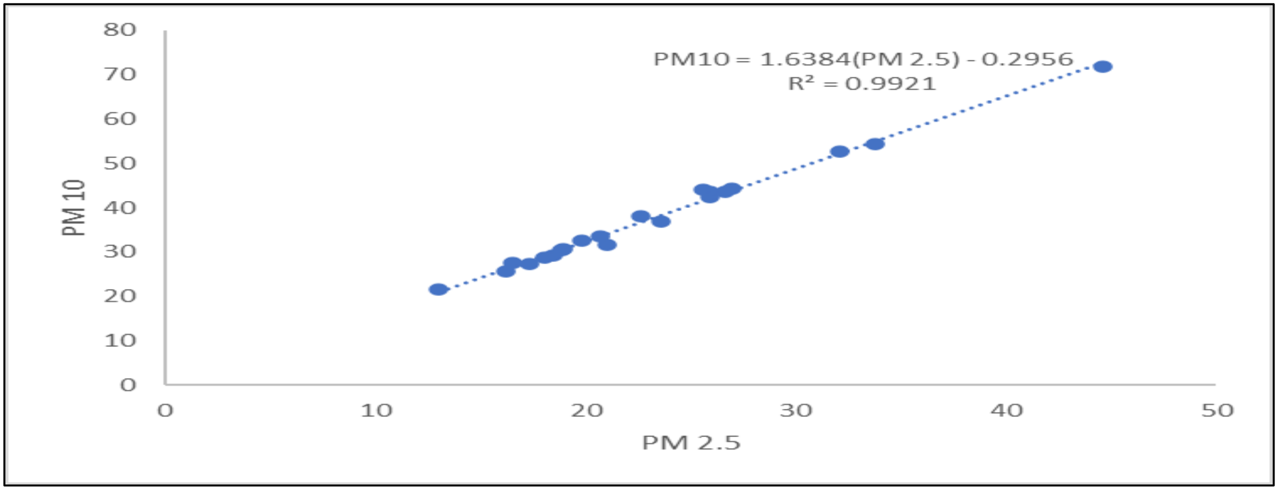


Fig. 13: PM 10 Vs PM 2.5 (Wet Season)

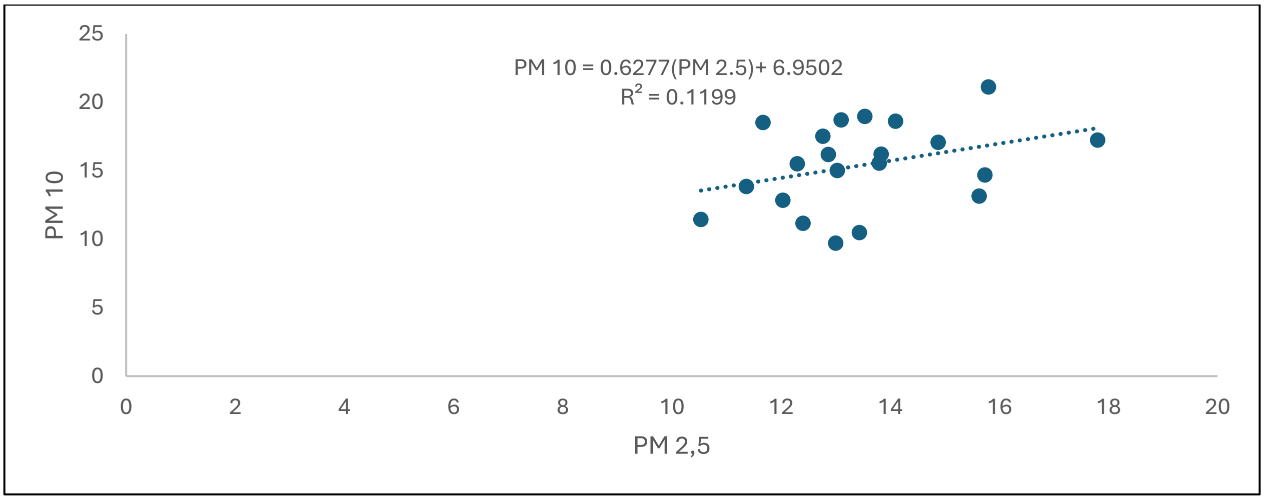


Fig. 14: PM 10 Vs PM 2.5 (Dry Season)

Table 11: Descriptive Statistics of Dry and Rainy Season Air Quality

AIR QUALITY								
					95% Confidence Interval for Mean			
	N	**Mean**	**Std. Deviation**	**Std. Error**	**Lower Bound**	**Upper Bound**	**Minimum**	**Maximum**
DRY SEASON	21	604.154	20.5047	4.4745	594.820	613.487	555.8	637.1
RAINY SEASON	21	533.685	29.2567	6.3843	520.368	547.003	495.3	612.9
Total	42	568.920	43.5242	6.7159	555.356	582.483	495.3	637.1

Dry and Wet Season Air Quality Comparative Statistical Analysis

The mean and standard deviations for the dry season air quality measured values were 604.2 and 20.5, respectively; while the variations during rainy season air quality 533.7 and 29.3, respectively (Table 11). The trend in this variation justifies earlier statistics calculations where dry season values were higher than wet season measurements. This agrees with the findings of other authors (Abdul et al;2020; Bhunia & Ding.2020; Butenko & Topchiy,2023 and Ekoh,2020).

The Analysis of variance (ANOVA) result of the variation in means between and within groups of the dry and wet season sampled air quality parameters in Abuja showed a significant variation in the means between and within groups of concentration of air quality parameters sampled in rainy and dry seasons (Table 12).

Table 12: ANOVA Of Dry and Rainy Season Air Quality

AIR QUALITY					
	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	52140.565	1	52140.565	81.700	.000
Within Groups	25527.942	40	638.199		
Total	77668.507	41			

CONCLUSION AND RECOMMENDATIONS

This study employed geo-statistical and geo-spatial analysis to assess ambient air quality across Abuja Metropolis, focusing on $PM_{2.5}$, PM_{10}, CO_2, CO, NO_2, and VOCs alongside meteorological parameters during both dry and wet seasons. This study shows that Abuja's atmospheric pollutant distribution is highly variable, shaped by land-use intensity, traffic density, and seasonal meteorology. Geo-statistical and geo-spatial analyses reveal significant hotspots, spatial clustering, and structured pollutant dispersion patterns. These findings affirm the urgent need for strengthened air-quality governance, enforcement of emission standards, and improved urban planning strategies. Furthermore, the results revealed clear spatial and seasonal variations in pollutant concentrations, largely influenced by vehicular emissions, quarrying, construction, and wind dynamics.

5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed to address air quality concerns in Abuja and mitigate the associated health and environmental risks:

1. There is a need for a comprehensive air quality monitoring network across Abuja, equipped with real-time monitoring stations to track pollutants continuously.
2. Strict enforcement of emission regulations for industries, construction activities, and vehicles should be prioritized to control excessive emissions.
3. Integrate pollution mapping into urban planning frameworks.
4. Enforce emission standards for vehicles and construction.
5. Implement low-emission zones in high-risk districts.
6. Expand research with machine-learning spatial modelling.

7. Integrate green technology by expanding green spaces, urban forests, and vegetative buffer zones can help absorb pollutants and improve overall air quality.

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