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The Role of Meteorological Parameters in Atmospheric Scavenging Across the Seasons: A Case Study of the Coastal Areas of Akwa Ibom State

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Abstract

In this study, the meteorological parameters were studied to assess their contributions to atmospheric scavenging in the different contrasting seasons of Mkpat Enin Local Government Area, Akwa Ibom State, Nigeria. Ambient concentrations of $PM_{2.5}$, PM_{10}, gaseous oxides (NO_2, SO_2, CO, CO_2, NH_3, H_2S, CH_2O, TVOCs) and meteorological parameters were estimated during both the dry (January-March) and wet (May-July) seasons at six strategic monitoring sites (S1—6) using ZN-NT22 and Holdpeak-HP5800G mobile air sensors. Statistically significant ($P < 0.05$) seasonal changes were found. The pollutant concentrations during the dry season were significantly higher than the limits set by the World Health Organization (WHO), with mean concentrations of $PM_{2.5}$, PM_{10}, CO_2, NO_2, SO_2 and CO being 109.84 $\mu g/m^3$, 155.50 $\mu g/m^3$, 863.33 ppm, 0.237ppm, 0.353ppm and 10.33ppm, respectively. The high values were due to the atmospheric stability and low relative humidity (53.83%). In contrast, the pollutant loads in the wet season were significantly reduced as expected likely due to rain washout and better dispersion, with $PM_{2.5}$ and PM_{10} concentrations of 32.33 $\mu g/m^3$ and 55.42 $\mu g/m^3$ respectively, as well as higher relative humidity (68.67%) and wind speed (1.15 m/s). However, during the dry season, the relationship between co-emissions was very strong for CO with NO_2 ($r = 0.997$) and SO_2 with NO_2 ($r = 0.995$), which signifies the main sources of heavy vehicular and industrial logistics. Main pollutants, on the other hand, had negative correlation with wind speed and temperature, indicating atmospheric dilution ($r = -0.584$ to -0.895). These findings reveal a set of acute public health risks during dry periods and the importance of integrating the seasonally-varying meteorological processes into local air quality management and regulatory frameworks.

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1.0 Introduction

Urban centers are continuously defined by intense industrial operations, rapid population growth, and heavy vehicular traffic, all of which substantially compromise local air quality (Okon et al., 2024; Ekpa et al., 2023).

Additionally, meteorological conditions play a pivotal role in governing air quality and dictating spatial pollutant dispersion. Elucidating the interactions between weather parameters and air quality is fundamental to evaluating and mitigating environmental and public health hazards (Ndoma et al., 2025). In Mkpat Enin, the interplay between growing anthropogenic emissions and seasonal monsoonal patterns leads to significant temporal variations in lower atmospheric air quality. (Ngele & Onwu 2015; Ogbemudia et al., 2025). Urban meteorological dynamics and atmospheric oxide concentrations are substantially modulated by natural ecosystems, which function as vital environmental buffers. These natural systems foster atmospheric stability via air quality enhancement, carbon sequestration, and microclimatic regulation. The study area forms a vital land and transit corridor for industrial and petroleum-related activities in the wider region which operates across Mkpat Enin and its neighboring coastal areas like Eastern Obolo and Ikot Abasi. Nevertheless, anthropogenic pressures such as fossil fuel combustion, deforestation, petroleum exploitation, industrial discharge, rapid urbanization, and mismanaged waste are deteriorating these areas (Ikpe et al., 2025). Consequently, their capacity to mitigate atmospheric pollutants and stabilize local meteorology across urban spaces, such as AKSU-Mkpat Enin setting, which is the transport corridor for these companies is increasingly compromised (Day et al., 2003; Ahmad et al., 2024; Ogbemudia, et al., 2025;). Such ecological deterioration presents profound environmental and public health hazards within the region. Industrial transport activities involve regular heavy-duty logistics and haulage (trucks carrying equipment, materials, and machinery) passing through the primary arterial roads of Mkpat Enin (e.g., the Ikot Akpaden axis connecting to Eastern Obolo).

Industrial and transportation activities discharge atmospheric pollutants, including like NO_2, SO_2, CO, and particulate matter; their accumulation in the lower atmosphere adversely impacts ecological integrity and human well-being (Ahmad, et. al. 2024; Ebri et al., 2025). The degradation of this ecosystem further compounds these issues by impairing natural filtration mechanisms, thereby elevating ambient pollutant concentrations and increasing exposure risks for adjacent populations (Zhang et al., 2024). By causing respiratory infections, heart disease, and chronic obstructive pulmonary disease, air pollution directly threatens human health locally and globally. Given that seasonal meteorological variations significantly govern the dispersion, concentration, and deposition of atmospheric pollutants, rigorous empirical studies are imperative to formulate effective mitigation strategies (Kurmi et al., 2020). Lacking a nuanced comprehension of the spatiotemporal variations in air pollution dynamics and their corresponding epidemiological impacts, public health interventions will inevitably remain reactive rather than preventive (Zhou et al., 2020). This inadequacy perpetuates an escalation in respiratory morbidities, resulting in heightened healthcare expenditures, diminished economic output, and impaired quality of life, particularly among vulnerable demographics such as pediatric, geriatric, and chronically ill populations (Dias & Tchepel, 2018; Zhou et al., 2020). Given these critical knowledge gaps, an integrated, empirical investigation is urgently required to evaluate how meteorology interacts with urbanization gradients to influence air quality dynamics. Such an investigation would address a critical research imperative while offering actionable insights to inform environmental health policy, urban spatial planning, and strategic resource allocation in this metropolis and comparable settings (Wu et al., 2025; Ekanem, 2022; Udosen & George, 2018a). The imperative for the present study stems from the growing recognition of air pollution as a primary public health hazard rather than a strictly environmental concern, particularly within developing contexts such as the main campus of AKSU and Mkpat Enin where empirical data on exposure dynamics and associated meteorological variables remain sparse or fragmented. Additionally**,** Mkpat Enin LGA is the primary geographic crossroads where heavy industrial logistics from oil companies and high-density educational traffic from AKSU Main Campus converge. These activities constitute major sources of particulate matter and gaseous pollutants, thereby necessitating systematic air quality assessment. Although previous studies have examined seasonal air pollution and meteorological variability in parts of Akwa Ibom State, quantitative information on the combined seasonal behavior of particulate matter, gaseous pollutants and meteorological conditions within the AKSU–Mkpat Enin urbanizing corridor remains undocumented. The present study therefore investigates the comparisons between a university environment and industrial/transport corridors. In fact, this research is the first empirical study of the combined seasonal trend of PMs, gaseous pollutants and meteorological parameters for the special industrial and educational transport corridor of AKSU – Mkpat Enin.

2.0 Study Area

Field sampling was carried out within the main campus of Akwa Ibom State University (AKSU) and selected sectors in Mkpat Enin Local Government Area (Figure 1). Topographically, the study locations featured elevations spanning 15 m to 24 m above sea level, geographically bounded by coordinates 4.558185° N to 4.664° N latitude and 7.748° E to 7.7488185° E longitude.

Geologically, the investigation area is situated within the Tertiary-aged Coastal Plain Sands of the Benin Formation, characterized by unconsolidated sand, silt, and clay deposits (Obianwu et al., 2011; Uwa et al., 2019; George et al., 2022a, 2020; Udosen & George 2018b). The high porosity and permeability inherent to these lithologies promote subterranean fluid transport and gas migration dynamics (George et al., 2025). Consequently, this hydrogeological configuration exerts an indirect control on atmospheric quality through soil-air gas exchange mechanisms and wetland emissions (George 2021a, b). The study area is characterized by a humid tropical climate characterized by two contrasting seasons: a wet season spanning April through October and a dry season extending from November to March (Ekanem et al., 2021). Mean annual precipitation exceeds 2,500 mm, accompanied by high relative humidity (70%–95%) and ambient temperatures fluctuating between 24°C and 32°C. High relative humidity and ambient temperatures significantly influence atmospheric chemical transformations and pollutant dynamics (Udosen et al., 2024 a, b, c). Peak dry-season temperatures reach up to 35°C; however, global climate change has introduced slight variations in the boundary thresholds of these meteorological parameters (George et al., 2022a, b, c; Udosen et al., 2023, 2024d; Ekanem et al., 2024, Thomas et al., 2020).

Anthropogenic activities in the study area are extensive and include oil and gas exploration, gas flaring, artisanal refining, Agricultural, transportation, and domestic biomass combustion. Mkpat Enin - Akpaden –Iko road serves as a transitional zone with increasing urbanization and vehicular emissions.

3.0 Materials and Methods

3.1 Methodology

This study adopted a field-based observational and cross-sectional research design aimed at assessing ambient air quality at the selected location within the study area. The design integrated real-time data acquisition using ZN-NT22 and Holdpeak-HP5800G mobile air sensors with temporal analysis technique to evaluate pollutant distribution patterns as well as Statistical evaluation of relationships among measured parameters. This method was apt for environmental monitoring studies where the objective was to characterize ambient conditions rather than establish causality.

A multi-parameter monitoring strategy was employed, allowing simultaneous measurement of particulate and gaseous pollutants alongside meteorological variables. This integrated approach provided a more comprehensive understanding of air quality dynamics compared to single-parameter studies. The mobile sensors operated based on a combination of detection technologies such as optical scattering method for particulate matter ($PM_{2.5}$ and PM_{10}), electrochemical sensors for carbon monoxide (CO), Non-dispersive infrared sensors for carbon dioxide (CO_2), thermistors and capacitive sensors for temperature and relative humidity and ultrasonic anemometer for measuring wind speed.

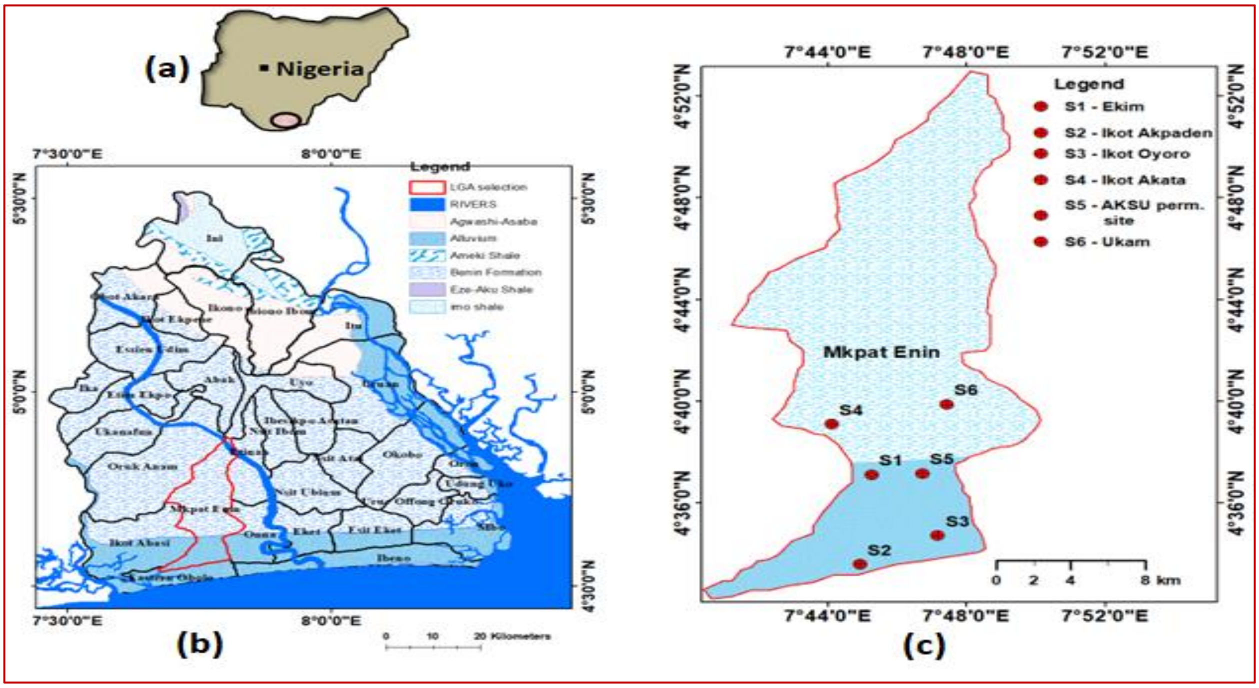

Figure 1: Schematic map showing (a) Nigeria highlighting Akwa Ibom State, (b) Akwa Ibom State showing Mkpat Enin Local Government Area (LGA), and (c) Mkpat Enin LGA detailing the specific study sites.

Sampling for gaseous pollutants was carried out during dry season (January - March 2026) and wet season (May – July, 2026). For the purpose of this study, six sampling sites were chosen within Mkpat Enin local government area. These gaseous pollutants were determined using their respective gas detectors which worked by electrochemical principles of detection, allowing gases diffuse through a porous membrane to an electrode where it is either chemically oxidized or reduced. The amount of current produced was determined by how much of the gas was either oxidized or reduced at the electrode, indicating the concentration of the gas.

Simultaneous measurements of the gases were taken with the Holdpeak HP-5800G (0-100 ppm, ±5% of full scale, 0.1 ppm resolution) which was zero calibrated in synthetic air and multi-point calibrated with reference gases. At the same time, the ZN-NT22 particulate air sensor was calibrated in a hermetically-sealed dynamic chamber after a 30-minute stabilization in dry air and stepped exposure to the target gas by mass flow controllers. Signal responses and recovery cycles continually recorded using digital data acquisition system, where measurement drift and empirical limits of error quantified.

3.2 Statistical analyses

Descriptive statistics were used to evaluate the meteorological and air quality data, with the results summarized in tables 1 and 2. Using Pearson correlation matrix statistical Package, multivariate correlation technique was employed to identify highly significant p - values ($P< 0.05$) associations between pollutant concentration and meteorological data from Python software version 3.11 according to the methods employed by Mbong et al. (2014) and Edem et al. (2023).

4.0 Results and Discussion

4.1 Variation in Air Quality parameters across the study Area

During the dry season, air quality parameters showed significant variation across the different sampling locations. Table 1 gives the summary of mean ambient air pollutant concentrations and meteorological variables at Sites 1 - 6 during the dry season. Nitrogen dioxide (NO_2) concentrations were highest at S1 (0.500 ± 0.025 ppm) and lowest at S2 and S3 (0.100 ± 0.005 ppm). Sulfur dioxide (SO_2) peaked at S1 (0.600 ± 0.030 ppm), with the lowest detectable concentration at S2 (0.200 ± 0.010 ppm). Carbon monoxide (CO) levels were highest at S5 (17.00 ± 0.90 ppm) and least at S2 (5.00 ± 0.25 ppm). Particulate matter ($PM_{2.5}$) was significantly higher at S4 (180 ± 9.00 μg/m³) than anywhere else in the study, while PM_{10} was highest at S4 (275.05 ± 13.75 μg/m³). Relative humidity (RH) varied, with S2 recording the highest value (63.00 ± 2.00 %), and S3 had the highest average temperature (36.0 ± 2.0°C). CH_20, S5 recorded the highest value (0.195 + 0.004) with S3 being the least (0.05 + 0.03). The wind speed (w/s) was strongest at S3 (2.15m/s) and slowest at S4 (0.75m/s).

During the wet season, air quality parameters demonstrated marked spatial variations across the designated monitoring stations. The summary of mean ambient air pollutant concentrations and meteorological variables across all 6 sites during the rainy season is shown in Table 2. NO_2 concentration reached its maximum at sites S3 and S4 (0.2 ± 0.44 ppm), while the lowest value (0.1 ± 0.00 ppm) was recorded simultaneously at S1, S2, and S5. SO_2 was most concentrated at S4 (0.3 ± 0.37 ppm) and least at S2 (0.1± 0.27 ppm). CO levels were highest at S4 (5.00 ± 3.72 ppm) and lowest at S1 and S2 (2.00 ± 0.04ppm). $PM_{2.5}$ had the largest reading at S5 (41.0 μg/m³) and the least at S3 (14.0 μg/m³). PM_{10} peaked at three stations, 4, 5, and 6 (65.00 ± 76.40 μg/m³), and was lowest at S3 (24.26 ± 0.02 μg/m³). Also, CO_2 recorded 787 ppm at S3 being the highest, while S1 (10.5ppm) was the least. A reading of 2.288 ppm at S1 was most elevated for TVOC, and lowest at S5 (0.569 ppm). Two sites (S1& 5) reported 0.4 ppm being topmost for H_2S, and S2& 4 with 0.2 ppm as the lowest values. NH_3 was highest at S4 but lowest at S1, with readings of 4.5 ppm and 0.5 ppm, respectively. Relative humidity (RH) was highest at S1 (83.42 ± 0.21%), while the temperature was highest at S3 (29.90 ± 0.45°C). Wind speed measured at S1 was the fastest (2.2 m/s) while 0.4 m/s being the least was obtained at S3.

4.2 Correlation between Meteorological Indices and Air Pollutants (Dry Season and Wet seasons)

The Pearson correlation coefficient (r) matrix and its heatmap for the dry season are shown in Figures 2 and 3 respectively. In the dry season, NO_2 revealed a strong positive correlation with SO_2 (r = 0.995), CO (r = 0.997) and $PM_{2.5}$ (r = 0.864), suggesting that they have similar emission sources and that both are influenced by the same meteorological factors. Furthermore, NO_2 was also positively correlated with PM_{10} (r = 0.893), suggesting that coarse particulates may be influenced by common meteorological conditions, such as atmospheric stability. However, NO_2 presented a very weak correlation with RH (r = 0.038), presenting that its injection into the local air mass happened really fast like immediate plume transport or raw emission rates for slow, humidity-driven atmospheric chemical reactions to exert any statistically visible control. Similarly, SO_2 displayed a strong positive correlation with NO_2 (r = 0.995) and CO (r = 0.995), implying that industrial emissions contributed to both gaseous pollutants. However, SO_2 had a negative correlation with w/s (r = -0.861), reinforcing the idea that higher wind speed enhances the dispersal of sulfur-based pollutants from the atmosphere. Relative humidity also showed a weak correlation with SO_2. Carbon monoxide (CO) showed a strong positive correlation with $PM_{2.5}$ (r = 0.861), indicating that incomplete combustion processes contributed significantly to fine particulate pollution.

Table 1: Summary of Mean Ambient Air Pollutant Concentrations and Meteorological Variables at Monitoring Sites during the Dry Season

Site	$PM_{2.5}$ (µg/m³)	PM_{10} (µg/m³)	CH_2O (ppm)	CO_2 (ppm)	NO_2 (ppm)	TVOC (ppm)	SO_2 (ppm)	CO (ppm)	NH_3 (ppm)	H_2S (ppm)	Temperature (°C)	Relative Humidity (%)	Wind Speed (m/s)
S1	93.05±4.65	120.00 ± 6.00	0.084± 0.004	622.00± 31.00	0.500± 0.025	0.549 ±0.2	0.600±0.030	15.00± 0.70	8.50±0.40	0.400±0.020	35.00± 2.0	63.00± 2.0	0.898± 0.04
S2	172.00 ±8.60	209.00±10.45	0.056±0.003	722.00±36.0	0.100±0.005	0.321 ±0.5	0.200±0.010	5.00±0.65	3.00±0.150	0.200±0.010	29.00±2.2	60.00±2.0	1.220± 0.05
S3	16.00± 0.70	19.00± 0.95	0.031± 0.002	528.00±26.0	0.100±0.005	0.245± 0.3	0.300.0150±	4.00 ±0.83	0.50 ±0.025	0.100±0.005	36.00±2.0	50.00± 2.0	0.750±0.04
S4	180.00±0.00	275.00± 13.75	0.038± 0.002	1872.00± 94.0	0.300±0.015	0.373 ± 1.8	0.4025 ±0.125	10.00± 0.54	2.00±0.100	0.100± 0.005	35.00± 2.0	46.00± 2.0	0.750±0.04
S5	93.00±0.00	159.00±7.90	0.089±0.004	440.00±22.0	0.200±0.010	0.443± 1.6	0.300±0.015	17.00± 0.55	7.00±0.350	0.300±0.015	32.00± 2.0	52.00±2.0	0.860± 0.04
S6	105.00± 0.00	151.00± 7.50	0.068±0.003	1032.00±52.0	0.220± 0.011	0.398± 1,5	0.320±0.016	11.00±0.74	4.90±0.245	0.270± 0.135	34.002.0± 2.1	52.00± 2.0	0.880± 0.04

Table 2: Summary of Mean Ambient Air Pollutant Concentrations and Meteorological Variables at Monitoring Sites during the Rainy Season

Site	$PM_{2.5}$ (µg/m³)	PM_{10} (µg/m³)	CH_2O (ppm)	CO_2 (ppm)	NO_2 (ppm)	TVOC (ppm)	SO_2 (ppm)	CO (ppm)	NH_3 (ppm)	H_2S (ppm)	Temperature (°C)	Relative Humidity (%)	Wind Speed (m/s)
S1	31.00±12.10	56.00±17.10	0.108±0.003	10.50±15	0.100±0.010	2.288±0.3	0.100±0.025	2.00±0.500	0.50±0.342	0.40±0.02	29.00±2.0	83.00±2.0	2.20±0.03
S2	35.00±7.00	57.50±9.10	0.204±0.002	410.00±12.0	0.100±0.010	1.329±0.6	0.100±0.025	2.00±0.500	3.00±0.015	0.20±	28.88±2.	68.00±3.0	0.90±0.04
S3	14.00±1.40	24.00±2.40	0.130±0.004	787.00±23.3	0.200±0.020	0.973±1.0	0.200±0.015	3.00±0.831	4.00±0.025	0.30±0.015	29.90±2.0	66.00±2.0	0.40±0.03
S4	38.00±5.80	65.00±12.00	0.114±0.003	755.00±43.30	0.200±0.020	0.544±0.7	0.300±0.010	5.00±0.644	4.50±0.030	0.20±0.10	28.80±2.7	58.00±1.0	0.50±0.25
S5	41.00±6.10	65.00±12.00	0.078±0.002	613.00±0.002	0.100±0.010	0.569±1.2	0.200±0.010	4.00±0.353	4.00±0.025	0.40± 0.02	29.05±3.5	62.00±1.5	1.10±0.05
S6	35.00±9.50	65.00±12.05	0.110±0.001	450.00±0.001	0.130±0.013	1.800.0±0.4	0.150±0.012	2.50±0.267	2.00±0.350	0.300±0.02	28.80±4.6	75.00±2.5	1.80±0.25

Parameter	$PM_{2.5}$	PM_{10}	NO_2	SO_2	CO	CO_2	NH_3	H_2S	CH_2O	TVOC	TEMP	RH	W/S
$PM_{2.5}$	1												
PM_{10}	0.978	1											
NO_2	0.864	0.893	1										
SO_2	0.849	0.888	0.995	1									
CO	0.861	0.899	0.997	0.995	1								
CO_2	0.828	0.887	0.916	0.938	0.931	1							
NH_3	-0.106	-0.052	0.024	-0.035	-0.007	-0.211	1						
H_2S	0.83	0.876	0.985	0.988	0.983	0.957	-0.119	1					
CH_2O	0.804	0.852	0.974	0.983	0.969	0.963	-0.177	0.996	1				
TVOC	0.821	0.862	0.976	0.979	0.974	0.942	-0.138	0.991	0.985	1			
TEMP	-0.584	-0.638	-0.73	-0.713	-0.741	-0.793	0.001	-0.743	-0.743	-0.681	1		
RH	0.172	0.056	0.038	-0.003	0.01	-0.046	0.704	-0.002	-0.056	-0.048	-0.246	1	
W/S	-0.892	-0.895	-0.875	-0.861	-0.887	-0.88	-0.245	-0.872	-0.835	-0.857	0.54	-0.32	1

Figure 2: Karl Pearson correlation matrix for Dry season

Figure 3: Pearson Correlation Heatmap for dry season

CO also exhibited a strong positive correlation with PM_{10} (r = 0.899), suggesting that re-suspended dust and emissions from biomass burning may increase both CO and larger particulate matter concentrations. CO had a weak correlation with RH (r = 0.01), highlighting the impact of dry conditions in increasing pollutant retention in the lower atmosphere. Particulate matter ($PM_{2.5}$) had a strong positive correlation with PM_{10} (r = 0.978), further proving a common origin for both fine and coarse particulates. However, $PM_{2.5}$ showed a weak correlation with RH (r= 0.172), emphasizing the efficiency of precipitation in removing fine particulate pollutants from the air. PM_{10} was poorly correlated with RH (r = 0.058), suggesting that lower humidity in the dry season enhances dust re-suspension and particulate accumulation. Temperature, however, had negative correlation with NO_2 (r = -0.73), and also with CO (r = -0. 741). Overall, the weak relationships between RH and pollutants in both seasons indicated that humidity plays a major role in regulating air quality, while positive correlations between pollutants suggested common emission sources, primarily from vehicular and industrial activities.

The rainy season revealed strong positive correlation between SO_2 and CO (r= 0.961, p= 0.0022) indicating co-emission from common combustion/industrial activities. Furthermore, CO_2 and NH_3 (r= 0.947) were, highly correlated suggesting common biogenic or organic decomposition origin. $PM_{2.5}$ and PM_{10} exhibited a strong correlation (r = 0.975) confirming that both fine and coarse particulate matter shared common primary sources. RH and Wind Speed (r=0.879) presented strong positive meteorological relationship.

Strong negative correlations were obtained for NH_3 and Relative Humidity (r = -0.981) buttressing the role of high moisture levels in dissolution of ammonia gas. The correlation of temperature with both PM_{10} and $PM_{2.5}$(r = -0.957 and -0.900) respectively signaled a strong inverse thermal association (George et al., 2010). The trend was also obtained for NH_3 and Wind Speed (r = -0.928) showing strong dispersion effect with increasing wind speed. Higher humidity and wind dispersion significantly reduce ground-level CO_2 accumulation as presented in Figure 4.

	$PM_{2.5}$	**PM_{10}**	**NO_2**	**SO_2**	**CO**	**CO_2**	**NH_3**	**H_2S**	**CH_2O**	**TVOC**	**TEMP**	**RH**	**W/S**
$PM_{2.5}$	1												
PM_{10}	0.918	1											
NO_2	-0.674	-0.578	1										
SO_2	-0.55	-0.233	0.765	1									
CO	-0.442	-0.081	0.562	0.961	1								
CO_2	-0.892	-0.677	0.735	0.797	0.713	1							
NH_3	-0.856	-0.622	0.59	0.783	0.769	0.947	1						
H_2S	0.333	0.384	-0.455	-0.295	-0.186	-0.423	-0.442	1					
CH_2O	-0.125	-0.411	-0.078	-0.414	-0.48	-0.077	-0.003	-0.692	1				
TVOC	0.804	0.551	-0.366	-0.663	-0.713	-0.86	-0.951	0.204	0.109	1			
TEMP	-0.846	-0.579	0.573	0.808	0.814	0.91	0.964	-0.208	-0.209	-0.962	1		
RH	0.745	0.483	-0.513	-0.8	-0.823	-0.886	-0.981	0.468	0.013	0.936	-0.937	1	
W/S	0.922	0.816	-0.683	-0.652	-0.574	-0.886	-0.928	0.592	-0.272	0.823	-0.862	0.879	1

Figure 4: Karl Pearson Correlation matrix for Wet season

5.0 Discussion

The findings highlighted distinct seasonal and spatial differences in air pollution across Mkpat Enin, demonstrating how strongly local weather conditions influence air quality. Remarkably, pollutant concentrations (particularly NO_2, SO_2, CO, $PM_{2.5}$, and PM_{10}) were really elevated during the dry season compared to the rainy season. For the dry season, $PM_{2.5}$ and PM_{10} averaged at 109.84 µg/m³, and 155.50 µg/m³ respectively, while CO_2, NO_2, SO_2, CO, NH_3 and H_2S concentrations recorded mean values of at 863.333 ppm, 0.237 ppm, 0.353 ppm, 10.333, 4.317 ppm and 0.228 ppm respectively. However, in the rainy season, these values reduced to 32.33 µg/m³, 55.417 µg/m³, for both $PM_{2.5}$ and PM_{10} respectively and 504.250 ppm, 0.138 ppm, 0.175 ppm, 3.083 ppm, 3.000 ppm and 0.300 ppm for the atmospheric pollutants in the order previously listed. These values from both seasons were above WHO permissible limits for these pollutants. Based on the results, the research locations were severely polluted, using the WHO 2021 Air Quality Index benchmarks of 15 µg/m³ for $PM_{2.5}$ and 45 µg/m³ for PM_{10} as the international standards as shown in Figure 5. The same for NO_2, SO_2 and CO with the safety threshold been 0.013ppm (25 µg/m³), 0.015ppm (40 µg/m³), and 3.5ppm (4mg/m³). The recent local studies also revealed similar seasonality's and higher levels of atmospheric oxides, indicating public health threats of poor air quality (Ekpa et al., 2025; Dominic et al., 2025).

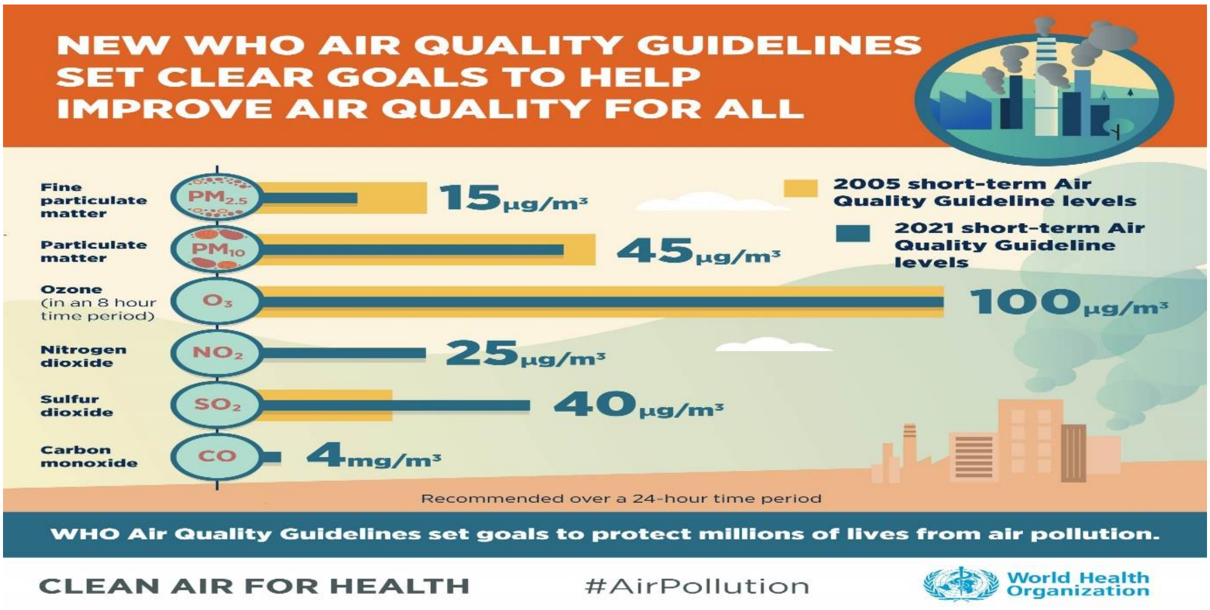

Figure 5: WHO Air Quality Guidelines level (WHO, 2021)

These persistence high values can be ascribed to reduced relative humidity (RH), limited precipitation, and increased atmospheric stability that inhibit pollutant dispersion and promote accumulation. This phenomenon is similarly reported by Chamseddine et al. (2019), Sahin et al. (2021) and Onyegbule et al. (2025). For the meteorological parameter, temperature was higher in the dry season than in rainy season, unlike relative humidity and wind speed which were higher in the wet than dry season giving an average of 68.667 and 1.150 m/s (wet) against (53.833% and 0.895 m/s) in dry respectively. This enhanced wind speed may be due to maritime air mass creating sustained, higher average surface wind speeds at coastal and near-coastal sites compared to the stagnant, light-and-variable winds common during dry season continental high-pressure periods. This trend was observed across all monitoring stations, where ambient levels recorded during the dry season significantly exceeded those of the wet season. During the wet season, pollutant levels declined significantly. For example, NO_2

concentrations which were highest at S1 dropped to 0.100 ppm and SO_2 was also lower. The higher RH (peaking 83% at S1) and frequent rainfall during this period likely enhanced pollutant washout through wet deposition, especially for water-soluble gases like SO_2 and NO_2, in line with findings by Landim et al. (2020) and Dhital et al. (2022). The inverse relationship between wind speed and pollutant concentrations was statistically validated through Pearson correlation analysis, which demonstrated a strong negative association between wind speed and (r = -0.861), NO_2 (r = -0.875), and $PM_{2.5}$ (r = -0.892) in the dry season. Carbon monoxide (CO) displayed unique seasonal pattern. Although dry season concentrations were notably high around S5, the highest wet season value was unexpectedly associated with S4 area, suggesting localized emission sources, possibly due to ongoing industrial activities. However, its atmospheric persistence was still modulated by meteorological factors, with temperature and RH exerting significant control. CO was negatively correlated with temperature (r =-0.7141) and weakly with RH (r = 0.01) during the dry season, affirming that higher temperatures promote CO accumulation due to decreased vertical mixing and chemical transformation to CO_2, a trend supported by Signori et al. (2023). Particulate Matter (**$PM_{2.5}$ and PM_{10}**) had a very strong positive correlation, implying that their concentrations move tightly together across all six monitoring sites (r = 0.978). Temperature exhibited deep negative correlations with organic compounds like TVOCs (-0.681) while relative humidity shared a very strong positive correlation with TVOCs implying higher moisture loading in the air being tightly connected with elevated total volatile organic concentrations during this specific sampling interval. Wind speed showed a powerful, uniform negative correlation (ranging from r = -0.835 to r = -0.895) with almost all major pollutants, indicative of the local dispersion dynamics. Higher wind speeds act as a potent dilution mechanism, sweeping the pollutants away from the monitoring point, while calm conditions or low wind speeds lead to rapid pollutant accumulation near the source. Similarly, temperature, displayed moderate-to-strong negative correlations (r = -0.584 to r = -0.793) with the primary pollutants. This relationship is typically driven by boundary layer dynamics. Higher temperatures warm the ground, increasing convective mixing and raising the planetary boundary layer height. This expands the volume of air available for mixing, which dilutes ground-level pollutant concentrations. A strong positive correlation specifically between NH_3 and RH (r = 0.704), was observed while displaying negligible or slightly negative correlations with all other combustion-related pollutants. This suggested that NH_3 likely originated from a completely different physical source such as agricultural activity, biogenic emissions, or waste decomposition than the combustion gases. High humidity often facilitates the volatilization or stabilization of agricultural ammonia, cementing this unique relationship.

$PM_{2.5}$ and PM_{10} climaxed at S5 (41μg/m³ and 65 μg/m³ respectively). These values far exceeded both WHO thresholds, signaling substantial air quality deterioration in the campus. The likely sources include vehicular emissions and dust from largely damaged portions of tarred road in front of the school gate especially under the dry season's stagnant atmospheric conditions. Wet deposition caused particulate matter levels to drop significantly across all the six sites, affirming the role of precipitation in atmospheric cleansing. Strong positive correlations between $PM_{2.5}$ and CO (r = 0.861) and a near perfect correlation between $PM_{2.5}$ and PM_{10} (r = 0.918) supported the hypothesis that they share combustion-related origins (Losacco and Perillo, 2018; Liu et al., 2020). Correlation data from both seasons further emphasize the synergistic roles of pollutants and meteorological drivers. For instance, in the dry season, NO_2 had strong positive correlations with $PM_{2.5}$ (r = 0.864) and

PM_{10} (r = 0.893), suggesting atmospheric stability promoted the coexistence of these pollutants. Meteorological factors such as temperature and wind speed were again negatively correlated with most pollutants, particularly CO_2 (r = - 0.793), and PM10 (-0895), highlighting the season's vulnerability to pollution accumulation. These results confirmed that Mkpat Enin's tropospheric air is significantly affected by seasonal climatic shifts. Industrial emissions and vehicular activities remain constant, but their impact is modulated by meteorological parameters. Dry season pollution poses serious environmental and public health risks, especially at sites S2 and S4 (Ikot Akpaden and Ikot Akata respectively). In line with this, Song et al. (2023) and Hu et al. (2024) opined that elevated pollutant concentrations, particularly gaseous species ($PM_{2.5}$, NO_2, and CO) have been strongly linked to higher rates of respiratory and cardiovascular diseases, increased hospital admissions, and premature mortality. Moreover, high SO_2 and NO_2 levels surged the potentials for acid rain, damaging ecosystems and reduced agricultural productivity (Kawichai et al., 2023). These results underscore the necessity of embedding seasonal and spatial meteorological dynamics into air quality surveillance frameworks to inform evidence-based public health interventions and environmental policy formulation in tropical urban centers.

For rainy season, wind speed had a very strong positive correlation with $PM_{2.5}$ (r = 0.922) and PM_{10} (r = 0.816) as depicted in Figure 6. This is an indication that wind-driven re-suspension like dust or soil particles were being lifted by stronger winds or probably that the sensor was downwind of a major source where higher winds carried the plume directly to the monitoring site. This is an indication that wind-driven re-suspension like dust or soil particles were being lifted by stronger winds or probably that the sensor was downwind of a major source where higher winds carried the plume directly to the monitoring site.

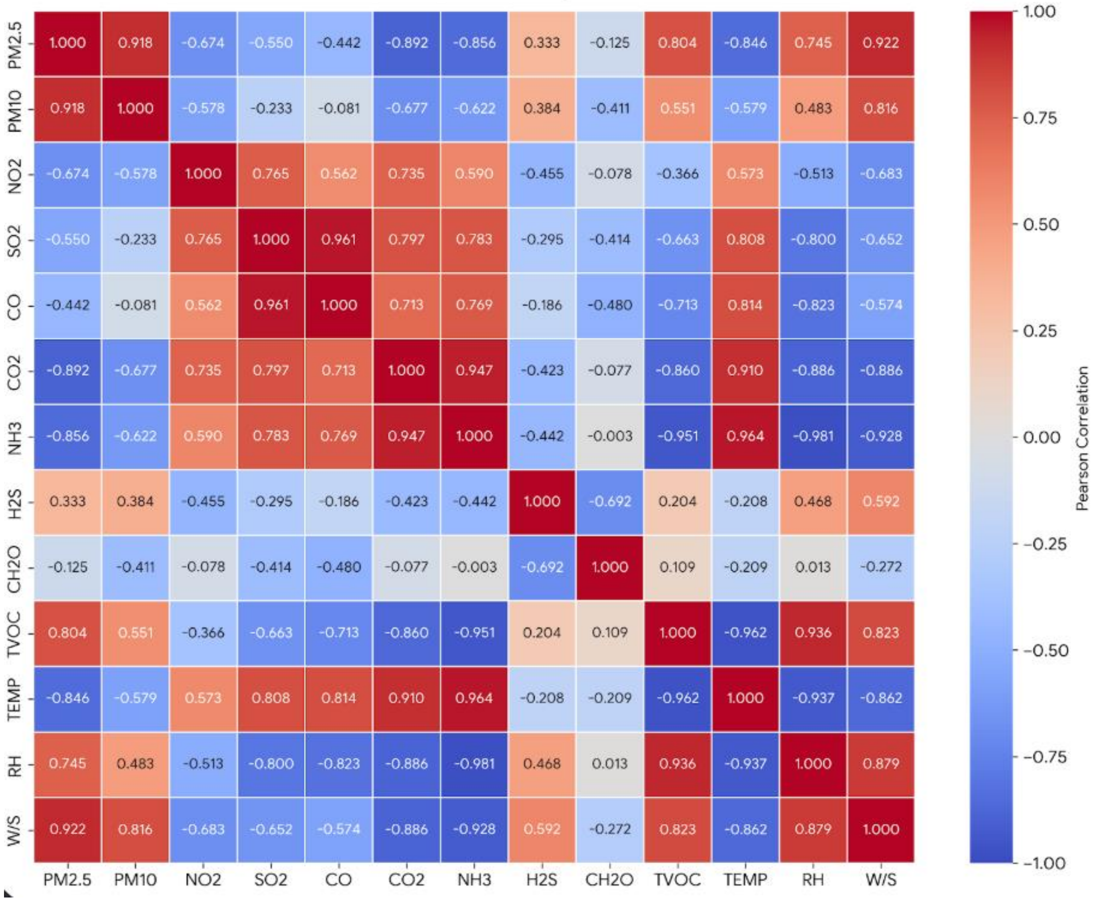

Figure 6: Pearson Heatmap for rainy season

Similarly, TVOC had a very strong negative correlation with temperature (r = -0.962). This suggested that TVOC levels peak during cooler, high-humidity conditions like early morning or nighttime inversions when the atmospheric boundary layer was shallow and trapped organic gases close to the surface. Particulates matter exhibited negative correlations with the combustion gases like NO_2, SO_2, and CO. This pointed to the fact that strong winds physically lifted and re-suspend crustal dust, soil, and coarse road particles into the air, causing particulate concentrations spike. At the same time, these strong winds rapidly diluted and dispersed localized combustion gases NO_2, SO_2, CO away from the monitoring site.

6.0 Conclusion

Local meteorology decisively drives air quality in Mkpat Enin, with dry-season atmospheric stability, reduced dispersion, and lower humidity fueling higher pollution levels. Strong positive correlations among NO_2, SO_2, CO, and $PM_{2.5}$ suggest that these pollutants may have shared or co-varying sources and/or common meteorological controls, while strong negative correlations with RH depicted that humidity plays a critical role in pollutant removal. These findings highlighted the need for targeted air quality management strategies to curb pollution, especially during the dry season. Consequently, comprehensive emission control frameworks must be enforced, encompassing stringent vehicular standards, continuous industrial emissions monitoring, and the strategic transition toward cleaner energy alternatives. Public health campaigns must educate communities on air pollution risks and encourage protective behaviors, while real-time monitoring systems are critical for early threat detection and response. The study is based on short-duration seasonal monitoring and does not directly establish long-term population exposure or health outcomes.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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