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Assessment of the Seasonal Variation of Air Quality of some Locations in Port Harcourt Metropolis, River State, Nigeria

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Abstract

Clean and unpolluted air is necessary for human existence and survival. However, air pollution has become a global phenomenon and of great concern. This study assessed the seasonal variation of air quality in some locations in Port Harcourt metropolis, namely Eleme, Trans-Amadi, and GRA-Port Harcourt. Sampling was done within the period of September, 2024 to February, 2025 covering wet and dry season. Particulate matter ($PM_{2.5}$ and PM_{10}), gaseous emissions (SO_2, VOCs, CH_4, CO, CO_2, O_3, NO_2) and meteorological factors (Temperature, wind speed, relative humidity and wind direction) were measured at geolocated stations using air monitors Aeroqual 500 series and 4250 Kestrel weather trackers. Data analysis include T-test and Air quality index (AQI); the results revealed that the mean concentrations of $PM_{2.5}$ at Eleme (dry), and Trans-Amadi (wet) were above the permissible limits of 35µg/m^3 recommended by NAAQS, while PM_{10} except at Eleme (both dry and wet) were below the permissible limits of 150µg/m^3. The observed significant difference ($P < 0.05$) in volatile organic compounds (VOC) concentrations in which a high value was recorded in dry season and a near zero during wet could be due to seasonal variations influenced by changes in temperature, humidity, and atmospheric dispersion. Further studies should be carried out to monitor the concentrations and sources of pollutants in the study area.

Keywords: Assessment, water quality, concentration, health risk, heavy metals, River Ethiope.

Introduction

Air quality has become a critical environmental and public health concern worldwide, particularly in rapidly urbanizing and industrializing regions. Poor air quality has been associated with adverse respiratory and cardiovascular diseases, reduced visibility, and ecosystem degradation (World Health Organization [1].

In Nigeria, increasing industrialization, urban growth, and vehicular emissions have contributed significantly to deteriorating air quality, with the Niger Delta region being particularly affected due to its dense concentration of oil and gas activities [2, 3].

Port Harcourt, the capital of Rivers State and a major industrial hub in the Niger Delta, has gained international attention in recent years due

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to recurrent episodes of severe air pollution, often characterized by the presence of fine particulate matter commonly referred to as “black soot” [4].

The city’s air quality challenges stem from multiple anthropogenic sources, including petrochemical industries, artisanal crude oil refining, flaring of associated gas, heavy vehicular traffic, and open waste burning [5,6,7]. These activities release a wide range of air pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), volatile organic compounds (VOCs), nitrogen oxides (NOx), sulfur dioxide (SO_2), and carbon monoxide (CO), which pose risks to both environmental and human health.

This study focuses on air quality assessment in three strategic locations within Port Harcourt Metropolis, **Eleme, Trans-Amadi, and Government Reserved Area (GRA)**, which represent distinct land-use and anthropogenic activity profiles. Eleme is notable for hosting major industrial facilities, including petrochemical complexes and refineries, making it a potential hotspot for industrial emissions. Trans-Amadi, a mixed industrial and commercial hub, is characterized by heavy vehicular movement and small-scale industries. In contrast, the GRA is primarily a residential area with relatively lower industrial activity, but it is still influenced by regional air pollution transport and localized emissions. By comparing these locations, this study seeks to provide insights into the spatial variation of air pollutants across the metropolis. This study is also crucial because it focuses on how climatic conditions influence air pollution levels, providing insights for effective air quality management [8]. Understanding the role of weather conditions in modulating pollutant concentration will provide relevant data for policymakers to mitigate health risks associated with poor air quality. The study will fill gaps in literature concerning the interaction between climate and air quality in Port Harcourt, offering a localized perspective that is often lacking in broader studies. This study therefore was aimed to assess seasonal variation of air quality assessment of some locations in Port Harcourt metropolis

Materials and Methods

Study Area

The study focuses on three key locations within Port Harcourt, Rivers State, Nigeria: Trans Amadis, Eleme, and GRA (Government Residential Area). These areas are characterized by varying levels of industrial activities, vehicular emissions, and residential settlements, making them suitable for assessing the impact of climate weather conditions on air quality.

Trans Amadi is an industrial area located in the northern part of Port Harcourt, known for supporting strong manufacturing industries and is considered as an important industrial zone in Port Harcourt. It is Situated at 4°48'53" N latitude and 7°2'14" E longitude. Materials such as glass

bottles, tires, aluminium and paper have production plants in the area.

Eleme is another industrial hub in Port Harcourt, particularly known for its oil refineries and petrochemical plants. It lies at 4.7709° N latitude and 7.1051° E longitude. The population of Eleme is estimated to be around 200,000 individuals, largely due to the presence of major industrial establishments like the Eleme Petrochemical Plant [9].

Government reserved areas (GRA) is a well-developed residential area located in the central part of Port Harcourt. Unlike the other two areas, GRA has less industrial activity but experiences significant vehicular traffic, which contributes to air pollution. The coordinates for GRA are 4.8176° N latitude and 7.0018° E longitude. The population of GRA is about 80,000, consisting mostly of middle to upper-class residents and government officials [10].

Sample Collection

Samples were collected between September 2024 and February 2025, particulate matters ($PM_{2.5}$ and PM_{10}) and gaseous emissions (NO_2, CO. CO_2, NO_2 and VOCs) were measured monthly at three different geolocated stations using Aeroqual Series 500 held up at average height of human at the study area. Meteorological data (temperature, wind speed, humidity, and rainfall) were obtained using 4250 Kestrel weather tracker thermometers. All equipment and instruments were calibrated prior to use for quality assurance in order to ascertain the accuracy of the results obtained.

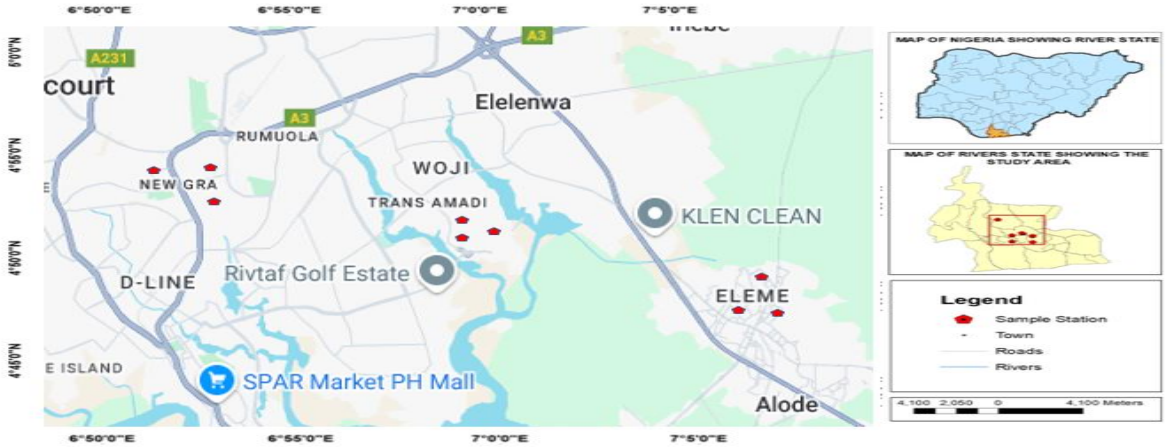


Fig. 1: Map of the study area

Data Analysis

The data obtained in the study is presented as Tables and Graphs. Mean concentrations, Standard Deviations of air quality parameters were also calculated. T-test for significant differences ($p < 0.05$) was carried out using SPSS Version 23.

Air Quality Index (AQI) of the Study Area

The Sim-air quality software were used to calculate the AQI of the air pollutants using equation below (Akinfolarin et al., 2017).

$$I_P = \frac{I_{HI} - I_{LO}}{BP_{HI} - BP_{LO}} (C_P - BP_{LO}) + I_{LO}$$

I_P = Index for pollutant P
C_P = Actual ambient concentration of pollutant P
BP_{HI} = Breakpoint that is greater than or equal to C_p
BP_{LO} = Breakpoint that is less than or equal to C_p
I_{HI} = AQI value corresponding to BP_{HI}
I_{LO} = AQI value corresponding to BP_{LO}

Results and Discussion

The descriptive statistical summary (mean, standard deviation, minimum and maximum) of air quality parameters at Eleme axis by Akpajo (E), Trans-Amadi (T) and Government Reserved Area (GRA) – (G) for both dry and wet season are presented in Tables 1 to 3. The particulate matters for $PM_{2.5}$ for dry and wet season ranged from 15.00 to 231.00 μgm^{-3} and 7.00 to 59.00 μgm^{-3} at Eleme, 18.00 to 51.00 μgm^{-3} and 8.00 to 166.00 μgm^{-3} at Trans-Amadi and 16.00 to 30.00 μgm^{-3} and 2.00 to 25.00 μgm^{-3} at GRA respectively. There was no significant difference at the first two locations, but significant at GRA. The PM_{10} ranged from 73.00 to 999.00 μgm^{-3} (dry) and 20.00 to 467.00 μgm^{-3} (wet) at Eleme, no significant difference; 44.00 to 84.00 μgm^{-3} and 10.00 to 208.00 μgm^{-3} at Trans-Amadi, no significant difference; 56.00 to 83.00 μgm^{-3} and 5.00 to 35.00 μgm^{-3} μgm^{-3} at GRA, there was significant difference.

The volatile organic compounds (VOCs) in the same order, ranged from 45.30 to 543.10 μgm^{-3} and 0.00 to 0.40 μgm^{-3} at Eleme; 15.40 to 208.20 μgm^{-3} and 0.00 to 1.10 μgm^{-3} at Trans Amadi and 18.30 to 69.50 μgm^{-3} and 0.00 to 0.10 μgm^{-3} at GRA, all means values at dry season significantly different from wet season.

Other gaseous emissions measured at different seasons were significantly different. They are CH_4 ranging from 0.00 to 27.00 ppm and 0.00 to 34.00 ppm at Eleme, not detected at Trans-Amadi and GRA; Carbon monoxide (CO), ranged from 0.00 to 0.20ppm and 0.00 at Eleme; 0.00 to 21.20 ppm and 0.00 to 18.62 ppm at Trans-Amadi; 0.00 to 3.50 ppm and 0.00ppm at GRA. Carbon dioxide was not detected at Eleme and Trans-Amadi but ranged from 0.00 to 0.20ppm dry season only. Nitrogen dioxide (NO_2) varied from 0.00 to 0.54 ppm and 0.02 to 0.98 ppm at Eleme, 0.00 to 0.64 ppm and 0.02 to 0.99 ppm at Trans-Amadi and 0.00 to 0.62 ppm and 0.01 to 0.99 ppm at GRA, with all mean values at dry significantly different from wet season. Sulphur dioxide (SO_2) varied from 0.00 to 0.28 ppm and 0.00 to 0.30 ppm at Eleme, 0.00 to 0.55 ppm and 0.00 ppm at Trans-Amadi and 0.01 to 0.92 ppm and 0.00 to 0.01 ppm at GRA. Ozone varied from 0.00 to 0.01 ppm for both seasons at Eleme, 0.00 to 0.01ppm and 0.00 to 0.01 and 0.02 ppm at Trans-Amadi and 0.00 to 0.01 and 0.00 to 0.06 ppm, mean

values at all locations significantly different within the seasons.

The meteorological factors showed that there was significant difference between the temperature at Trans-Amadi and GRA, but not at Eleme, while there was significant difference at all locations for Relative humidity. No significant difference was observed for wind speed at Eleme and GRA, but not at GRA. The wind direction is from WSW to SW at Eleme, SW to N at Trans-Amadi and SW to SW to NW (Tables 1 to 3) respectfully.

The Figures 1 to 6 show the seasonal variation of the air quality parameters. The observable trend are as follows: Ewet > Edry > Gdry > Twet > Tdry > Gwet for CH_4; Tdry > Twet > Gdry > Edry > Ewet > Gwet for CO; Twet > Gwet > Twet > Gdry > Edry > Tdry for NO_2; Sulphur dioxide and ozone levels were low across the locations. The meteorological factors have the trend Tdry > Gdry > Edry > Twet > Twet > Gwet for temperature; Twet > Gwet > Twet > Edry > Gdry > Edry for relative humidity and Gwet > Ewet > Edry > Twet > Gdry > Tdry.

Table 1: Statistical Summary of Air Quality Parameters at Eleme Station (E)

	E Dry Season				E Wet Season					
Parameters	Mean	Std	Min	Max	Mean	Std	Min	Max	P value	Remark
$PM_{2.5}$ (μgm^{-3})	70.17	82.33	15.00	231.00	28.17	20.51	7.00	59.00	0.13	NS
PM_{10} (μgm^{-3})	361.67	327.32	73.00	999.00	155.50	165.18	20.00	467.00	0.10	NS
VOCs (ppm)	196.82	177.49	45.30	543.10	0.10	0.15	0.00	0.40	0.01	S
CH_4 (ppm)	4.50	11.02	0.00	27.00	6.33	13.65	0.00	34.00	0.40	NS
CO (ppm)	0.37	0.90	0.00	2.20	0.00	0.00	0.00	0.00	0.17	NS
CO_2 (ppm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-
NO_2 (ppm)	0.28	0.23	0.00	0.54	0.50	0.53	0.02	0.98	0.18	NS
SO_2 (ppm)	0.08	0.12	0.00	0.28	0.05	0.12	0.00	0.30	0.35	NS
O_3 (ppm)	0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.30	NS
Temp (^0C)	34.68	4.45	29.40	42.70	31.55	2.31	27.60	33.90	0.08	NS
RH (%)	65.13	8.26	51.10	74.00	76.93	10.36	61.20	86.00	0.03	S
WS (km/hr)	7.22	1.77	5.00	9.40	7.77	5.60	1.50	14.80	0.41	NS
WD	WSW - SW				WSW- SW					

NS-not significant, S-significant

Table 2: Statistical Summary of Air Quality Parameters at Trans-Amadi Station (T)

Parameters	T Dry Season Mean	Std	Min	Max	T Wet Season Mean	Std	Min	Max	P value	Remark
$PM_{2.5}$ (μgm^{-3})	25.83	12.58	18.00	51.00	48.00	60.73	8.00	166.00	0.20	NS
PM_{10} (μgm^{-3})	65.83	15.98	44.00	84.00	66.17	72.16	10.00	208.00	0.50	NS
VOCs (ppm)	82.95	66.33	15.40	208.20	0.23	0.43	0.00	1.10	0.01	S
CH_4 (ppm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-
CO (ppm)	6.03	8.60	0.00	21.20	3.10	7.60	0.00	18.62	0.27	NS
CO_2 (ppm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-
NO_2 (ppm)	0.31	0.32	0.00	0.64	0.50	0.53	0.02	0.99	0.24	NS
SO_2 (ppm)	0.27	0.19	0.00	0.55	0.00	0.00	0.00	0.00	0.00	-
O_3 (ppm)	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.02	0.34	NS
Temp. (^{0}C)	37.78	3.73	34.10	44.70	34.53	2.39	32.70	38.80	0.05	S
RH (%)	47.13	9.88	30.80	57.00	66.90	13.02	48.60	79.40	0.01	S
WS (km/hr)	4.83	2.07	3.00	8.60	6.15	3.66	2.20	13.00	0.23	NS
WD	SW - N				SW - N				-	-

NS-not significant, S-significant

Table 3: Statistical Summary of Air Quality Parameters at Government Reserved Area (G)

Parameters	G Dry Season Mean	Std	Min	Max	G Wet Season Mean	Std	Min	Max	P value	Remark
$PM_{2.5}$ (μgm^{-3})	21.83	6.21	16.00	30.00	11.83	8.47	2.00	25.00	0.02	S
PM_{10} (μgm^{-3})	65.83	11.05	56.00	83.00	18.83	10.96	5.00	35.00	0.00	S
VOCs (ppm)	40.98	22.94	18.30	69.50	0.02	0.04	0.00	0.10	0.00	S
CH_4 (ppm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-
CO (ppm)	1.18	1.57	0.00	3.50	0.00	0.00	0.00	0.00	0.05	S
CO_2 (ppm)	0.37	0.90	0.00	2.20	0.00	0.00	0.00	0.00	0.17	NS
NO_2 (ppm)	0.33	0.27	0.04	0.62	0.50	0.53	0.01	0.99	0.25	NS
SO_2 (ppm)	0.37	0.31	0.01	0.92	0.00	0.01	0.00	0.01	0.01	S
O_3 (ppm)	0.01	0.01	0.00	0.01	0.01	0.02	0.00	0.06	0.31	NS
Temp. (^{0}C)	35.68	2.16	32.10	37.80	31.22	1.47	29.60	33.40	0.00	S
RH (%)	55.52	11.78	47.00	73.60	68.72	4.61	59.50	72.00	0.01	S
WS (km/hr)	5.70	2.03	4.00	8.60	8.50	2.80	5.00	13.00	0.04	S
WD	S - NW				SW - NW					

NS-not significant, S-significant

Table 4: Air Quality Index of Particulate Matter and Nitrogen Dioxide

Air Quality Index of Particulate Matter and Nitrogen Dioxide						
			Wet Season			
	E		T		G	
Parameters	AQI	Category	AQI	Category	AQI	Category
$PM_{2.5}$	86	Moderate	132	Unhealthy for sensitive groups	56	Moderate
PM_{10}	101	Unhealthy for sensitive groups	56	Moderate	17	Good
NO_2	175	Unhealthy	175	Unhealthy	175	Unheathy
			Dry Season			
	E		T		G	
Parameters	AQI	Category	AQI	Category	AQI	Category
$PM_{2.5}$	161	Unhealthy	82	Moderate	75	Moderate
PM_{10}	210	Very unhealthy	56	Moderate	56	Moderate
NO_2	135	Unhealthy for sensitive groups	141	Uhealthy for Sensitive groups	144	Unhealthy for sentitive grpous

The particulate matters for $PM_{2.5}$ for dry and wet season including mean, ranged from 15.00 to 231.00 (70.17 ± 82.33) μgm^{-3} and 7.00 to 59.00 (28 ± 20.51) μgm^{-3} at Eleme, 18.00 to 51.00 (25.83 ± 12.58) μgm^{-3} and 8.00 to 166.00 (48.00 ± 60.73) μgm^{-3} at Trans-Amadi and 16.00 to 30.00 (21.83 ± 6.21) μgm^{-3} and 2.00 to 25.00 (11.83 ± 8.47) μgm^{-3} at GRA respectively.

There was no significant difference ($P > 0.05$) in the mean values at the first two locations, but significant at GRA. The PM_{10} ranged from 73.00 to 999.00 (361.67 ± 327.32) μgm^{-3} (dry) and 20.00 to 467.00 (155.50 ± 165.18) μgm^{-3} (wet) at Eleme, no significant difference; 44.00 to 84.00 (65.83 ± 15.98) μgm^{-3} and 10.00 to 208.00 (66.17 ± 72.16) μgm^{-3} at Trans-Amadi, no significant difference; 56.00 to 83.00 (65.83 ± 11.05) μgm^{-3} and 5.00 to 35.00 (18.83 ± 10.96) μgm^{-3} μgm^{-3} at GRA, there was significant difference. The non-significant difference report in this study contrasted with the one reported by Akinfolarin et al. (2017) [7].

The mean concentrations of $PM_{2.5}$ in this study at Eleme (dry), and Trans-Amadi (wet) were above the permissible limits of $35\mu g/m^3$ recommended by NAAQS (2017), while others were below. These results were in line with the report of Gobo *et al*. (2012) in Okrika communities who recorded values below permissible limits [11]. The observed $PM_{2.5}$ values are opposed to Oweisana *et al.* (2021b) who had values higher than the permissible limits in Obrikom and Omoku communities [12]. The mean concentrations of PM_{10} in this study except at Eleme (both dry and wet) were below the permissible limits of $150\mu g/m^3$. This is in contrast to the one reported by Akinfolarin et al. (2017), in which the result obtained at dry season were higher than the wet

season [7]. The non-significant difference in this study at Eleme and Trans-Amadi could be due to consistent emission sources from industrial activities and vehicular, also, areas with relatively stable weather patterns or those influenced by dominant wind patterns might experience less pronounced seasonal variations in PM levels. Furthermore, limited seasonal change in emissions from sources like biomass burning, agricultural activities or residential heating do not vary significantly with seasons in the area, this could result in similar PM levels [13]. Sources could be vehicular, generator, emissions from electric generating plants, biomass and fossil fuel burning [11].

Particulate matters are very dangerous to human health as they can cause asthma and even lung cancer. They are linked with most of pulmonary and cardiac associated morbidity and mortality [13]. Depending on the level of exposure, particulate pollutants may cause mild to severe illnesses. Wheezing, cough, dry mouth, and limitation in activities due to breathing problems are the most prevalent clinical symptoms of respiratory disease resulted from air pollution [14]. It can also enhance metal corrosion, damage by discoloring or destroying painted surfaces, corrode metals and building surfaces, soil, textiles and clothing [7].

The volatile organic compounds (VOCs) in the same order, ranged from 45.30 to 543.10 (196.82 ± 177.49) ppm and 0.00 to 0.40 (0.10 ± 0.15) ppm at Eleme; 15.40 to 208.20 (82.95 ± 66.33) ppm and 0.00 to 1.10 (0.23 ± 0.43 ppm at Trans-Amadi and 18.30 to 69.50 (40.98 ± 22.94) ppm and 0.00 to 0.10 (0.02 ± 0.04) ppm at GRA, all means values at dry season were significantly higher than wet season. The observed significant difference in VOC concentrations between the dry season and the wet season can be attributed to various factors. According to research, seasonal variations in VOC concentrations are influenced by changes in temperature, humidity, and atmospheric dispersion [15].

The higher VOC concentration during the dry season might be due to increased emissions from biogenic sources, such as vegetation, which can be enhanced by high temperatures and drought conditions. Additionally, reduced atmospheric dispersion and less scavenging of VOCs during the dry season might contribute to the accumulation of pollutants, leading to higher concentrations [16]. In contrast, the lower VOC concentration during the wet season can be attributed to the effective removal of VOCs from the atmosphere through wet deposition, including rainout and washout. Furthermore, increased atmospheric humidity during the wet season might reduce VOC emissions from certain sources, such as soil and vegetation. High level of VOCs can contribute to ground-level ozone formation and particulate matter, negatively impacting air quality and human health. Exposure to VOCs can cause respiratory problems, irritation, and other health issues. It can also

contribute to climate change, affect ecosystems, and impact biodiversity.

Other gaseous emissions measured at different seasons were significantly different. They are CH_4 ranging from 0.00 to 27.00 (4.59 ± 11.02) ppm and 0.00 to 34.00 ppm at Eleme, not detected at Trans-Amadi and GRA. The observed difference in methane (CH_4) concentrations between the dry season (4.50 ppm) and the wet season (6.33 ppm) at Eleme suggests a seasonal variation in CH_4 emissions or atmospheric processes. Research indicates that CH_4 emissions can be influenced by factors such as temperature, soil moisture, and vegetation growth. The higher CH_4 concentration during the wet season might be attributed to increased anaerobic conditions in waterlogged soils, which can enhance methanogenesis and CH_4 emissions. Additionally, wetlands and flooded areas can be significant sources of CH_4, particularly during the wet season.

In contrast, the lower CH_4 concentration during the dry season might be due to reduced methanogenesis and CH_4 emissions from soil and vegetation sources [17]. However, it's also possible that changes in atmospheric transport and dispersion patterns during the dry season could influence CH_4 concentrations.

Carbon monoxide (CO) is a colorless, odorless gas primarily produced through incomplete combustion of carbon-containing fuels [17]. Ambient CO concentrations are influenced by traffic density, industrial activity, and meteorological conditions such as wind speed, temperature, and humidity [18].

In this context, the variation in CO levels observed at Eleme, Trans-Amadi, and GRA during dry and wet seasons provides insight into both anthropogenic emissions and seasonal atmospheric dynamics. At Eleme, CO concentrations ranged from 0.00 to 0.20 ppm in the dry season, with a mean ± standard deviation (SD) of 0.37 ± 0.90 ppm, while in the wet season, the level dropped to 0.00 ppm. This near-zero CO concentration suggests minimal emission sources or effective atmospheric dispersion, especially during the wet season.

The higher mean compared to the maximum range in the dry season might indicate occasional spikes, possibly from localized emissions such as vehicular traffic or industrial activities. At Trans-Amadi, the data shows the most substantial CO levels: 0.00 to 21.20 ppm (6.03 ± 8.60 ppm) during the dry season and 0.00 to 18.62 ppm (3.10 ± 7.60 ppm) in the wet season. These elevated levels, especially the high variability, point toward intermittent but significant pollution events, likely linked to industrial emissions, given that Trans-Amadi is a known industrial zone.

The reduction in mean CO values during the wet season may be attributed to increased atmospheric scavenging due to rainfall and higher humidity,

which promotes vertical dispersion of pollutants [19]. For GRA, a more residential and possibly less industrialized area, CO ranged from 0.00 to 3.50 ppm (1.18 ± 1.57 ppm) in the dry season and 0.00 ppm in the wet season. The moderate dry season levels could stem from vehicular emissions and domestic fuel use, while the complete absence of CO in the wet season reinforces the efficacy of precipitation and lower combustion-related activity in reducing ambient CO.

Overall, the seasonal difference highlights the impact of meteorological conditions on CO dispersion. The wet season, characterized by higher rainfall and humidity, typically enhances atmospheric cleansing, reducing pollutant concentrations [20]. Conversely, during the dry season, stagnant air masses and higher temperatures can trap pollutants closer to the ground, elevating exposure levels, especially in areas with dense industrial or traffic activity.

Carbon dioxide (CO_2) is a naturally occurring greenhouse gas, but it is also released into the atmosphere through human activities such as fossil fuel combustion, biomass burning, and industrial processes (IPCC, 2021). In urban environments, CO_2 levels tend to rise due to traffic emissions, energy consumption, and reduced vegetation cover, especially in densely populated or industrialized areas [21].

In this study, CO_2 was not detected at Eleme and Trans-Amadi during both dry and wet seasons. The absence of measurable CO_2 in these locations is notable, particularly considering that Trans-Amadi is known for industrial activity. This could be due to either effective emission control technologies, rapid atmospheric dispersion, or limitations in the sensitivity of detection instruments used.

Alternatively, other more dominant gases like carbon monoxide (CO) might be outcompeting CO_2 in measurable concentrations, especially in areas where incomplete combustion is more prevalent. At GRA, carbon dioxide levels were detected only during the dry season, ranging from 0.00 to 0.20 ppm with a mean ± standard deviation of 0.37 ± 0.90 ppm. Although this concentration appears low, the data suggests occasional emissions likely related to domestic fuel combustion, vehicular traffic, or power generation common in urban residential areas during dry months when energy demand for cooling and power back-up tends to increase [21].

The lack of detection in the wet season aligns with findings that precipitation and lower temperatures can reduce combustion-related emissions and promote greater atmospheric dilution of gases [22]. Additionally, dry seasons are often associated with thermal inversion, reduced vegetation cover, and stagnant air masses, all of which can contribute to the accumulation of gases like CO_2 at ground level [23]. However, the

standard deviation being higher than the mean (0.90 vs. 0.37 ppm) indicates significant variability, possibly from localized sources or episodic pollution events.

Overall, the absence of detectable CO_2 at industrial locations but its presence in a residential area during the dry season underlines the importance of microclimate, urban form, and activity patterns in shaping ambient air composition. It also raises the need for improved monitoring sensitivity to better capture trace gas fluctuations across seasons and land-use types.

Nitrogen dioxide (NO_2) is a toxic gas primarily emitted from high-temperature combustion processes, such as those in vehicle engines, power plants, and industrial operations [17]. It plays a significant role in atmospheric chemistry, contributing to the formation of ground-level ozone and secondary particulate matter ($PM_{2.5}$), with serious implications for human health and environmental quality [24].

In the current analysis, NO_2 concentrations showed a seasonal increase from the dry to the wet season across all sites, Eleme, Trans-Amadi, and GRA. At Eleme, levels ranged from 0.00 to 0.54 ppm (0.28 ± 0.23 ppm) in the dry season and 0.02 to 0.98 ppm (0.50 ± 0.53 ppm) in the wet season. Similarly, Trans-Amadi recorded 0.00 to 0.64 ppm (0.31 ± 0.32 ppm) in the dry season and 0.02 to 0.99 ppm (0.50 ± 0.53 ppm) in the wet season, while GRA followed the same trend with 0.00 to 0.62 ppm (0.33 ± 0.27 ppm) in the dry and 0.01 to 0.99 ppm (0.50 ± 0.53 ppm) in the wet season. All three locations exhibited significantly higher mean NO_2 concentrations during the wet season compared to the dry season. This pattern may appear counterintuitive, as wet seasons are often associated with better dispersion due to rainfall and higher humidity. However, the increase can be explained by atmospheric stagnation during heavy rains and low wind speeds, which can trap pollutants near ground level [25]. Increased use of power generators during wet months due to erratic electricity supply, especially in urban Nigerian contexts, leading to spikes in combustion-related emissions [26]. All three sites—industrial (Trans-Amadi), semi-industrial (Eleme), and residential (GRA)—shared similar ranges and variability. This points to a widespread source pattern, likely dominated by transport emissions and domestic fuel combustion, with possible contributions from industrial activities in Trans-Amadi and Eleme [27].

The standard deviation values indicate considerable temporal fluctuation, especially during the wet season, suggesting episodic peaks, likely tied to rush-hour traffic or power generator use during rain-induced outages. The significant differences between dry and wet season means (as stated) underscore the need for seasonal policy interventions, particularly during the wet season when vulnerable populations may be more

exposed to high NO_2 levels over sustained periods.

Sulphur dioxide (SO_2) is a colourless, pungent gas primarily produced by the combustion of Sulphur-containing fossil fuels, especially coal and oil, and is emitted largely from industrial processes, power generation, and vehicular emissions [17]. SO_2 is a critical pollutant due to its health impacts, particularly on the respiratory system, and its contribution to acid rain formation and particulate matter (PM) production [28].

At **Eleme**, SO_2 levels ranged from **0.00 to 0.28 ppm (0.08 ± 0.12 ppm)** in the dry season, and from **0.00 to 0.30 ppm (0.05 ± 0.12 ppm)** in the wet season. The relatively low mean values and standard deviations suggest moderate and possibly diffuse sources of SO_2. Eleme, being semi-industrial, may experience emissions from small-scale combustion and industrial residues, but the minimal increase in the wet season suggests efficient pollutant dispersion due to higher humidity and rainfall [26]. In **Trans-Amadi**, a known industrial hub, SO_2 levels in the **dry season** peaked at **t 0.55 ppm (0.27 ± 0.19 ppm) but** dropped to **0.00 ppm** in the **wet season**. This stark contrast may reflect **reduced combustion processes during rainy periods**, when certain outdoor industrial operations may slow down. **Enhanced wet deposition and atmospheric cleansing** in the wet season, which is particularly effective for soluble gases like SO_2 [25].

The dry season's elevated levels point to **intensive fossil fuel combustion**, likely from industrial operations, heavy-duty transport, or use of diesel-powered generators, all of which are common in Nigerian industrial zones [27]. At **GRA**, a primarily residential area, SO_2 ranged from **0.01 to 0.92 ppm (0.37 ± 0.31 ppm)** in the dry season**,** falling sharply to **0.00 to 0.01 ppm (0.00 ± 0.01 ppm)** in the **wet season**. The dry season peak and high standard deviation suggest intermittent and intense SO_2 emissions, likely from domestic activities such as **burning of kerosene, firewood**, or **use of backup diesel generators**, which become more frequent during dry periods marked by power instability and low humidity [29]. The wet season data indicates near-total dispersion or atmospheric removal of SO_2, likely due to **scavenging by rainwater** and low combustion demand.

Ozone (O_3) is a secondary pollutant formed in the troposphere through complex photochemical reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight [16]. Unlike primary pollutants, ozone is not directly emitted but rather formed through atmospheric chemical processes, which makes its presence highly dependent on meteorological conditions, precursor availability, and solar radiation [30]. Across the three sites, **Eleme, Trans-Amadi,** and **GRA**, ozone levels remained consistently low in both dry and wet seasons**,** with mean concentrations mostly ranging between 0.00 and 0.01 ppm, except for a

slight uptick at GRA in the wet season (0.06 ppm maximum). The **mean ± standard deviation** values across seasons were as follows: **Eleme** 0.01 ± 0.01 ppm (dry and wet), **Trans-Amadi** 0.00 ± 0.01 ppm (dry), 0.01 ± 0.01 ppm (wet), **GRA** 0.01 ± 0.01 ppm (dry), 0.01 ± 0.02 ppm (wet). The data shows **no significant difference in ozone mean values across seasons and locations,** indicating a relatively stable and low-level ozone environment. The consistently low O_3 levels observed may be attributed to limited precursor availability, especially volatile organic compounds (VOCs), which are essential for O_3 formation in the presence of NO_x and sunlight [31]. Rapid O_3 titration by nitric oxide (NO), particularly in urban/industrial environments like Trans-Amadi and Eleme, where NO can react with O_3 to form NO_2, thereby reducing ambient O_3 concentrations [21]. High relative humidity and **wet deposition**, especially in the rainy season, which can lower ozone formation and enhance removal from the atmosphere [32]. Despite higher solar radiation during the dry season, which theoretically supports ozone formation, the lack of significant seasonal change suggests that **photochemistry is not the limiting factor**. Instead, the region may lack sufficient VOCs or has high NO levels that suppress net O_3 accumulation [15]. Trans-Amadi, an industrial showed a slight increase in ozone during the wet season (up to 0.02 ppm). This might reflect **reduced NO levels due to wet scavenging,** lowering the O_3 titration rate. GRA, a more residential area, recorded the **highest wet season maximum (0.06 ppm),** possibly due to **s** reduced NO emissions and the presence of biogenic VOCs from vegetation, promoting ozone formation under certain conditions. Overall, these findings are in line with studies from urban areas in West Africa showing that ozone pollution is typically **secondary in concern** compared to primary pollutants like NO_2, SO_2, and CO [27].

Meteorological Parameters

Meteorological conditions such as **temperature, relative humidity, wind speed,** and wind direction play a critical role in influencing the distribution, dispersion, transformation, and deposition of air pollutants [16&32].

The present study provides insights into how these variables vary across **Eleme, Trans-Amadi**, and **GRA** during **dry and wet seasons**, and how they might affect air quality dynamics in the region. Temperature significantly differed between the dry and wet seasons at **Trans-Amadi** and **GRA**, but not at **Eleme. Trans-Amadi,** dry **37.78 ± 3.73°C** and wet **34.53 ± 2.39°C; GRA,** dry **35.68 ± 2.16°C** and wet: **31.22 ± 1.47°C; Eleme,** dry **34.68 ± 4.45°C** and wet: **31.55 ± 2.31°C** (not significantly different). This seasonal temperature variation is consistent with the tropical monsoon climate found in southern Nigeria, where higher solar radiation in the dry season elevates ambient temperatures [33]. The greater difference observed in Trans-Amadi may be due to **urban heat island (UHI) effects**, exacerbated by **dense industrial infrastructure**

and reduced vegetation, which retain more heat compared to the semi-industrial or residential settings of Eleme and GRA [34&35].

All locations showed **significant differences in Relative Humidity** between dry and wet seasons: **Eleme,** dry 65.13 ± **8.26%** and wet: **76.93 ± 10.36%, Trans-Amadi**, dry **47.13 ± 9.88%** and wet, **66.90 ± 13.02%; GRA,** dry 55.52 ± **11.78%** and wet, 68.72 ± **4.61%.**These differences reflect the **seasonal monsoon pattern**, where **increased precipitation and cloud cover** in the wet season raise RH levels. High humidity affects air quality by Enhancing **wet deposition of pollutants**, particularly soluble gases like SO_2 [36]. Influencing **secondary aerosol formation**, as many chemical reactions in the atmosphere are humidity-dependent [37]. Wind speed varied across locations but showed **no significant seasonal difference at Eleme and Trans-Amadi,** while GRA had a significant increase during the wet season. **Eleme**, dry: **7.22 ± 1.77 km/h** and wet: **7.77 ± 5.60 km/h** (not significant). **Trans-Amadi,** dry, **4.83 ± 2.07 km/h** and wet, **6.15 ± 3.66 km/h** (not significant). **GRA**, dry, **5.70 ± 2.03 km/h** and wet, **8.50 ± 2.80 km/h** (significant); Wind plays a crucial role in **pollutant dispersion**. Higher speeds typically enhance **horizontal transport**, reducing pollutant accumulation near emission sources [38]. The observed increase at GRA during the wet season could promote cleaner air, while slower winds in Trans-Amadi may **trap pollutants locally,** contributing to poor air quality. **Wind Direction**. **Eleme, WSW to SW**, **Trans-Amadi, SW to N and** GRA, SW to NW. The **dominant south-westerly winds** are characteristic of the **moist maritime air mass** from the Atlantic Ocean during the wet season. Directional variability influences **inter-site pollutant transport** and potential **pollution hotspots**, especially if upwind sources align with residential zones [33].

The figures 1 to 6 show the seasonal variation of the air quality parameters. The observable trend are as follows: Ewet > Edry > Gdry > Twet > Tdry > Gwet for CH_4; Tdry > Twet > Gdry > Edry > Ewet > Gwet for CO; Twet > Gwet > Twet > Gdry > Edry > Tdry for NO_2; Sulphur dioxide and ozone levels were low across the locations. The meteorological factors have the trend Tdry > Gdry > Edry > Twet > Twet > Gwet for temperature; Twet > Gwet > Twet > Edry > Gdry > Edry for relative humidity and Gwet > Ewet > Edry > Twet > Gdry > Tdry.

AQI and Its Health Categories

The **Air Quality Index (AQI)** is a standardized indicator used to communicate the quality of air and its potential health effects. AQI values are typically divided into categories such as **0–50**: Good, **51–100**: Moderate, **101–150**: Unhealthy for sensitive groups, **151–200**: Unhealthy and **201–300**: Very Unhealthy and **301–500**: Hazardous [39].

The $PM_{2.5}$ levels are highest in location T, which falls into the **"Unhealthy for sensitive groups"**

category. This suggests potential respiratory risks for individuals with asthma, the elderly, and children. Locations E and G had **moderate levels**, indicating acceptable air quality, though prolonged exposure could still pose mild health risks [17].

The PM_{10} concentration is notably high at location E, suggesting a risk of upper respiratory tract irritation in sensitive individuals. G enjoys the cleanest air among the sites for this pollutant. This may reflect differences in local emission sources (e.g., traffic, construction) or more effective natural dispersion in G (e.g., wind flow, vegetation).

The consistent **"Unhealthy"** NO_2 levels across all locations indicate a probable widespread source, possibly combustion from vehicles or industrial activities. Chronic exposure to NO_2 can lead to decreased lung function and increased risk of respiratory infections [40]. Its persistence even during the wet season suggests inadequate dispersion or high emission loads.

The dry season shows a spike in $PM_{2.5}$ at location E, reaching the **"Unhealthy"** category, likely due to increased dust resuspension, biomass burning, or reduced atmospheric cleansing due to lack of rainfall. T and G remained moderate, but health risks remain for prolonged exposure.

Location E again stands out with **very unhealthy** levels of PM_{10}. This could significantly impact public health, especially causing aggravation of heart and lung diseases. The dry conditions could favor suspension of dust and particulate accumulation. **Higher PM concentrations** (especially PM_{10}) were recorded in the **dry season**, especially at **location E**. This pattern aligns with literature showing that dry seasons often have higher dust and particulate pollution due to less precipitation and increased resuspension of particles [41].

Nitrogen dioxide (**NO_2) levels** remained high in both seasons across all sites, indicating continuous combustion sources such as traffic or industrial activities. Populations in **location E** are at the highest risk, especially during the dry season, where **both PM_{10} and $PM_{2.5}$** exceed safe limits. **Sensitive groups** (children, the elderly, and individuals with respiratory conditions) are particularly at risk and may require protective measures or advisories. **Regulatory action**, including emission control, dust suppression in the dry season, and traffic reduction strategies, may be warranted.

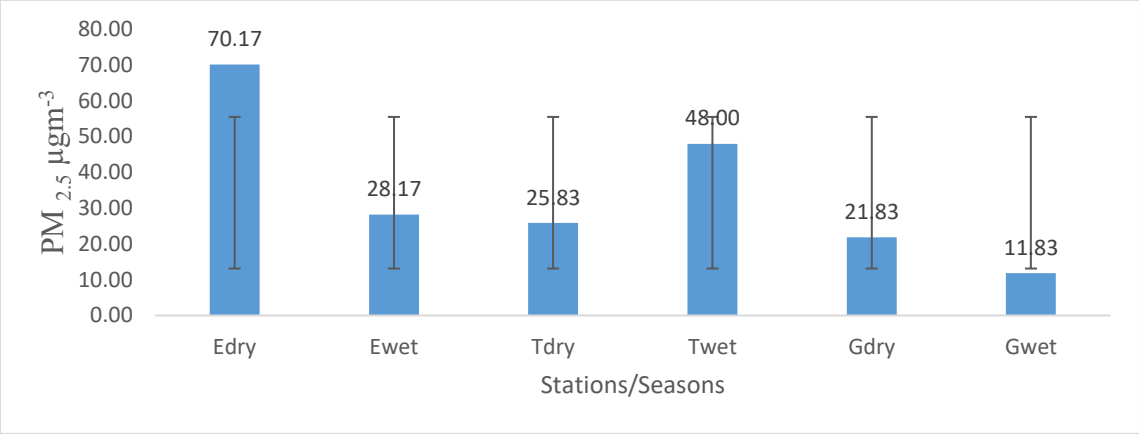


Fig. 1: Seasonal variations of $PM_{2.5}$ at different stations

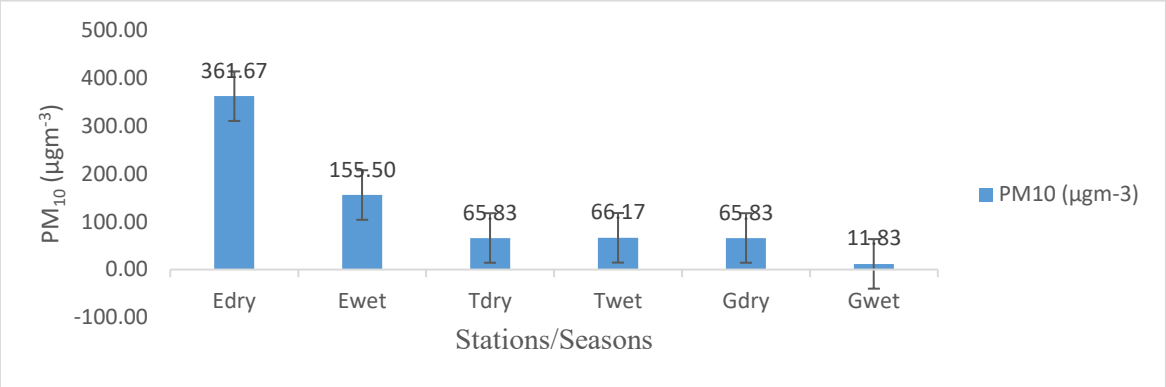


Fig. 2: Seasonal variations of PM_{10} at different stations

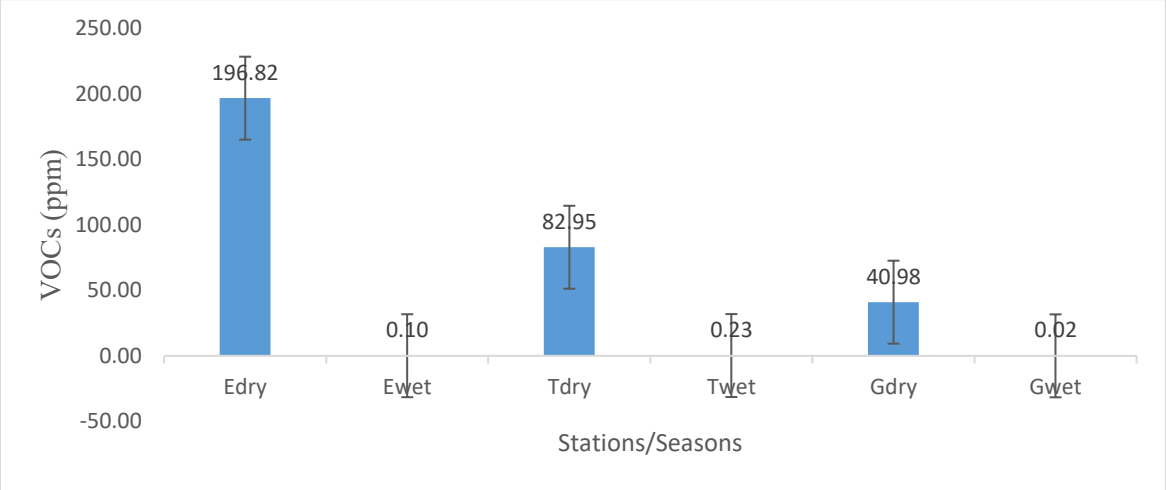


Fig. 3: Seasonal variations of VOCs at different stations

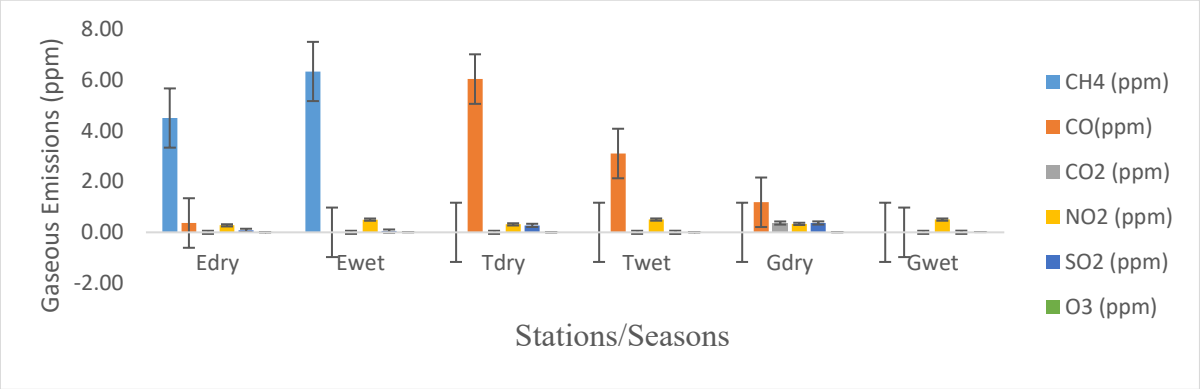


Fig. 4: Seasonal variations of Gaseous Emissions at different stations

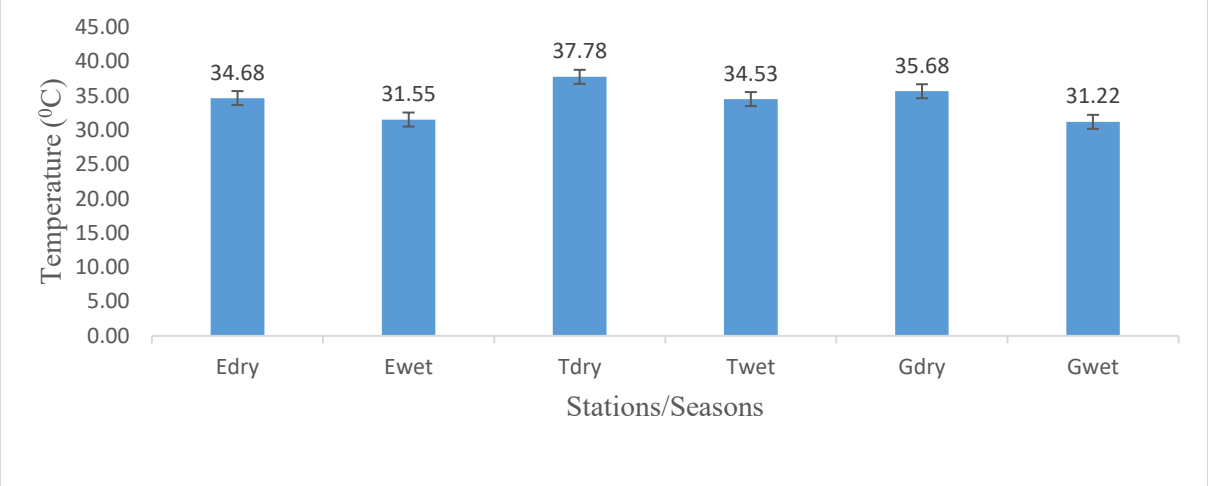


Fig. 5: Seasonal variations of Temperature at different stations

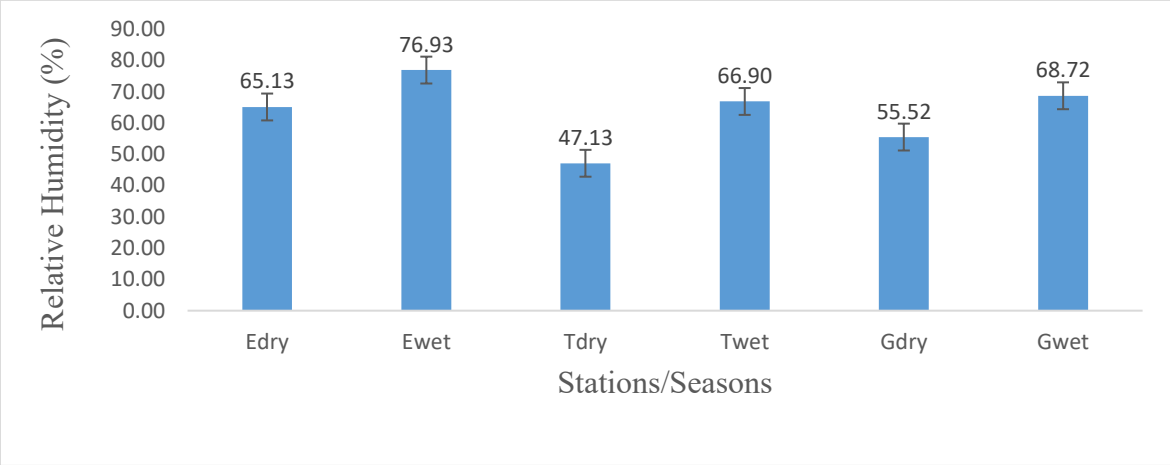


Fig. 6: Seasonal variations of Relative Humidity at different stations

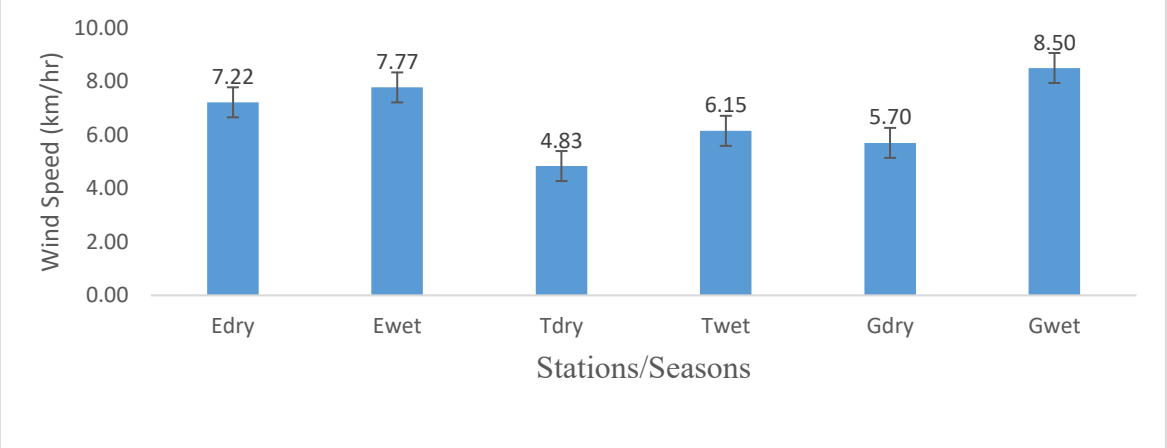


Fig. 7: Seasonal variations of Wind Speed at different stations

Conclusion

The observed significant difference in VOC concentrations in which a high value was recorded in dry season and a near zero during wet could be due to seasonal variations influenced by changes in temperature, humidity, and atmospheric dispersion.

The absence of detectable CO_2 at Eleme and Trans-Amadi (industrial locations) but its presence at GRA (a residential area) during the dry season underlines the importance of microclimate, urban form, and activity patterns in shaping ambient air composition. **Higher temperatures and lower humidity in the dry season** create conditions favorable for

photochemical reactions and pollutant accumulation.

All three locations exhibited significantly higher mean NO_2 concentrations during the wet season compared to the dry season. This pattern may appear counterintuitive, as wet seasons are often associated with better dispersion due to rainfall and higher humidity. **Higher humidity and stronger winds in the wet season** support pollutant removal and dispersion, improving air quality.

Temperature significantly differed between the dry and wet seasons at **Trans-Amadi** and **GRA**, but not at **Eleme. Trans-Amadi,** dry **37.78 ± 3.73 °C** and wet **34.53 ± 2.39 °C; GRA,** dry **35.68 ± 2.16 °C** and wet: **31.22 ± 1.47 °C; Eleme,** dry **34.68 ± 4.45 °C** and wet: **31.55 ± 2.31 °C** (not significantly different).

All locations showed **significant differences in Relative Humidity** between dry and wet seasons: **Eleme,** dry 65.13 ± **8.26%** and wet: **76.93 ± 10.36%, Trans-Amadi**, dry **47.13 ± 9.88%** and wet, **66.90 ± 13.02%; GRA,** dry 55.52 ± **11.78%** and wet, 68.72 ± **4.61%.**

Wind speed varied across locations but showed **no significant seasonal difference at Eleme and Trans-Amadi,** while GRA had a significant increase during the wet season. **Eleme**, dry: **7.22 ± 1.77 km/h** and wet: **7.77 ± 5.60 km/h** (not significant). **Trans-Amadi,** dry, **4.83 ± 2.07 km/h** and wet, **6.15 ± 3.66 km/h** (not significant). **GRA**, dry, **5.70 ± 2.03 km/h** and wet, **8.50 ± 2.80 km/h** (significant);

Recommendations

Further studies should be carried out to monitor the concentrations and sources of pollutants in the study area. Further Studies on other Pollutants such as polyaromatic hydrocarbons should be monitored in other urban areas.

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