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Spatio-temporal Variations of Air Pollutants in Urban Zones of Port Harcourt: Influence of Climatic Conditions, and Human Activities

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ABSTRACT

The study examines the spatial and temporal variations in air pollutant concentrations across four urban zones in Port Harcourt (residential, central business district (CBD), industrial, and suburban) between September and December. Data were collected using portable gas sensors and anemometers, capturing sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), particulate matter (PM_{10}), wind speed, and temperature during morning and evening periods. The industrial zone recorded the highest pollutant levels, including SO_2 at 0.28 ppm, NO_2 at 0.11 ppm, CO at 40.03 ppm, and PM_{10} at 3.12 ppm, while suburban areas had the lowest, with NO_2 at 0.04 ppm and CO at 18.61 ppm. Morning measurements consistently revealed higher concentrations. Temporally, NO_2 declined from 0.08 ppm in September to 0.05 ppm by October and December ($p = .031$). ANOVA confirmed significant spatial variation for CO ($F = 165.518$, $p < .001$) and PM_{10} ($F = 953.316$, $p < .001$), with an adjusted R^2 of 0.989 for PM_{10}. The findings highlight that urban land use strongly influences air quality, with industrial and commercial activities posing significant risks. The study contributes empirical evidence on localized pollution dynamics in sub-Saharan urban contexts and recommends targeted emission controls, urban greening, and sustained air quality surveillance to guide environmental policy and urban health planning.

Keywords: Air pollution, Urban zones, Spatial variation, Temporal analysis, Environmental policy

INTRODUCTION

Urban air pollution remains a critical environmental concern, particularly in rapidly developing cities where industrial expansion, population growth, and inadequate regulatory frameworks converge to exacerbate atmospheric degradation (Zhang et al., 2022). Port Harcourt, the capital of Rivers State in Nigeria, exemplifies such urban environments where escalating anthropogenic activities have significantly altered the air quality. The city, known for its vibrant oil and gas industry, is frequently exposed to emissions from petrochemical operations, vehicular exhaust, open waste burning, and unauthorized artisanal refining. Industrial activities contribute to elevated concentrations of particulate matter and gaseous pollutants, raising considerable public health concerns and ecological risks (Anjum, 2021; Akinfolarin et al., 2021).

The spatial and temporal distribution of air pollutants in urban landscapes is often influenced by an interplay of climatic conditions and human activities (Wang et al., 2022). Temperature, wind speed, humidity, and precipitation have been documented to significantly modulate the dispersion and concentration of pollutants, creating variable exposure patterns across different locations and seasons (Shelton et al., 2022). In Port Harcourt, the city's tropical monsoon climate, marked by alternating wet and dry seasons, further complicates the dynamics of pollutant accumulation and dispersal. The absence of comprehensive monitoring systems in

Nigerian urban centres, such as Port Harcourt, has hindered effective environmental management and policy formulation.

The study examines spatial differences in air pollutant concentrations across residential, industrial, commercial, and suburban zones of Port Harcourt, with emphasis on the roles of land use and human activities. Moreso, assessed the temporal stability and variation of selected air pollutants (SO_2, NO_2, CO, PM_{10}, H_2S) from September to December, identifying peak pollution periods and their possible causes. The study also evaluates the interactive effects of urban zones and time (monthly and diurnal) on pollutant levels, determining the key environmental and anthropogenic drivers of air quality in different city sectors. The rationale for this investigation stems from the necessity to develop a data-driven understanding of air quality dynamics in the region. While previous studies have acknowledged the high pollution levels in Port Harcourt, there remains a gap in literature that systematically explores the spatial heterogeneity of pollutants across various urban microenvironments and their temporal evolution in relation to meteorological influences and human behaviours (Ngele et al., 2020).

The implications of such a study are substantial. By identifying pollution hotspots and temporal trends, policymakers and environmental agencies can design targeted mitigation strategies, enforce emission controls, and implement adaptive environmental health policies. Additionally, understanding how local climatic variations interact with human activities to shape air quality can enhance predictive modelling and early warning systems for pollution episodes. The study is also timely, as global and national efforts intensify towards achieving the United Nations Sustainable Development Goals, particularly those related to health, sustainable cities, and climate action (United Nations, 2015). The study contributes to the growing body of knowledge on urban air pollution in sub-Saharan Africa by offering a detailed analysis of spatial and temporal pollutant patterns in Port Harcourt. It further underscores the urgency of integrating environmental monitoring with urban planning and public health policy in rapidly urbanizing contexts.

Conceptual Issues

Urban air pollution is a multifaceted environmental issue that encapsulates the complex interplay between anthropogenic emissions and natural atmospheric processes in densely populated and industrialized urban spaces. Within the conceptual framework of urban air pollution, this study explores how climatic conditions and human activities influence the spatial and temporal distribution of air pollutants across urban zones in Port Harcourt. The city presents a relevant context due to its high levels of industrial activity, particularly in the oil and gas sector, coupled with unregulated urban expansion and limited environmental governance (Obioha, 2023). At the core of the conceptual issues lies the understanding that urban air pollution is not uniform. It is influenced by varying factors that operate both spatially and temporally. The spatial variability arises from differences in land use, population density, emission sources, and topographical features, while temporal variability is shaped by changes in weather patterns, seasonal cycles, and human behavioural patterns (Swamy et al. 2024). The integration of these dimensions forms a critical lens through which urban air pollution is examined, offering insight into the distributional inequities of pollution exposure and their underlying causes.

The degree to which weather factors like temperature, humidity, wind speed, and precipitation affect pollution concentrations and diffusion is one of the main concerns. These factors have a major impact on the pollutants' residence period and transformation in the atmosphere, particularly in towns like Port Harcourt that experience tropical monsoons. A thorough analysis of these interdependencies is necessary since seasonal variations in weather further compound the complexity of pollution dynamics (Akinfolarin et al., 2021). The part that emissions caused by humans play in changing the quality of the air in cities is another important problem. Significant volumes of dangerous gases and fine particulate matter are released into the atmosphere by Port Harcourt's industrial emissions, especially from petrochemical operations and illicit refining activities. These activities together with open burning of rubbish and vehicle emissions make up the majority of the city's pollution sources (Ngele et al., 2020). According to the conceptual framework of urban air pollution, the cumulative effect of these sources causes a persistent decline in air quality in the absence of efficient monitoring and regulatory measures.

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The absence of real-time, spatially resolved air quality data presents a significant conceptual limitation. Urban air pollution studies require robust data inputs to capture the variability and trends accurately. However, in many African cities, including Port Harcourt, monitoring infrastructure is either rudimentary or non-existent, leading to an overreliance on episodic or modelled data (Ubani & Onyejekwe, 2013). This undermines the capacity to formulate effective policies and interventions, reinforcing the need for empirical studies that bridge this knowledge gap. The conceptualization of urban air pollution in this study acknowledges its broader implications for public health and environmental justice. Disparities in exposure to air pollutants across urban zones often mirror socio-economic inequalities, highlighting the intersection of environmental degradation and social vulnerability. Addressing these disparities requires a conceptual shift towards integrated urban planning and environmental governance frameworks that prioritize sustainability and health equity.

MATERIALS AND METHODS

Port Harcourt lies along the Bonny River and is located in Rivers State (Fig 1). The city lies approximately between longitude $6^0 56^1$E and $7^0 03^1$E and latitude $4^0 43^1$N and $4^0$54N of the equator. The areal expansion of Port Harcourt during the past two decades has been remarkable with results over 360 km^2 and elevation of 18m above sea level (Okwere et al., 2022). The study area is bounded to the North by Obio/Akpor Local Government area, to the South by Okrika, to the East by Eleme and to the West by Degema Tour Local Government Area. In terms of size, the city has grown from 15.54Km^2 in 1914, to a Local Government Area covering an area of 360Km^2 in 2008. The Port Harcourt urban fringe today stretches to Choba, Rumuokoro, Elelewon Rukpoku and Woji. Much of this growth is unplanned and unregulated (Echendu & Georgeou, 2021). Topographical conditions affect dispersion and transport of these pollutants, which can result in ambient concentrations that may harm people, structures, and the environment. Port Harcourt's population has grown significantly due to urbanization, rural-urban migration, and industrial opportunities. As of the last official census, the city had an estimated population of over 1.8 million, with current estimates suggesting figures above 3 million when including the Greater Port Harcourt Area (NPC, 2006; UN-Habitat, 2014). This demographic expansion has led to increased anthropogenic pressures on the urban environment, particularly through emissions from vehicular traffic, domestic energy use, industrial processes, and informal economic activities (Ngele et al., 2020). These activities collectively contribute to the complex pollution landscape observed in the region.

Port Harcourt's climatic conditions are typified by a tropical monsoon climate, which significantly influences air quality dynamics. The city experiences high relative humidity levels year-round, averaging between 80 and 90 percent, and receives substantial rainfall primarily between March and October (Samson, 2024). The mean annual rainfall exceeds 2,500 millimetres, and prevailing wind patterns determine the dispersion and transport of airborne pollutants. Vegetation in Port Harcourt has undergone significant degradation due to extensive urban development, with much of the natural vegetation replaced by built infrastructure, fragmented green spaces, and patches of secondary growth. This alteration in land cover affects the city's microclimatic conditions (Erell & Zhou, 2022), and limits the natural filtration capacity of the environment, reducing the ability of vegetation to mitigate the effects of air pollutants through processes such as absorption and deposition (Odu & Adewusi, 2019). Understanding these contextual characteristics is essential for interpreting pollutant.

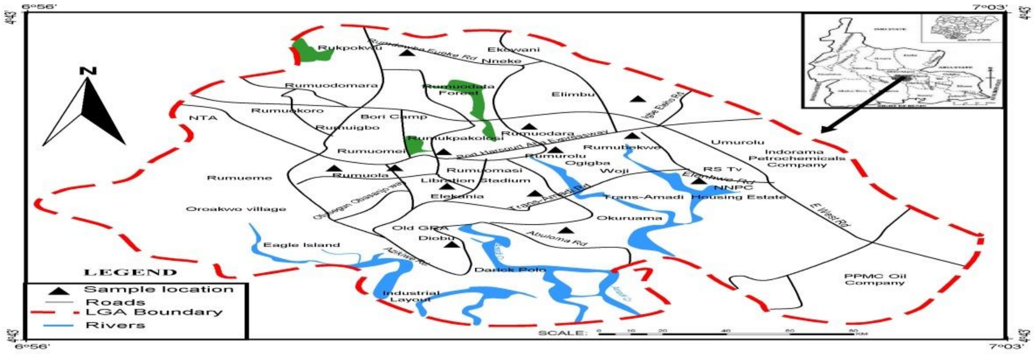

Fig. 1: Map of Port Harcourt Showing Sample locations

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The study adopted a quantitative research design involving systematic field sampling, direct measurement, and inferential statistical analysis to investigate spatial and temporal variations in air quality across four urban zones in Port Harcourt (residential (Ikwere Rd., Rumuodara Rd., and Staduim Rd.), industrial (Trans Amadi Rd., Elenwo Rd., and Abuloma Rd.), central business district (CBD) (Rumuola Rd., Old Aba Rd., and Port Harcourt express Rd.), and suburban or fringe areas (Rumuewha-eneke Rd., Igunta Rd., and Igbe-Eleho Rd). These zones were deliberately selected to reflect a gradient of land use intensities, population densities, and anthropogenic activities, which are known to influence air pollution patterns. A stratified spatial sampling technique was employed. Each urban zone was subdivided into three representative sampling points, selected based on land use characteristics and proximity to likely pollution sources such as roadways, markets, and industrial sites. Sampling was conducted consistently over a four-month period, from September to December, capturing transitional climatic conditions between the wet and dry seasons. This timeframe was chosen due to its relevance for understanding pollution accumulation and dispersion under varying meteorological conditions.

Measurements were taken twice daily; morning (7:00–9:00 a.m.) and evening (5:00–7:00 p.m.) to reflect diurnal variations associated with peak human and vehicular activity. Air pollutants monitored included sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), hydrogen sulphide (H_2S), and particulate matter (PM_{10}). These pollutants were selected due to their public health significance and prevalence in emissions from transportation, domestic energy use, and industrial processes. Meteorological variables, including wind speed and ambient temperature, were also recorded to examine their influence on pollutant dispersion. Portable, calibrated instruments were used for direct measurement: the Aerocet 531S measured PM_{10}; the GasAlert Extreme detected SO_2 and NO_2; the Crowcon Gasman was used for CO and H_2S. Wind speed and temperature were recorded using digital anemometers and thermometers. Each reading was taken three times per session and averaged to enhance reliability and reduce measurement error. To assess the health implications of observed pollutant concentrations, the Air Quality Index (AQI) was calculated using the formula recommended by Tiwari and Ali (1987) and applied by Kaushik et al. (2006). The formula is:

$$Q = (V / S) \times 100$$

Where:

Q = quality rating

V = observed concentration of a given pollutant

S = standard or permissible limit of the pollutant as defined by regulatory agencies

Table 1: Standard or permissible limit of the pollutant

Pollutant	**Standard Limit (ppm)**
PM_{10}	0.0183
CO	35
NO_2	0.1
SO_2	0.053

Source: NAAQS Table | US EPA (2024)

Table 2: Air quality index for priority pollutants in Parts per Million (ppm)

AQI Category	**AQI Rating**	**PM_{10}**	**CO**	**NO_2**	**SO_2**
Very Clean	I	0.0-0.9	0-2	0.00-0.02	0.00-0.02
Clean	II	1.1-1.7	2.1-4.0	0.02-0.03	0.02-0.03

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Fairly Clean	III	1.7-2.3	4.1-6.0	0.03-0.04	0.03-0.04
Moderately Polluted	IV	2.4-3.4	6.1-9.0	0.04-0.06	0.04-0.05
Polluted	V	>3.4	>9.0	>0.06	>0.06

Source: USEPA (2000); Barman et al. (2010)

This index was computed for each pollutant and aggregated to evaluate the overall air quality status in each zone. AQI values were classified using both Nigerian National Air Quality Standards (NNAQS) and United States Environmental Protection Agency (USEPA) permissible limit (Table 1) and AQI categorisation: I (Good), II (Clean), III (Moderate), IV (Polluted), and V (Heavily Polluted) (Table 2). These classifications translated quantitative data into qualitative categories reflecting potential health risks. Collected data were tabulated and illustrated through charts and statistical diagrams. Descriptive statistics, including percentages and cross-tabulations, were employed to interpret spatial patterns. Descriptive statistics summarised pollutant concentrations, wind speed, and temperature across spatial zones and months. A two-way Analysis of Variance (ANOVA) tested for main and interaction effects of urban zone and month on pollutant levels. Where significant differences were found, Tukey's Honestly Significant Difference (HSD) test was applied to identify specific group differences. Model fit was assessed using R^2 and adjusted R^2 values, along with effect sizes (partial eta squared), to determine the strength and explanatory power of zone and temporal variations. The methodological approach ensured high temporal and spatial resolution, accuracy in data collection, and interpretability of findings through AQI computation. It advances methodological rigor in urban air quality research and contributes to the growing body of knowledge on environmental health in rapidly urbanising cities in sub-Saharan Africa.

RESULTS AND DISCUSSION

Table 3: Air quality and meteorological conditions in Port Harcourt

Areas	**Wind Velocity (Knots)**	**Temperature (^{O}C)**	**SO_2 (ppm)**	**NO_2 (ppm)**	**CO (ppm)**	**PM_{10} (ppm)**
Residential Areas	6.14	29.85	0.16	0.05	39.18	2.67
Central Business District	4.87	30.62	0.20	0.06	28.80	3.46
Industrial Areas	5.18	30.62	0.22	0.07	37.89	3.12
Fringe/Sub Urban Areas	6.28	29.83	0.14	0.04	21.54	1.30

Field Work (2024)

Table 3 compares the wind speed, temperature, and concentrations of the main air pollutants in four different urban areas: Port Harcourt's residential neighbourhoods, the CBD, industrial neighbourhoods, and the outskirts or suburbs. In addition to climatic data like temperature and wind speed, the detected variables include sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter (PM_{10}). The largest concentrations of pollutants are found in the central business district and industrial districts. The industrial zone has the highest amounts of SO_2 (0.22 ppm), NO_2 (0.07 ppm), and PM_{10} (3.12 ppm). These high levels are consistent with heavy traffic and industrial activity, which are usually concentrated in these locations. Despite having somewhat lower total emissions than the industrial zone, the CBD nonetheless has high levels of pollutant, especially PM_{10}, which are a reflection of traffic and business congestion. Modest amounts of pollutants are seen in residential areas, indicating localised emissions from household activities and modest vehicle mobility. The lowest quantities of all pollutants were found in suburban or fringe regions, which may help disperse pollutants because of more plant cover and lower densities of human activity. The residential and periphery zones had the highest wind velocities, which could have contributed to the decreased retention of pollutants. There was little change in temperature, indicating that the effects of thermal conditions varied little

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between zones. Overall, the results show that land use patterns and the level of human activity are associated with geographical differences in air quality.

Table 4: Temporal Analysis of Meteorological Parameters and Air Pollutant Concentrations from September to December

	September	**October**	**November**	**December**	**Mean**
Wind Velocity (Knots)	5.64	5.59	5.69	5.55	**5.62**
Temperature (^{O}C)	30.11	30.45	30.28	30.13	**30.24**
SO_2 (ppm)	0.18	0.18	0.18	0.18	**0.18**
H_2S (ppm)	15.33	15.33	15.21	15.28	**15.29**
NO_2 (ppm)	0.08	0.05	0.05	0.05	**0.06**
CO (ppm)	31.75	31.93	31.94	31.80	**31.85**
PM_{10} (ppm)	2.63	2.65	2.67	2.63	**2.64**

Field Work (2024)

Table 4 shows the temperature, wind speed, and concentrations of a few chosen air pollutants throughout a four-month period from September to December. In order to evaluate stability and fluctuation over time, the monthly values and overall mean of the measured parameters which include sulphur dioxide (SO_2), hydrogen sulphide (H_2S), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter (PM_{10}) are computed. With a mean of 5.62 knots and very minor variations, wind velocity was comparatively constant throughout the time, suggesting a constant capability for air dispersion. Stable thermal conditions were suggested by the temperature, which varied very little from 30.11°C in September to a peak of 30.45°C in October.

Throughout the time period, the SO_2 content was consistent at 0.18 ppm, suggesting a stable source of emissions or no variation in sulphur emitting activity. H_2S levels ranged from 15.21 ppm to 15.33 ppm, indicating marginal variance that may be caused by changes in industrial or waste-related emissions over time. Better air dispersion or less combustion activity may be the cause of the NO_2 concentration's decline from 0.08 ppm in September to a constant 0.05 ppm in the months that followed. With an average of 31.85 ppm, CO concentrations stayed high and steady, indicating ongoing human emissions, maybe from burning and driving. Indicating consistent particle emissions during the monitored months, PM_{10} readings also shown little variation, averaging 2.64 ppm. Overall, the data point to stable emission patterns and little seasonal effect over this time, indicating temporal stability in both pollutant concentrations and climatic conditions with very minor fluctuations.

Table 5: Spatio-Temporal Trends in Meteorological and Air Quality Parameters Across Urban Zones in Port Harcourt (September–December)

	Areas	**Wind Velocity (Knots)**	**Temperature (^{O}C)**	**SO_2 (ppm)**	**H_2S (ppm)**	**NO_2 (ppm)**	**CO (ppm)**	**PM_{10} (ppm)**
September	Residential Areas	6.20	29.59	0.17	14.50	0.07	39.25	2.68
	Central Business District	4.93	30.58	0.20	18.43	0.08	28.88	3.48
	Industrial Areas	5.14	30.50	0.22	19.76	0.11	37.50	3.06
	Fringe/Sub Urban Areas	6.29	29.79	0.14	8.65	0.06	21.38	1.33
October	Residential Areas	6.09	30.33	0.16	14.24	0.03	39.13	2.68

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	Central Business District	4.94	30.70	0.21	18.53	0.06	28.88	3.46
	Industrial Areas	5.09	30.80	0.23	19.91	0.06	38.05	3.16
	Fringe/Sub Urban Areas	6.24	29.96	0.15	8.66	0.04	21.66	1.29
November	Residential Areas	6.18	29.88	0.16	14.11	0.05	39.38	2.69
	Central Business District	4.89	30.53	0.19	18.25	0.06	28.88	3.51
	Industrial Areas	5.38	30.61	0.22	19.89	0.06	37.96	3.13
	Fringe/Sub Urban Areas	6.33	30.09	0.14	8.59	0.04	21.54	1.35
December	Residential Areas	6.09	29.71	0.16	14.14	0.03	39.00	2.64
	Central Business District	4.69	30.64	0.19	18.46	0.05	28.63	3.44
	Industrial Areas	5.14	30.64	0.22	19.88	0.07	38.04	3.15
	Fringe/Sub Urban Areas	6.29	29.54	0.14	8.63	0.04	21.54	1.28

Field Work (2024)

Table 5 presents a complete spatio-temporal study of weather conditions and air pollution concentrations in four separate urban zones (residential areas, central business district (CBD), industrial regions, and peripheral or suburban areas) from September to December. Wind speed, temperature, and concentrations of sulphur dioxide (SO_2), hydrogen sulphide (H_2S), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter (PM_{10}) are among the factors that are monitored. The industrial and central business district (CBD) areas continuously had the highest air pollution levels across all months. Significantly, SO_2 levels continued to be high in industrial regions, peaking at 0.23 ppm in October, and H_2S levels also peaked in same regions, suggesting that industry and vehicle emissions constitute a continuous source of pollution. September had the greatest levels of NO_2 (0.11 ppm) in industrial zones, indicating significant levels of combustion. In contrast, fringe or suburban areas maintained the lowest pollutant concentrations, indicating the influence of lower population density and reduced anthropogenic activity. Although residential areas were less polluted than industrial and CBD zones, they had persistently high CO levels above 39 ppm throughout all months, likely due to localised traffic emissions and domestic fuel combustion. PM_{10} levels followed a similar spatial pattern, with the industrial and CBD zones showing consistently higher concentrations compared to peripheral areas. In terms of weather, wind velocity was generally higher in residential and fringe areas, which may have helped improve pollutant dispersion. Temperatures remained relatively stable across zones and months, ranging between 29.54°C and 30.80°C, suggesting minimal seasonal thermal variation. The analysis underscores the correlation between land use intensity and air quality, highlighting industrial and commercial zones as critical targets for environmental policy and urban health interventions.

Table 6: Diurnal Variation of Meteorological Conditions and Air Pollutants Across Urban Zones

Sessions	**Areas**	**Wind Velocity (Knots)**	**Temperature (^{O}C)**	**SO_2 (ppm)**	**H_2S (ppm)**	**NO_2 (ppm)**	**CO (ppm)**	**PM_{10} (ppm)**
Morning	Residential Areas	6.07	29.49	0.21	15.19	0.06	39.87	2.75
	Central Business District	4.88	30.75	0.29	19.02	0.07	29.47	3.47

	Industrial Areas	4.93	30.47	0.28	20.61	0.08	40.03	3.06
	Fringe/Sub Urban Areas	6.09	29.27	0.17	8.85	0.04	22.53	1.33
Average		5.49	30.00	0.24	15.92	0.06	32.97	2.65
Evening	Residential Areas	6.21	30.21	0.12	13.31	0.04	38.50	2.59
	Central Business District	4.85	30.50	0.10	17.79	0.05	28.13	3.46
	Industrial Areas	5.44	30.77	0.17	19.09	0.07	35.75	3.19
	Fringe/Sub Urban Areas	6.47	30.39	0.11	8.42	0.05	20.54	1.26
Average		5.74	30.47	0.12	14.65	0.05	30.73	2.62

Field work (2024)

Table 6 compares morning and evening observations of meteorological and air quality indicators in four urban land use zones: residential, core business district (CBD), industrial, and periphery or suburban. Wind speed, temperature, and the levels of sulphur dioxide (SO_2), hydrogen sulphide (H_2S), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter (PM_{10}) are among the characteristics that are examined. The morning session results show greater pollutant concentrations, especially for SO_2, H_2S, and CO. The morning SO_2 (0.28 ppm), H_2S (20.61 ppm), and CO (40.03 ppm) readings were greatest in industrial districts, indicating higher industrial activity in the morning and less atmospheric dispersion in the colder hours. Due to early traffic and business activity, the CBD also displayed higher pollutant levels in the morning, particularly in SO_2 and H_2S.

On the other hand, pollution levels often dropped in the evening. All zones saw a sharp decline in SO_2 levels, with the residential area dropping to 0.12 ppm and the industrial zone to 0.17 ppm. Indicating better air mixing and less human activity later in the day, CO and H2S concentrations also decreased. Particulate matter (PM_{10}), on the other hand, was mostly constant over sessions, with the greatest concentrations seen in industrial and central business districts, suggesting persistent emissions from construction and vehicles. In the evening, wind speeds were somewhat higher in most zones, which helped the pollutants spread more widely. The evening session saw a slight increase in temperature, especially in the industrial and central business districts. The study highlights the connection between land use intensity and air quality, highlighting the importance of commercial and industrial districts for environmental policy initiatives and urban health.

Table 7: Assessment of Gaseous Pollutants in Port Harcourt's Urban Functional Zones for the Air Quality Index (AQI)

Areas	**SO_2 (ppm)**	**AQI**	**NO_2 (ppm)**	**AQI**	**CO (ppm)**	**AQI**	**PM_{10} (ppm)**	**AQI**
Residential Areas	0.16	3.01 (Polluted)	0.05	0.5 (Moderately Polluted)	39.18	1.12 (Very Clean)	2.67	145.90 (Polluted)
Central Business District	0.20	3.77 (Polluted)	0.06	0.6 (Moderately Polluted)	28.80	0.82 (Very Clean)	3.46	189.07 (Polluted)
Industrial Areas	0.22	4.15 (Polluted)	0.07	0.7 (Polluted)	37.89	1.08 (Very Clean)	3.12	170.49 (Polluted)
Fringe/Sub Urban Areas	0.14	2.64 (Polluted)	0.04	0.4 (Fairly Clean)	21.54	0.62 (Very Clean)	1.30	71.04 (Polluted)

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Field Work (2024)

Where Residential areas (Ikwere Rd., Rumuodara Rd., and Staduim Rd.); Central Business Districts (CBD) areas (Rumuola Rd., Old Aba Rd., and Port Harcourt express Rd.); Industrial areas (Trans Amadi Rd., Elenwo Rd., and Abuloma Rd.); and Fringe/suburban zone (Rumuewha-eneke Rd., Igunta Rd., and Igbe-Eleho Rd).

The data presented in Table 7 provides an analytical summary of the concentration and associated Air Quality Index (AQI) values of four key gaseous pollutants (sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter (PM_{10})) across different urban functional zones in Port Harcourt. The zones assessed include residential, central business district, industrial, and fringe or suburban areas. The findings reveal that sulphur dioxide concentrations are highest in industrial zones at 0.22 ppm, followed closely by the central business district and residential areas at 0.20 ppm and 0.16 ppm respectively, while fringe areas recorded the lowest level at 0.14 ppm. The AQI ratings for SO_2 in all zones classify the air quality as polluted, with industrial zones experiencing the most severe pollution. This indicates significant sulphur compound emissions, likely from industrial fuel combustion and vehicular traffic in high-density zones. Nitrogen dioxide levels exhibit a similar trend, with industrial areas registering the highest concentration at 0.07 ppm, followed by the central business district (0.06 ppm), residential areas (0.05 ppm), and fringe areas (0.04 ppm). While most zones are categorized under moderately polluted or fairly clean AQI levels for NO_2, the industrial zone's classification as polluted reflects the impact of combustion processes typical of manufacturing and transportation hubs. Carbon monoxide levels are notably highest in residential areas (39.18 ppm), suggesting elevated indoor or localized outdoor CO emissions possibly from generators, vehicular idling, or biomass burning. Industrial and central business districts follow, with fringe areas recording the lowest concentration. Despite the higher concentrations, all zones report CO under the very clean AQI category, indicating that while concentrations appear elevated in some areas, they remain within permissible exposure limits as defined by AQI thresholds. PM_{10} concentrations are most alarming, with all zones showing AQI values indicative of pollution. The central business district has the highest PM_{10} AQI at 189.07, followed by industrial areas (170.49), residential areas (145.90), and fringe zones (71.04). This suggests widespread particulate pollution primarily arising from unpaved roads, construction, industrial activity, and open burning, which collectively compromise respiratory health. The findings underscore the urgency of implementing comprehensive air quality management strategies in Port Harcourt, especially in zones with critical pollutant thresholds being surpassed. Continuous monitoring, public health education, and the enforcement of emission control measures are necessary to mitigate environmental and health risks.

Table 8: Multivariate Tests of Between-Subjects Effects for Air Quality Indicators across Urban Zones and Months in Port Harcourt

Tests of Between-Subjects Effects							
Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	SO_2	.032[a]	15	.002	.279	.991	.207
	NO_2	.011[b]	15	.001	2.092	.077	.662
	CO	1648.810[c]	15	109.921	33.119	.000	.969
	PM_{10}	21.583[d]	15	1.439	190.898	.000	.994
Intercept	SO_2	1.051	1	1.051	137.306	.000	.896
	NO_2	.104	1	.104	301.127	.000	.950

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	CO	32471.713	1	32471.713	9783.583	.000	.998
	PM_{10}	223.979	1	223.979	29715.239	.000	.999
Zones	SO_2	.031	3	.010	1.371	.287	.205
	NO_2	.005	3	.002	5.006	.012	.484
	CO	1648.067	3	549.356	165.518	.000	.969
	PM_{10}	21.557	3	7.186	953.316	.000	.994
Months	SO_2	.000	3	8.333E-5	.011	.998	.002
	NO_2	.005	3	.002	4.473	.018	.456
	CO	.209	3	.070	.021	.996	.004
	PM_{10}	.008	3	.003	.361	.782	.063
Zones * Months	SO_2	.000	9	3.333E-5	.004	1.000	.002
	NO_2	.001	9	.000	.327	.953	.155
	CO	.535	9	.059	.018	1.000	.010
	PM_{10}	.018	9	.002	.271	.974	.132
Error	SO_2	.123	16	.008			
	NO_2	.006	16	.000			
	CO	53.104	16	3.319			
	PM_{10}	.121	16	.008			
Total	SO_2	1.206	32				
	NO_2	.120	32				
	CO	34173.627	32				
	PM_{10}	245.683	32				
Corrected Total	SO_2	.155	31				
	NO_2	.016	31				
	CO	1701.914	31				
	PM_{10}	21.704	31				
a. R Squared = .207 (Adjusted R Squared = -.536)							
b. R Squared = .662 (Adjusted R Squared = .346)							
c. R Squared = .969 (Adjusted R Squared = .940)							
d. R Squared = .994 (Adjusted R Squared = .989)							

Source: SPSS Computation

Table 8 presents the results of a two-way Analysis of Variance (ANOVA) examining the effects of urban zones, months, and their interaction on the concentrations of four air pollutants: sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter (PM_{10}) in Port Harcourt. The independent variables are urban zones and months, while the dependent variables are the pollutant concentrations. The study found that SO_2 levels did not significantly differ across urban zones or months, with low F-values and high p-values ($p>0.05$) indicating no significant differences. The model explained a modest portion of variance ($R^2 = 0.207$), but the adjusted R^2 was negative, suggesting poor model fit and overfitting. However, NO_2 levels showed a significant effect of zones and months ($F = 5.006$, $p = .012$) and months ($F = 4.473$, $p = .018$), indicating varied levels across spatial and temporal dimensions. However, the interaction effect between zones and months was not significant ($p=0.953$). The model explained a substantial proportion of variance ($R^2 = 0.662$), but the adjusted R^2 of 0.346 suggests overfitting or sampling variability.

The study found that zones significantly affect CO levels ($F = 165.518$, $p < 0.001$), with a large effect size, indicating that most variability in CO concentrations is due to differences among zones. However, neither months nor the interaction term significantly contributed to CO variation. The model's fit was strong, confirming the dominance of spatial over temporal influences in determining CO concentration. PM_{10} concentrations also varied significantly across zones ($F = 953.316$, $p < 0.001$), with a high effect size, reflecting strong spatial disparity. Similar to CO, neither months nor their interaction with zones had significant effects. The model fit was nearly perfect ($R^2 = .994$; adjusted $R^2 = .989$), indicating that zone-specific factors are critical determinants of PM_{10} levels. The study found that spatial variation, specifically zone effects, significantly influences CO and PM_{10} concentrations, with no significant contribution from temporal or interaction effects. NO_2 showed moderate sensitivity to both spatial and temporal factors, while SO_2 showed no significant variation. The findings underscore the need for geographically targeted interventions to mitigate air pollution.

Table 9: Tukey HSD Post-hoc Comparison of Air Pollutant Levels across Urban Zones in Port Harcourt

Tukey HSD							
Dependent Variable	(I) in Port Harcourt	(J) in Port Harcourt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
NO_2	1.00 Residential Areas	2.00 Central Business Districts	-.0125	.00927	.547	-.0390	.0140
		3.00 Industrial areas	-.0287*	.00927	.031	-.0553	-.0022
		4.00 Fringe/suburban zone	.0038	.00927	.977	-.0228	.0303
	2.00 Central Business Districts	1.00 Residential Areas	.0125	.00927	.547	-.0140	.0390
		3.00 Industrial areas	-.0162	.00927	.331	-.0428	.0103
		4.00 Fringe/suburban zone	.0163	.00927	.331	-.0103	.0428
	3.00 Industrial areas	1.00 Residential Areas	.0287*	.00927	.031	.0022	.0553
		2.00 Central Business Districts	.0162	.00927	.331	-.0103	.0428
		4.00 Fringe/suburban zone	.0325*	.00927	.014	.0060	.0590
	4.00 Fringe/suburban zone	1.00 Residential Areas	-.0038	.00927	.977	-.0303	.0228
		2.00 Central Business Districts	-.0163	.00927	.331	-.0428	.0103
		3.00 Industrial areas	-.0325*	.00927	.014	-.0590	-.0060
CO	1.00 Residential	2.00 Central Business Districts	10.3750*	.91091	.000	7.7689	12.9811

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	Areas	3.00 Industrial areas	1.2987	.91091	.502	-1.3074	3.9049
		4.00 Fringe/suburban zone	17.6562*	.91091	.000	15.0501	20.2624
	2.00 Central Business Districts	1.00 Residential Areas	-10.3750*	.91091	.000	-12.9811	-7.7689
		3.00 Industrial areas	-9.0763*	.91091	.000	-11.6824	-6.4701
		4.00 Fringe/suburban zone	7.2812*	.91091	.000	4.6751	9.8874
	3.00 Industrial areas	1.00 Residential Areas	-1.2987	.91091	.502	-3.9049	1.3074
		2.00 Central Business Districts	9.0763*	.91091	.000	6.4701	11.6824
		4.00 Fringe/suburban zone	16.3575*	.91091	.000	13.7514	18.9636
	4.00 Fringe/suburban zone	1.00 Residential Areas	-17.6562*	.91091	.000	-20.2624	-15.0501
		2.00 Central Business Districts	-7.2812*	.91091	.000	-9.8874	-4.6751
		3.00 Industrial areas	-16.3575*	.91091	.000	-18.9636	-13.7514
PM_{10}	1.00 Residential Areas	2.00 Central Business Districts	-.8038*	.04341	.000	-.9279	-.6796
		3.00 Industrial areas	-.4562*	.04341	.000	-.5804	-.3321
		4.00 Fringe/suburban zone	1.3575*	.04341	.000	1.2333	1.4817
	2.00 Central Business Districts	1.00 Residential Areas	.8038*	.04341	.000	.6796	.9279
		3.00 Industrial areas	.3475*	.04341	.000	.2233	.4717
		4.00 Fringe/suburban zone	2.1613*	.04341	.000	2.0371	2.2854
	3.00 Industrial areas	1.00 Residential Areas	.4562*	.04341	.000	.3321	.5804
		2.00 Central Business Districts	-.3475*	.04341	.000	-.4717	-.2233
		4.00 Fringe/suburban zone	1.8137*	.04341	.000	1.6896	1.9379
	4.00 Fringe/suburban zone	1.00 Residential Areas	-1.3575*	.04341	.000	-1.4817	-1.2333
		2.00 Central Business Districts	-2.1613*	.04341	.000	-2.2854	-2.0371
		3.00 Industrial areas	-1.8137*	.04341	.000	-1.9379	-1.6896
Based on observed means. The error term is Mean Square (Error) = .008.							
*. The mean difference is significant at the .05 level.							

Source: SPSS computation

Table 9 shows the results of a Tukey Honestly Significant Difference (HSD) post-hoc test after a one-way ANOVA comparing the mean concentrations of nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter (PM_{10}) across four urban zones in Port Harcourt: residential areas, central business districts (CBD), industrial areas, and the fringe or suburban zone. The purpose is to establish which zones have substantial differences in pollution levels. The study found significant differences in air pollutant concentrations across Port Harcourt's urban zones. Industrial areas had higher NO_2 levels ($p = .031$) compared to residential and fringe zones, indicating that the industrial zone is the main source of NO_2 variation. The highest CO concentration was observed in residential areas, followed closely by the industrial zone, while the fringe zone recorded the lowest levels. The largest mean differences (mean difference = 16.36, $p < 0.001$) occurred between residential and fringe zones, indicating a strong spatial disparity in CO emissions.

At $p < 0.001$, PM_{10}, each zone differed significantly, with the central business district and industrial areas exhibiting higher PM_{10} levels than residential and fringe zones. The most significant contrasts occurred between the CBD and fringe zone, and between the industrial and fringe zones. These findings suggest that anthropogenic activities related to traffic, commerce, and industry strongly influence particulate matter levels. The post-hoc results confirm significant spatial variation in air pollutant concentrations across Port Harcourt's urban zones, with industrial areas being the most significant sources of NO_2. These disparities highlight the need for targeted air quality management policies and emission control strategies, especially in zones with higher pollutant concentrations, to mitigate public health risks and ensure sustainable urban living.

Table 10: Tukey Post Hoc Comparison of Monthly Variations in Nitrogen Dioxide (NO_2) Concentration in Port Harcourt

Tukey HSD							
Dependent Variable	(I) Months	(J) Months	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
NO_2	1 September	2 October	.0288*	.00927	.031	.0022	.0553
		3 November	.0250	.00927	.068	-.0015	.0515
		4 December	.0288*	.00927	.031	.0022	.0553
	2 October	1 September	-.0288*	.00927	.031	-.0553	-.0022
		3 November	-.0038	.00927	.977	-.0303	.0228
		4 December	.0000	.00927	1.000	-.0265	.0265
	3 November	1 September	-.0250	.00927	.068	-.0515	.0015
		2 October	.0038	.00927	.977	-.0228	.0303
		4 December	.0038	.00927	.977	-.0228	.0303

	4 December	1 September	-.0288*	.00927	.031	-.0553	-.0022
		2 October	.0000	.00927	1.000	-.0265	.0265
		3 November	-.0038	.00927	.977	-.0303	.0228
Based on observed means. The error term is Mean Square (Error) = .008.							
*. The mean difference is significant at the .05 level.							

Source: SPSS computation

Table 10 shows the Tukey Honestly Significant Difference (HSD) post hoc test findings for monthly differences in nitrogen dioxide (NO_2) concentrations in September, October, November, and December. The investigation aimed to identify months with substantial differences in NO_2 levels, based on an ANOVA with a significant main effect of time. The study found that NO_2 concentrations were significantly (mean difference = 0.0288, p = .031) higher in September compared to October and December, indicating a possible trend towards higher levels. The difference between September and November approached significance, indicating a possible but not conclusive trend. No other monthly comparisons yielded significant differences, suggesting a relative stability in NO_2 concentrations during these months. The findings suggest that NO_2 concentrations were elevated in September compared to later months, possibly due to seasonal factors like weather conditions, traffic density variations, or industrial activity. These temporal patterns underscore the importance of continuous monitoring to identify peak pollution periods and inform timely policy responses.

CONCLUSION

The study examined the spatial variation of atmospheric pollution in Port Harcourt Metropolis, Nigeria by identifying the atmospheric pollutants in Port Harcourt. There is a statistically significant difference in the spatial variation of PM_{10}, SO_2, NO_2 and CO in the various land uses (Residential, Central Business District, Industrial, and Fringe/Sub-urban) in Port Harcourt. The concentration of PM_{10}, SO_2, NO_2 and CO in the residential areas is significantly different from the concentration of PM_{10}, SO_2, NO_2 and CO in the industrial areas of Port Harcourt. Similarly, the concentration of PM_{10}, SO_2, NO_2 and CO in the fringe/sub-urban areas is significantly different from the concentration of PM_{10}, SO_2, NO_2 and CO in the CBD and industrial areas of Port Harcourt. The findings of this study suggest that the lower atmosphere of Port Harcourt is polluted by gases and particulates, and that this is already affecting the quality of life and productivity of the people. This study thus recommends that governments have to implement many policy measures such as improving vehicular technology, revising traffic-management schemes, implementing stricter emission controls, introducing cleaner fuels, and promoting alternative fuels (CNG and LPG) to control atmospheric pollution.

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