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Tropospheric Assessment of Carbon Monoxide, Nitrogen Dioxide, and Aerosol in Port-Harcourt Metropolis, Rivers State, Southern Nigeria from 2019-2024

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ABSTRACT: Air pollution is a global environmental concern, particularly in urban and industrialized areas. Consequently, the objective of this paper is to assess the levels of tropospheric carbon monoxide (CO), nitrogen dioxide (NO_2), and aerosol in Port-Harcourt Metropolis, Rivers State, Southern Nigeria from 2019-2024 using the Sentinel-5 Precursor (Sentinel-5P) satellite data in Google Earth Engine (GEE) and other appropriate standard methods. The results revealed significant ($P<0.05$) temporal and spatial variations in pollutant concentrations, influenced by factors such as industrial activities, vehicular emissions, seasonal changes, and policy shifts, including the COVID-19 pandemic and fuel subsidy removal. CO levels peaked in the early months and declined in October across all years. NO□ concentrations followed a consistent pattern, peaking in December and reducing during the rainy season, highlighting the impact of meteorological factors. Aerosol concentrations were highest in dry-season months (January and February) and lowest in the rainy season, with a sharp reduction during the 2020 lockdown. Spatial analysis showed that pollution hotspots were concentrated in industrial zones such as Trans-Amadi, Diobu, and Borokiri. The study highlights the effectiveness of remote sensing in monitoring air quality and provides critical data for policymakers to implement sustainable air management strategies. It also highlights the urgent need for stricter environmental regulations and cleaner energy alternatives to mitigate the adverse effects of air pollution on human health and the environment.

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Globally, air quality has grown to be a serious environmental and public health concern, especially in urban and industrialized areas (Sicard *et al.,* 2023). Rapid urbanization, industrial growth, and rising vehicle emissions have all contributed to a major decline in air quality in emerging nations like Nigeria (Abaje *et al.,* 2020). One of the fastest-growing cities in Southern Nigeria is Port Harcourt, the capital of Rivers State, which is well-known for its industrial activity, especially in the oil and gas industry (Ugwu *et al.,* 2022). The city has seen extreme occurrences of air pollution in recent decades, which have been caused by both natural and man-made factors (Akinfolarin *et al.,* 2017). Air pollution in Port Harcourt is still a major problem in spite of several interventions and regulatory actions (Kanee *et al.,* 2021; Ojo and Sokari, 2022; Omisakin, 2022). High concentrations of CO, NO_2, and aerosols are common in the metropolis, having detrimental effects on the environment and human health (Stanley and Amesi,

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2021). Traditional air quality monitoring methods are restricted in their potential to produce complete data due to logistical and cost constraints. As a result, accurate and consistent data regarding the temporal and spatial distribution of important air pollutants are lacking. Increased industrial activity, urbanization, and the ongoing problem of illicit oil refining have all contributed to the declining air quality in the city (Kanee *et al.,* 2021). Nevertheless, little study has been done to track and examine changes in air quality using contemporary remote sensing equipment. The creation and execution of efficient air quality management policies are hampered by this data gap. In order to overcome these obstacles, this study evaluates the aerosol, NO_2, and CO concentrations in Port Harcourt using Sentinel-5P satellite data. The study intends to promote evidence-based decision-making and further the larger objective of enhancing environmental sustainability and health in the area by offering a thorough examination of air quality trends. Despite the known air pollution challenges in Port Harcourt, there has been a lack of comprehensive tropospheric air quality assessments, particularly for recent years. Pollutants, including aerosols, NO_2, and CO, have well-established negative health effects that have a big influence on everyone's health, especially the most susceptible. Studies using cutting-edge technologies like Sentinel-5P for air quality evaluation in Nigeria are limited, despite the seriousness of the problem. The shortcomings of ground-based monitoring systems are addressed by remote sensing, which provides an extensive, dependable, and reasonably priced way to monitor air quality. Hence, the objective of this paper is to assess the levels of tropospheric carbon monoxide (CO), nitrogen dioxide (NO_2), and aerosol in Port-Harcourt Metropolis, Rivers State, Southern Nigeria from 2019-2024. Policymakers, environmental organizations, and public health officials will find the results of this study useful in developing practicable plans to reduce air pollution.

MATERIALS AND METHODS

Study area: Port Harcourt in figure 1 is the capital city of Rivers State, Nigeria, and it is situated in the resource-rich Niger Delta region at roughly 4°45'N and 7°01'E (Ugwu *et al.,* 2022). The city is vulnerable to floods, especially during the rainy season, due to its low-lying topography and elevation of around 12 metres above sea level (Ugwu *et al.,* 2022). Sands, silts, and clays are among the sedimentary formations that make up the majority of the geology of Port Harcourt and are characteristic of the deltaic environment (Sam *et al.,* 2023). The abundance of organic matter in these sediments reflects the history of river discharge into the Atlantic Ocean (Sam *et al.,* 2023). There are distinct rainy and dry seasons in the tropical monsoon climate of Port Harcourt (Babatunde *et al.,* 2023). Heavy rainfall peaks in June and September during the wet season, which runs from April to October. This results in the 2,500 - 3,000 mm of precipitation that falls on average each year (Ugwu *et al.,* 2022). During the dry season, which runs from November to March, there is less rainfall and sporadic Harmattan winds. The average yearly temperature in the city is between 26°C and 28°C, and humidity is consistently high (Ekwe *et al.,* 2021). As a significant urban and economic center in the country, Port Harcourt has a high population density (Nsiegbe *et al.,* 2022). The oil and gas industry in Nigeria depends heavily on the city, which is home to refineries, large organizations, and a wide range of service providers (Wizor and Mpigi, 2020). Transportation, trade, agriculture, and manufacturing are further important economic sectors. These industries, along with Port Harcourt's expanding infrastructure, have made it one of the most important cities in Nigeria (Nsiegbe *et al.,* 2022).

Data type and source: Air pollution in Port Harcourt Metropolis was evaluated in this study utilizing Sentinel-5P remotely sensed data from the European Space Agency (ESA) database (ESA, 2019). The TROPOMI (Tropospheric Monitoring Instrument) sensor on the Sentinel-5P satellite provides high-resolution measurements of atmospheric pollutants, making it appropriate for air quality research (Guanter *et al.,* 2021; Okoduwa and Amaechi, 2023). Carbon monoxide (CO), nitrogen dioxide (NO_2), and aerosol were the parameters that were examined. To assess temporal trends and shifts in concentrations of the parameters, data from 2019 to 2024 were used. The Sentinel-5P datasets were chosen because of their high spatial resolution (ESA, 2019). The dataset for the analysis of these parameters is shown in Table 1. The vertical column densities of gases such as CO and NO_2 collected by Sentinel-5P and those measured at ground stations show a strong connection, as evidenced by the extensive validation of the data from the satellite against ground-based observations (Grzybowski *et al.,* 2023). High data quality and dependability were ensured by using only datasets with no cloud contamination. To make the processed data compatible with Geographic Information System (GIS) software and facilitate additional analysis, they were exported in GeoTIFF format.

Data analysis and presentation: The data were exported from GEE for additional analysis following pre-processing. ArcGIS 10.7.1 was used to process the exported data. For spatial analysis, the processed datasets (raster data in GeoTIFF format) were loaded into ArcGIS for visualization. The distribution of NO_2, CO, and aerosol in Port Harcourt for each year was displayed on spatial maps created from the processed data in ArcGIS using various colour codes (red, yellow, and green) and classes (red for high, yellow for medium, and green for low).

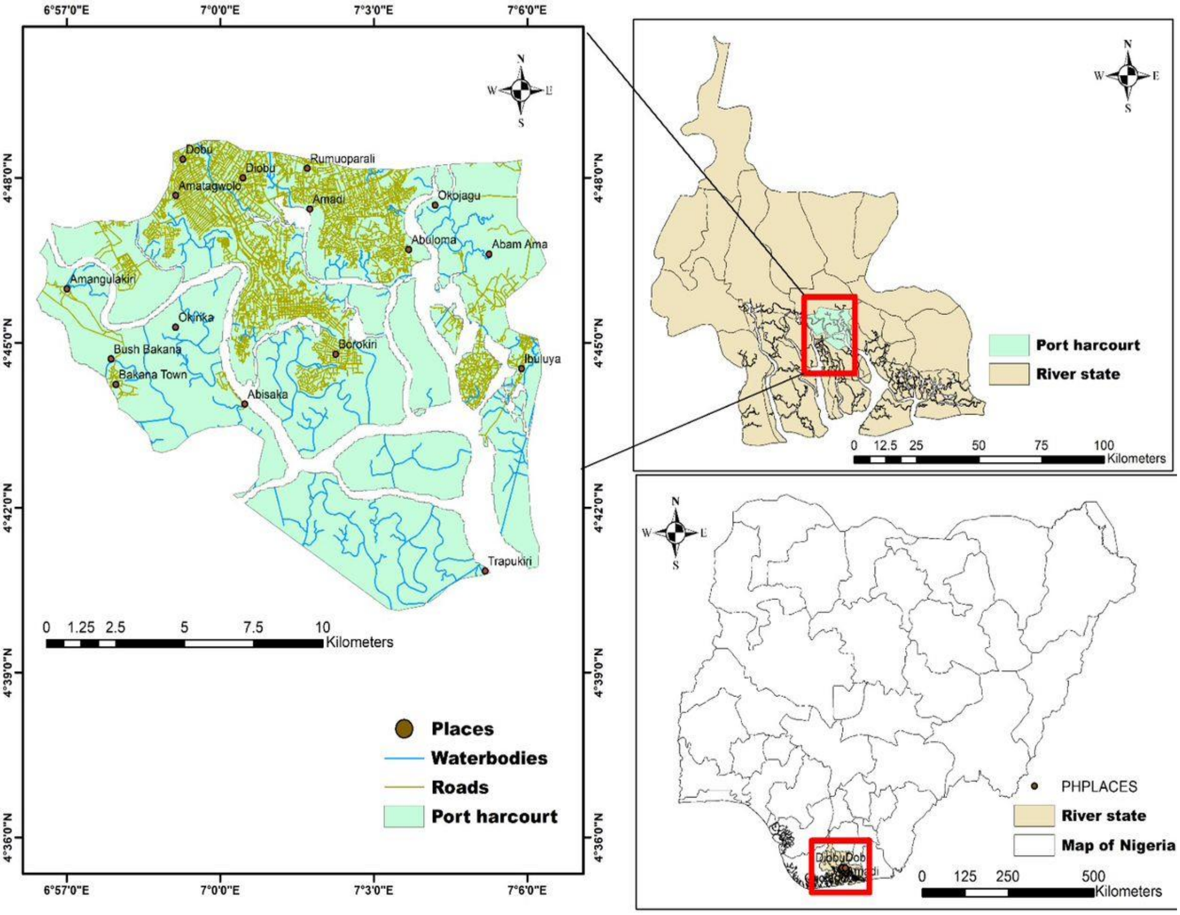

Fig. 1: Map of the study area

SPSS was used to compute a paired sample t–test. Paired sample t-test was used for further analysis because it compares the concentration of parameters between consecutive years while accounting for their dependence on each other. Paired sample t-test allows for assessing the year-to-year variations between CO, NO_2, and aerosol levels and whether they were statistically significant.

The parameters in this study were chosen because they are the primary indicators of urban air quality and are directly linked to major emission sources in Port Harcourt. CO, NO_2, and aerosols directly capture the impact of the most significant sources of emissions in Port Harcourt: vehicular traffic, industrial processes mostly from petroleum processing facilities, and waste burning.

The study focuses on the period from 2019 to 2024 because Sentinel-5P datasets, which provide high-resolution atmospheric pollution data, became fully available in 2019 as listed in the data catalog of Google Earth Engine.

The trend of the concentration levels of parameters over time was examined using Microsoft Excel. Tables and graphs were made to show how the concentrations of parameters changed over the course of six years. The methodology flowchart for this is shown in Figure 2.

Fig. 2: Methodology flowchart

Table 1: Dataset for analysis of parameters

Band name	Dataset	Unit	Min	Max	Description
CO_column_number_density	OFFL/L3_CO	mol/m^2	-34.43	5.71	Vertically integrated CO column density
NO_2_column_number_density	OFFL/L3_NO_2	mol/m^2	-0.00051	0.0192	Total vertical column of NO_2 (ratio of the slant column density of NO_2 and the total air mass factor).
Absorbing_aerosol_index	OFFL/L3_AER_AI	-	-21	39	A measure of the prevalence of aerosols in the atmosphere.

RESULTS AND DISCUSSION

Carbon Monoxide (CO) Results Presentation: Table 2 presents the annual minimum, maximum, mean, and standard deviation for CO concentration across the years. The highest maximum CO concentration occurred in 2020, supporting the hypothesis that emissions peaked before lockdown. 2023 had the lowest mean, aligning with subsidy removal effects, while 2024 recorded the highest mean, suggesting emissions are on the rise again. Figure 3 shows the trend of mean CO concentrations over the years. There was a noticeable peak in 2020, which may be due to emissions before the COVID-19 lockdown. The slight decline in 2021 and 2022 suggests partial recovery. 2023 recorded the lowest mean, reflecting the impact of fuel subsidy removal, but 2024 saw an increase, indicating a possible rebound in fuel use and emissions.

Monthly Distribution of CO: Table 3 depicts the monthly concentrations for CO for each year, along with the mean and standard deviation. In 2019, the highest CO concentration was recorded in February at 0.071 mol/m^2, while the lowest was in October at 0.037 mol/m^2. The mean concentration for the year was 0.0489 mol/m^2, with a standard deviation of 0.0109 mol/m^2, indicating moderate variations throughout the year. For 2020, February again had the highest concentration at 0.078 mol/m^2, while October had the lowest at 0.036 mol/m^2. The mean CO concentration was 0.0521 mol/m^2, and the standard deviation increased to 0.0130 mol/m^2, showing a larger variation compared to 2019. The spike in February suggests high emissions before the COVID-19 lockdown, whereas the decline in October aligns with reduced industrial activities and limited transportation. In 2021, the highest concentrations were observed in January and February, both at 0.067 mol/m^2, while October recorded the lowest value at 0.037 mol/m^2. The mean for the year was 0.0508 mol/m^2, and the standard deviation was 0.0102 mol/m^2, reflecting relatively stable emissions throughout the year. For 2022, January had the highest concentration at 0.067 mol/m^2, while October recorded the lowest at 0.035 mol/m^2. The mean was 0.0494 mol/m^2, with a standard deviation of 0.0111 mol/m^2. This indicates a gradual return to normal emissions patterns following the pandemic, but still lower than the peak levels of 2020. In 2023, the highest values were recorded in January and February at 0.063 mol/m^2, while May and October had the lowest at 0.037 mol/m^2. The mean CO concentration dropped to 0.0476 mol/m^2, the lowest in the observed period, with a standard deviation of 0.0094 mol/m^2. The reduction may be linked to the removal of the fuel subsidy, which likely caused changes in fuel consumption patterns, leading to lower emissions.

Table 2: Annual concentration of CO for 2019, 2020, 2021, 2022, 2023 and 2024

CO	2019	2020	2021	2022	2023	2024
Minimum	0.0481	0.0542	0.509	0.0497	0.0470	0.0538
Maximum	0.0521	0.0569	0.0533	0.0518	0.0501	0.0559
Mean	0.0505	0.0559	0.0520	0.0508	0.0489	0.0549
Standard Deviation	0.000918	0.000571	0.000541	0.000489	0.000849	0.00045

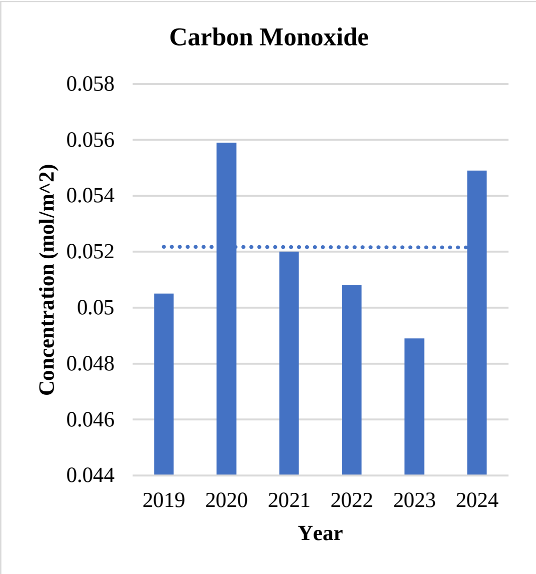

Fig 3: Trend showing annual concentration of CO (2019-2024)

Table 3: Monthly concentration of CO for 2019, 2020, 2021, 2022, 2023, and 2024

Months	2019	2020	2021	2022	2023	2024
January	0.066	0.07	0.067	0.067	0.063	0.065
February	0.071	0.078	0.067	0.066	0.063	0.073
March	0.056	0.066	0.058	0.06	0.053	0.061
April	0.046	0.048	0.048	0.048	0.044	0.045
May	0.039	0.042	0.04	0.037	0.039	0.047
June	0.044	0.042	0.042	0.038	0.039	0.045
July	0.045	0.045	0.052	0.046	0.043	0.053
August	0.044	0.05	0.052	0.051	0.051	0.059
September	0.04	0.041	0.042	0.041	0.038	0.044
October	0.037	0.036	0.037	0.035	0.037	0.041
NOVEMBER	0.043	0.05	0.045	0.046	0.045	0.048
DECEMBER	0.056	0.057	0.059	0.058	0.056	0.06
Mean	0.0489	0.0521	0.0508	0.0494	0.0476	0.0534
Standard deviation	0.0109	0.0130	0.0102	0.0111	0.0094	0.0100

For 2024, February had the highest concentration at 0.073 mol/m^2, while October had the lowest at 0.041 mol/m^2. The mean concentration increased to 0.0534 mol/m^2, with a standard deviation of 0.0100 mol/m^2. The rise in CO levels compared to 2023 suggests adjustments in transportation and fuel use post-subsidy removal.

Spatial variations of CO concentration across the study years (2019-2024): The spatial variation of CO concentration in Figure 4 reveals that in 2019, Diobu, located in the north-western part of Port Harcourt, had the highest concentration of carbon monoxide at 0.0521 mol/m². CO had moderate concentrations across the central region of Port Harcourt, which includes Old Bakana and Borokiri. The lowest concentration was found in the southern parts of Port Harcourt, at 0.0542 mol/m². The spatial variation of CO concentration in Figure 5 shows that in 2020, the variation closely followed that of 2019.

Diobu, located in the north-western part of Port Harcourt, had the highest concentration of carbon monoxide at 0.0569 mol/m², while CO had moderate concentrations across the central region, which includes Borokiri and Trans Amadi. The lowest concentration was again located in the southern parts of Port Harcourt, at 0.0542 mol/m².

In Figure 6, the spatial variation of CO concentration for 2021 shows that Diobu, in the north-western part of Port Harcourt, had the highest concentration of carbon monoxide at 0.0533 mol/m². CO had moderate concentration spread across the central region, including Port Harcourt City. The lowest concentration was found in the southern parts of Port Harcourt, at 0.0509 mol/m². The spatial variation of CO concentration in Figure 7 for 2022 shows that Okrika, located in the eastern part of Port Harcourt, and Borokiri in the central part, had the highest concentration of carbon monoxide at 0.0518 mol/m².

CO had moderate concentrations spread evenly across the northern and central regions, including Port Harcourt City, Transamadi, and Diobu. The lowest concentration was in the southern parts of Port Harcourt, at 0.0497 mol/m². Figure 8 shows that in 2023, the highest concentration was spread across Diobu, in the north-western part of Port Harcourt, and Transamadi, in the eastern part, with a concentration of 0.0501 mol/m². CO had moderate concentration evenly distributed across the central region, including Borokiri and Old Bakana.

The lowest concentration was located in the southern parts of Port Harcourt, at 0.0470 mol/m². Finally, the spatial variation of CO concentration in Figure 9 for 2024 shows that Diobu, located in the north-western part of Port Harcourt, had the highest concentration of carbon monoxide at 0.0559 mol/m².

CO had a moderate concentration spread evenly across the central region, including Port Harcourt City and Borokiri. The lowest concentration was found in the southern parts of Port Harcourt, at 0.0538 mol/m².

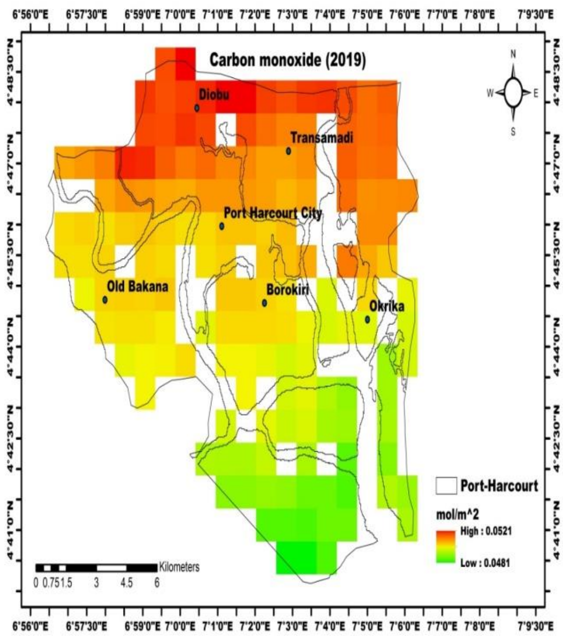

Fig.4: Map showing CO concentration for Port-Harcourt in 2019

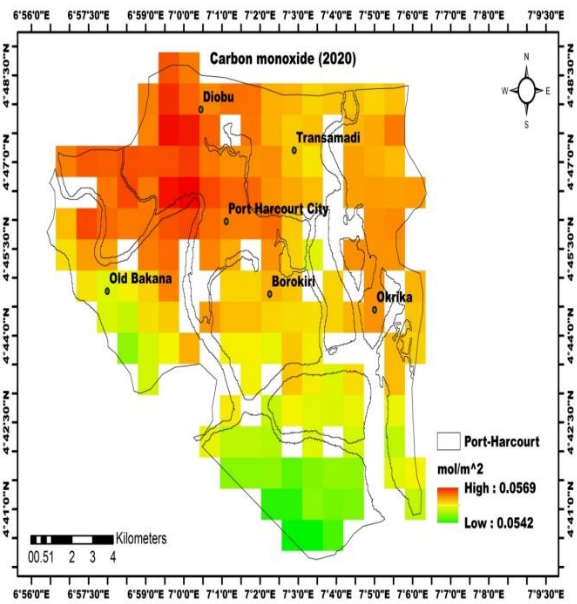

Fig. 5: Map showing CO concentration for Port Harcourt in 2020

CO distribution in Port-Harcourt across the study years: Analysis of the data provided in Table 3 reveals significant patterns in CO concentrations from 2019 to 2024, with distinct peaks corresponding to various factors, including seasonal variations, economic activities, and external events such as the COVID-19 pandemic and the removal of fuel subsidies. This study examines the highest and lowest CO concentrations annually, as well as their corresponding means and standard deviations, providing insight into emission trends and variability.

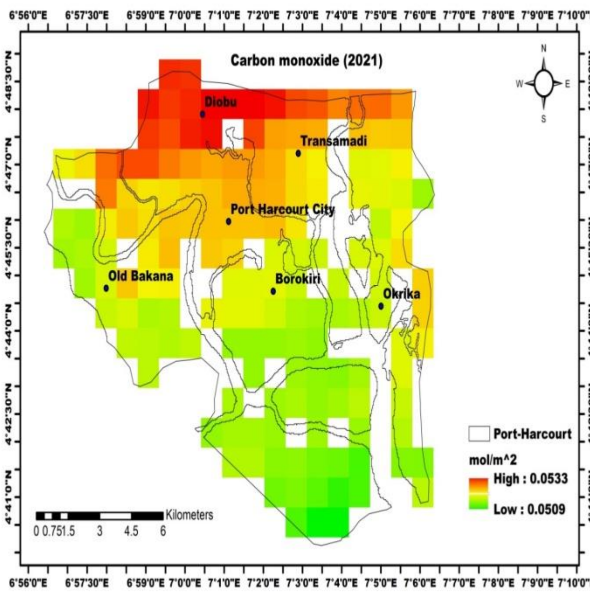

Fig. 6: Map showing CO concentration for Port Harcourt in 2021

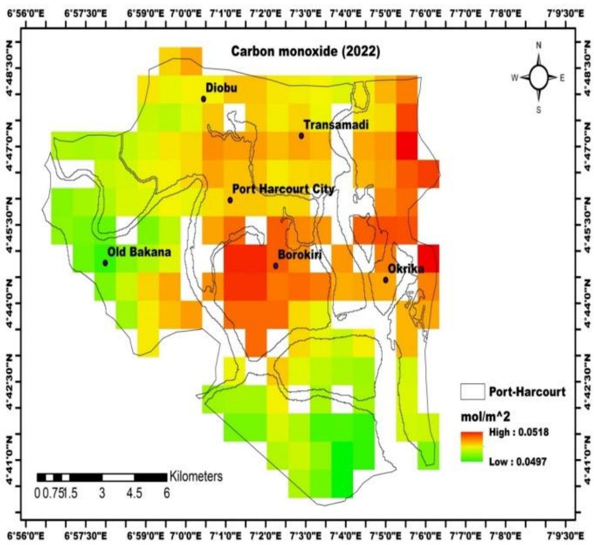

Fig. 7: Map showing CO concentration for Port Harcourt in 2022

In 2019, the highest CO concentration was recorded in February at 0.071 mol/m^2, while the lowest concentration occurred in October at 0.037 mol/m^2. The annual mean concentration was 0.0489 mol/m^2, and the standard deviation stood at 0.0109 mol/m^2, indicating moderate fluctuations in CO levels throughout the year. This variability may be attributed to the seasonal variations in temperature and traffic patterns, as colder months often see an increase in heating and industrial activities, which in turn could lead to higher emissions. A study done in Benin City by Okodwua and Amaechi in 2023 shows that meteorological conditions and seasonal variations can have an influence on the distribution of CO. However, the emissions remained relatively stable during the year, with no significant spikes or drops (Okodwua and Amaechi, 2023).

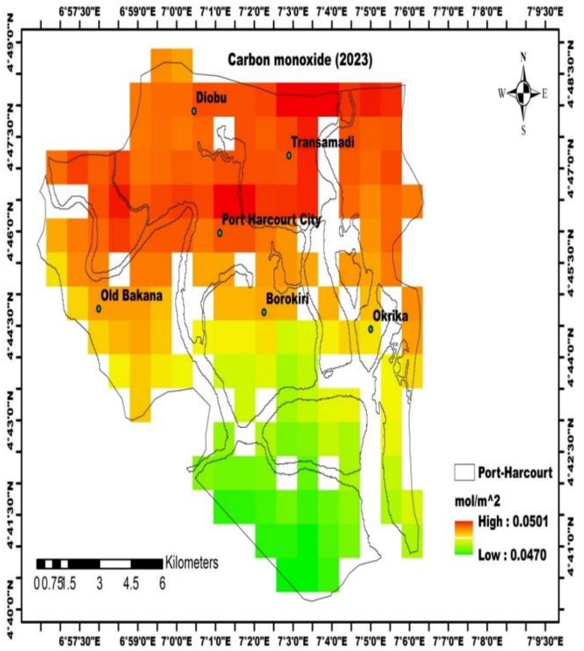

Fig. 8: Map showing CO concentration for Port Harcourt in 2023.

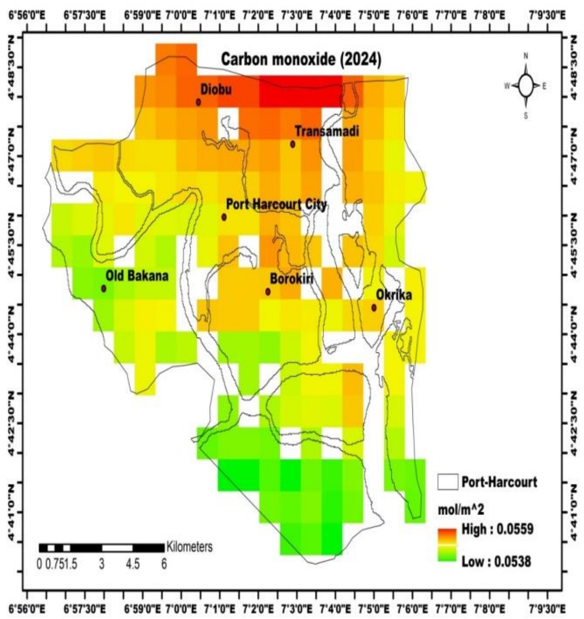

Fig. 9: Map showing CO concentration for Port Harcourt in 2024

In 2020, the highest concentration again occurred in February at 0.078 mol/m^2, while October had the lowest value at 0.036 mol/m^2. The mean CO concentration for the year rose slightly to 0.0521 mol/m^2, and the standard deviation increased to

0.0130 mol/m^2. This increase in variation can be largely attributed to the impacts of the COVID-19 pandemic, which began in early 2020 (Amaechi *et al.*, 2024). The spike in February suggests a peak in emissions before lockdown measures were enforced, potentially due to high levels of industrial activity and transportation. The significant decline in CO levels by October coincided with global lockdowns, where reduced economic activities, travel restrictions, and halted industrial operations led to a sharp decrease in emissions (Amaechi *et al*., 2023). This phenomenon, while drastic, reflects the sudden changes in pollution levels caused by a global health crisis. In 2021, both January and February recorded the highest CO concentrations at 0.067 mol/m^2, while October continued to exhibit the lowest levels at 0.037 mol/m^2. The mean concentration for the year was 0.0508 mol/m^2, with a standard deviation of 0.0102 mol/m^2. This relatively stable pattern of emissions could reflect the gradual reopening of economies and resumption of industrial activities following the initial wave of the pandemic. The seasonal peaks in early months align with typical winter increases in CO emissions, particularly in regions where heating demands rise (Atoui *et al.*, 2022). The lower CO levels in October suggest that emissions were still affected by lingering pandemic restrictions and shifts in economic behaviors (Lorente *et al*., 2019). For 2022, January once again marked the highest CO concentration at 0.067 mol/m^2, and October had the lowest at 0.035 mol/m^2. The mean for the year was 0.0494 mol/m^2, with a standard deviation of 0.0111 mol/m^2. These figures suggest a return to a more typical emission patterns post-pandemic, although still lower than the levels recorded in the pre-pandemic years. This pattern likely reflects the stabilization of industrial activities and transportation systems, which had previously been curtailed by COVID-19 measures. However, emissions had not fully returned to the levels seen in 2020, indicating the lasting effects of the pandemic on global supply chains and fuel consumption (Davis *et al*., 2022).

In 2023, the highest CO concentrations were recorded in January and February at 0.063 mol/m^2, while both May and October had the lowest levels at 0.037 mol/m^2. The mean concentration dropped to 0.0476 mol/m^2, the lowest observed during the entire period, and the standard deviation was the smallest at 0.0094 mol/m^2. The reduction in CO emissions in 2023 may be attributed to the removal of the fuel subsidy, a policy change that likely led to alterations in fuel consumption patterns (Amaechi *et al*., 2024). Higher fuel prices typically lead to reduced demand for transportation and industrial fuels, consequently lowering emissions. This decrease is also consistent with global efforts to address climate change and promote cleaner energy alternatives (Kazemi-Garajeh *et al.*, 2023). In 2024, February saw the highest CO concentration at 0.073 mol/m^2, while October recorded the lowest at 0.041 mol/m^2. The mean concentration increased to 0.0534 mol/m^2, with a standard deviation of 0.0100 mol/m^2, suggesting that emissions began to rise again compared to 2023. This increase may be a result of adjustments in transportation behaviors and fuel consumption following the removal of fuel subsidies, which could have influenced both industrial activities and personal vehicle use (Amaechi *et al*., 2023). While emissions remained higher than in 2023, they were still not at pre-pandemic levels, indicating a period of adjustment and adaptation (Behera *et al.*, 2022). Overall, the analysis of CO concentrations over these six years reflects a complex interplay of seasonal changes, the COVID-19 pandemic, and economic policy shifts, particularly the removal of fuel subsidies. While there were fluctuations, the overall trend suggests a decrease in emissions from 2020 to 2023, likely influenced by reduced human activity during the pandemic and adjustments in fuel consumption thereafter (Amaechi *et al.*, 2023). However, the increasing levels in 2024 suggest that the full impact of these shifts has yet to stabilize, and further changes in environmental policy may continue to influence emission trends in the years to come.

The oil and gas sector is a major contributor to CO emissions in Port Harcourt due to activities such as gas flaring, refining, and fuel combustion. Gas flaring, which involves the burning of excess gas during crude oil extraction, is a significant source of CO, carbon dioxide (CO_2), and other greenhouse gases (Blundell and Kokoza, 2022). Despite regulatory efforts, gas flaring remains prevalent in the Niger Delta region, releasing harmful pollutants into the atmosphere and affecting air quality in surrounding urban areas, including Port Harcourt (Ehumadu *et al*., 2021). Additionally, refineries and petrochemical plants in Transamadi and other industrial zones release CO and other pollutants through their combustion processes, further exacerbating air pollution (Ukoha-Onuoha and Kewve, 2023). Vehicular emissions are another significant source of CO pollution in Port Harcourt. The city experiences heavy traffic congestion, especially in commercial and industrial areas like Diobu, where thousands of vehicles operate daily. Incomplete combustion of fuel in motor vehicles produces CO, which accumulates in densely populated areas with poor ventilation and limited green spaces (Nasirov *et al*., 2023). The high CO concentration recorded in Diobu from 2019 to 2024 can be attributed to the combination of vehicular emissions and nearby industrial activities. The spatial distribution of carbon monoxide (CO) concentration in Port Harcourt from 2019 to 2024 highlights a persistent trend of high pollution levels in industrial and high-traffic areas, particularly Diobu, Transamadi, and Borokiri, which are known for their proximity to oil and gas activities. Port Harcourt serves as a major hub for Nigeria's petroleum industry, housing numerous refineries, petrochemical plants, and offshore servicing companies, all of which contribute significantly to air pollution (Zabbey *et al*., 2021). The burning of fossil fuels, gas flaring, and industrial emissions release large quantities of CO into the atmosphere, exacerbating air quality issues in the region (Ukhurebor *et al*., 2024). The high CO levels in Diobu, which recorded concentrations as high as 0.0569 mol/m² in 2020, can be linked to both industrial activities and vehicular emissions, as the area is densely populated and experiences significant traffic congestion (Zabbey *et al*., 2021). Similarly, Transamadi, home to one of the largest industrial layouts in the city, has seen rising CO levels, particularly from 2022 onward, coinciding with industrial expansion (Ugada and Momoh, 2022). In contrast, the southern parts of Port Harcourt, consistently recording the lowest CO concentrations, are farther from major industrial activities and traffic hotspots, which explains the comparatively cleaner air in those regions (Mahmud *et al*., 2023). Prolonged exposure to high CO levels poses severe health risks, including respiratory and cardiovascular diseases, which have been increasingly reported in Port Harcourt due to air pollution (Zabbey *et al*., 2021).

Table 4: Annual concentration of NO_2 for 2019, 2020, 2021, 2022, 2023 and 2024.

NO_2	2019	2020	2021	2022	2023	2024
Minimum	0.0000590	0.0000598	0.0000625	0.0000647	0.0000598	0.0000614
Maximum	0.0000774	0.0000815	0.0000876	0.0000869	0.0000804	0.0000832
Mean	0.0000661	0.0000684	0.0000724	0.0000729	0.0000692	0.0000708
Standard Deviation	0.00000522	0.00000629	0.00000732	0.00000618	0.00000562	0.0000598

Nitrogen Dioxide (NO_2) Results Presentation: Table 4 shows that 2021 had the highest mean NO_2level, while 2023 had the lowest mean. The fluctuations in standard deviation indicate varying levels of emissions control over the years. The table presents the concentration of nitrogen dioxide (NO_2) from 2019 to 2024, showing minimum, maximum, mean, and standard deviation values for each year. The data indicate a general increase in NO_2 concentration over time, with the mean values rising from 0.0000661 mol/m² in 2019 to 0.0000708 mol/m² in 2024, suggesting a gradual increase in pollution levels. The maximum concentration follows a similar trend, peaking in 2022 (0.0000869 mol/m²) before slightly decreasing in 2023 and 2024. The standard deviation values suggest variations in NO_2 levels, with 2021 exhibiting the highest variability (0.0000732 mol/m²) and 2023 showing a decrease (0.0000562 mol/m²), indicating more stable NO_2 levels in that year. The trend implies potential environmental or anthropogenic influences, such as increased industrial activities or vehicular emissions, contributing to the observed changes. This pattern highlights the need for continuous air quality monitoring and potential regulatory interventions to mitigate NO_2 pollution.

Figure 10 shows fluctuations in NO_2 levels, with a clear dip in 2020 during the COVID-19 lockdown. Post-pandemic recovery is visible in 2021 and 2022, followed by a slight reduction in 2023, potentially due to the fuel subsidy removal. The increase in 2024 suggests a gradual return to previous emissions levels.

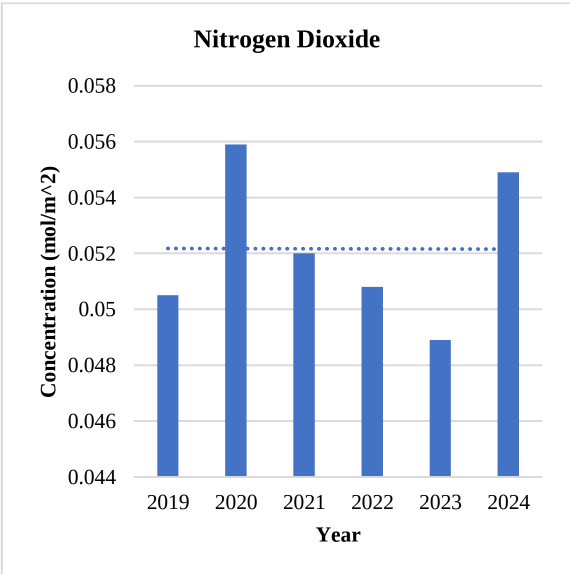

Fig. 10: Trend showing annual concentration of NO□ ($N0_2$) (2019-2024)

Monthly distribution of NO_2: Table 5 depicts the month with the highest and lowest NO_2 concentrations for each year. In 2019, December had the highest concentration at 0.000085 mol/m², while August had the lowest at 0.000048 mol/m². The mean for the year was 0.000065875 mol/m², with a standard deviation of 1.49233E-05 mol/m². For 2020, December recorded the highest concentration at 0.000092 mol/m², while April had the lowest at 0.000057 mol/m². The mean was 6.82917E-05 mol/m², with a standard deviation of 1.61309E-05 mol/m². The lower NO_2 values in March and April align with COVID-19 lockdown effects, where reduced traffic led to cleaner air. In 2021, December had the highest concentration at 0.0001 mol/m², while August recorded the lowest at 0.000053 mol/m². The mean was 7.21667E-05 mol/m², with a standard deviation of 1.33512E-05 mol/m². For 2022, the highest NO_2 concentration was in December at 0.000103 mol/m², while June had the lowest at 0.000059 mol/m². The mean was 7.39167E-05 mol/m², with a standard deviation of 1.39721E-05 mol/m². In 2023, December again recorded the highest concentration at 0.0000975 mol/m², while June had the lowest at 0.0000525 mol/m². The mean was 6.83333E-05 mol/m², with a standard deviation of 1.32952E-05 mol/m². For 2024, the highest concentration was in December at 0.000095 mol/m², while August had the lowest at 0.000047 mol/m². The mean was 0.000070875 mol/m², with a standard deviation of 1.55439E-05 mol/m².

Table 5: Monthly concentration of NO_2 for 2019, 2020, 2021, 2022, 2023 and 2024.

Year/Months	2019	2020	2021	2022	2023	2024
January	0.000076	0.000088	0.00009	0.000094	0.000097	0.0001
February	0.000095	9.75E-05	0.00009	0.000093	0.000082	0.000084
March	0.00008	0.000079	0.000079	0.00008	6.15E-05	0.00007
April	6.25E-05	0.000057	0.000068	0.000069	0.000061	0.000065
May	0.000056	0.000054	0.000057	0.00007	0.000061	0.000067
June	0.000053	0.00006	0.000062	0.000059	5.25E-05	0.000064
July	0.000053	0.000053	0.000056	0.000057	0.00006	0.000053
August	0.000048	0.000052	0.000053	0.000053	0.000057	0.000047
September	0.000055	0.000051	0.000061	0.000068	0.000055	0.000055
October	0.000053	0.000061	0.00007	0.000061	6.25E-05	0.000066
November	0.000074	0.000075	0.00008	0.00008	0.000073	8.45E-05
December	0.000085	0.000092	0.0001	0.000103	9.75E-05	0.000095
Mean	6.59E-05	6.83E-05	7.22E-05	7.39E-05	6.83E-05	7.09E-05
Standard deviation	1.49E-05	1.61E-05	1.34E-05	1.40E-05	1.33E-05	1.55E-05

Spatial variations of NO_2 concentration across the study years (2019-2024): The spatial variation of NO_2 concentration in Figure 11 reveals that in 2019, Diobu, located in the northwestern part of Port Harcourt, had the highest concentration of nitrogen dioxide at 0.0000774mol/m². NO_2 had moderate concentration across the central region of Port Harcourt, including Port Harcourt City and Borokiri.

The lowest concentration was found in the southern parts of Port Harcourt, at 0.0000590mol/m². The spatial variation of NO_2 concentration in Figure 12 shows that in 2020, the NO_2 distribution was similar to 2019, with a high concentration of 0.0000815mol/m² and a low concentration of 0.0000598mol/m². Figure 13 reveals that in 2021, the NO_2 distribution was similar to that of 2019 and 2020, with a high concentration of 0.0000876mol/m² and a low concentration of 0.0000623mol/m².

The spatial variation of NO_2 concentration in Figure 14 shows that in 2022, the distribution remained similar to previous years (2019, 2020, and 2021), with a high concentration of 0.0000869mol/m² and a low concentration of 0.0000647mol/m². In Figure 15, the spatial variation of NO_2 concentration for 2023 shows a similar distribution to 2019, 2020, 2021, and 2022, with a high concentration of 0.0000804 mol/m² and a low concentration of 0.0000598mol/m².

Finally, the spatial variation of NO_2 concentration in Figure 16 for 2024 shows a distribution similar to that of the previous years (2019 to 2023), with a high concentration of 0.0000832mol/m² and a low concentration of 0.0000614 mol/m².

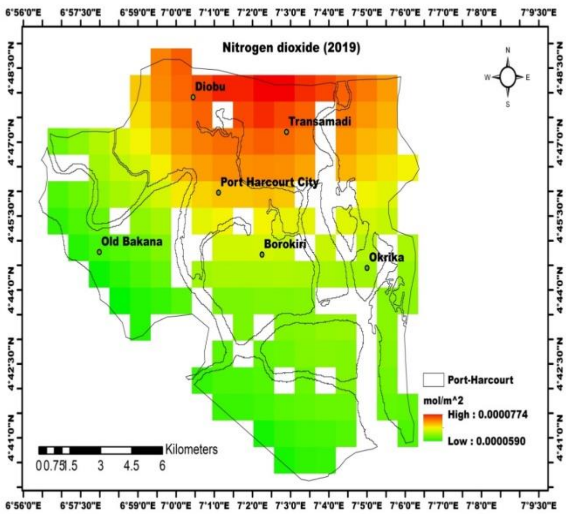

Fig. 11: Map showing NO_2 concentration for Port Harcourt in 2019

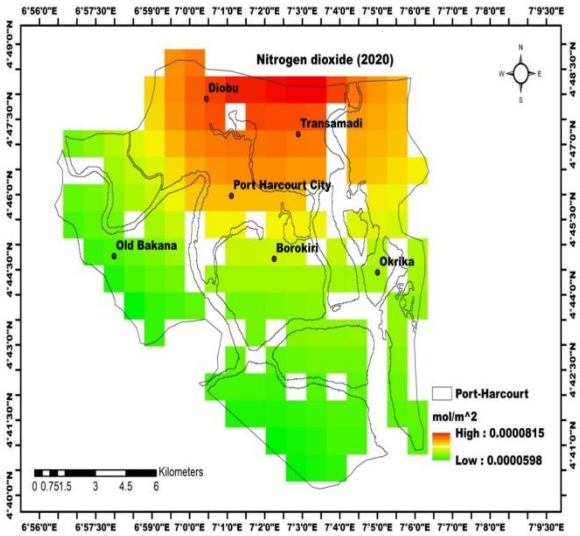

Fig. 12: Map showing NO_2 concentration for Port Harcourt in 2020

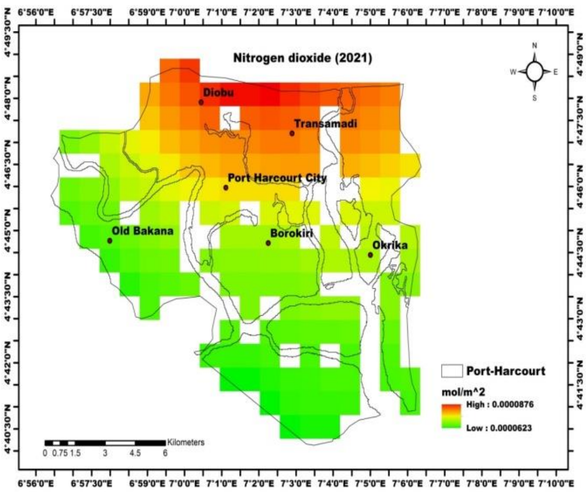

Fig. 13: Map showing NO_2 concentration for Port Harcourt in 2021

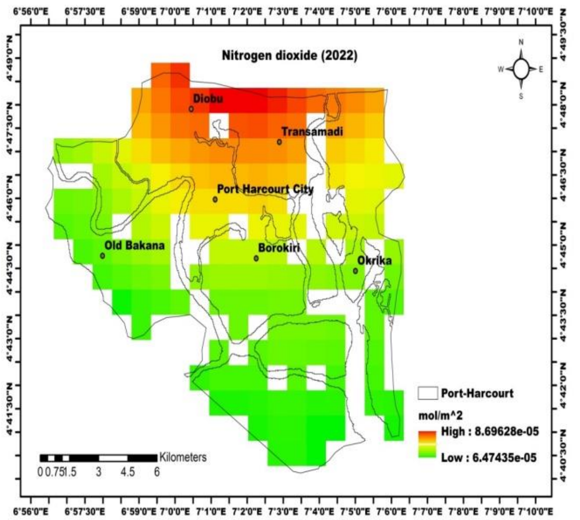

Fig. 14: Map showing NO_2 concentration for Port Harcourt in 2022

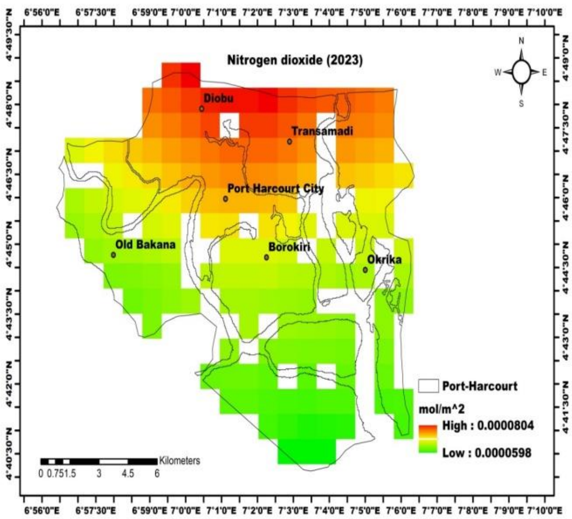

Fig. 15: Map showing NO_2 concentration for Port Harcourt in 2023

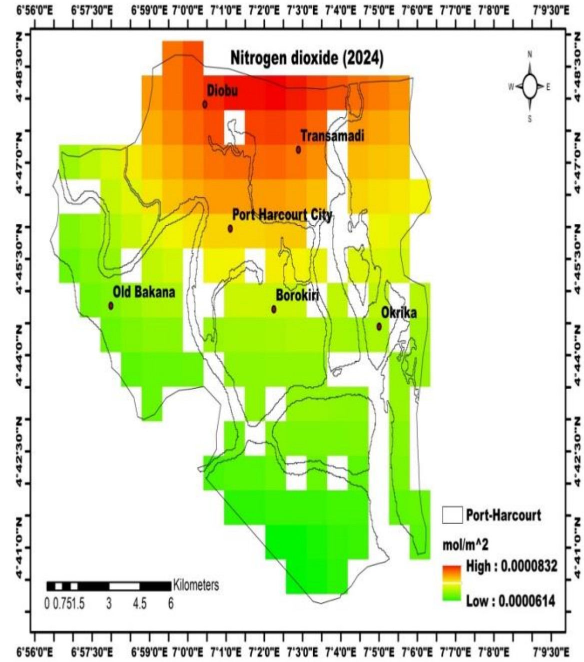

Fig. 16: Map showing NO_2 concentration for Port Harcourt in 2024

NO_2 distribution in Port-Harcourt across the study years: NO_2 is a significant air pollutant that poses serious environmental and health risks, particularly in highly industrialized and urban areas such as Port Harcourt. The analysis of NO_2 distribution from 2019 to 2024 highlights clear seasonal trends, with consistently high concentrations recorded in December and lower values observed in mid-year months such as June, April, and August. This pattern indicates that emissions from industrial activities, vehicular traffic, and meteorological conditions play a crucial role in NO_2 distribution across the city. The presence of oil and gas industries, particularly in

areas like Trans-Amadi and Diobu, significantly contributes to high NO_2 levels, making it essential to assess the sources, trends, and implications of this pollutant. From the annual analysis, it is evident that NO_2 levels peak in December, a trend observed consistently from 2019 to 2024. For instance, in 2019, December recorded the highest concentration at 0.000085 mol/m², while August had the lowest at 0.000048 mol/m². Similarly, in 2020, the highest NO_2 levels were in December (0.000092 mol/m²), while April recorded the lowest at 0.000057 mol/m². The trend continued in subsequent years, with December recording peak levels each year, reaching 0.000103 mol/m² in 2022 and 0.000095 mol/m² in 2024. This recurring pattern suggests that dry-season conditions favor NO_2 accumulation due to reduced atmospheric dispersion and increased industrial emissions. Conversely, the lowest concentrations were observed during the mid-year months, particularly in April, June, and August. For instance, in 2023, the lowest NO_2 concentration was recorded in June (0.0000525 mol/m²), a trend similar to 2022 and 2021, where June and August had the lowest values, respectively. This decrease in NO_2 levels during these months can be attributed to increased rainfall, which helps wash pollutants out of the atmosphere, reducing their concentration in the air.

One of the primary sources of NO_2 in Port Harcourt is emissions from industrial activities and vehicular traffic. The city is home to several oil and gas processing facilities, refineries, and petrochemical plants, which release large amounts of NO_2 into the atmosphere through fossil fuel combustion (Ugada and Momoh, 2022). Studies have shown that the Trans-Amadi industrial layout is a major hotspot for air pollution, including NO_2, due to the high concentration of industries and heavy machinery operating in the area. Vehicular emissions also contribute significantly to NO_2 pollution in Port Harcourt. The high number of vehicles, coupled with traffic congestion in areas such as Diobu and the central business district, leads to increased NO_2 emissions from the combustion of gasoline and diesel fuels. Research has shown that road transport is one of the leading contributors to NO_2 pollution, particularly in urban environments where traffic density is high (Amaechi *et al*., 2023). Seasonal variations play a crucial role in NO_2 distribution, with higher concentrations recorded during the dry season (November to February) and lower levels during the rainy season (April to August). The increase in NO_2 levels during the dry season is linked to reduced atmospheric dispersion and lower humidity, which allows pollutants to accumulate in the air. On the other hand, the rainy season helps cleanse the atmosphere by removing airborne pollutants through precipitation, leading to lower NO_2 levels during months like June and August. A significant decrease in NO_2 concentration was observed in March and April 2020, coinciding with the COVID-19 lockdown period. This decline was primarily due to restrictions on movement and industrial activities, which led to reduced vehicular emissions and lower industrial output. Studies have reported similar trends in other Nigerian cities, where air pollution levels significantly dropped during the lockdown due to decreased human activities (Okoduwa and Amaechi, 2023). However, NO_2 levels quickly rebounded after the lockdown restrictions were lifted, highlighting the strong influence of human activities on air pollution.

The spatial distribution of NO_2 concentrations in Port Harcourt reveals that pollution levels are highest in industrial and high-traffic areas. According to GIS-based studies, hotspots for NO_2 pollution include Trans-Amadi, Diobu, and Borokiri, where industrial emissions and vehicular traffic are concentrated. These areas consistently record higher NO_2 concentrations compared to the southern parts of the city, which have lower industrial activity and less traffic congestion. Prolonged exposure to high NO_2 concentrations poses significant health risks, particularly respiratory illnesses such as asthma, chronic bronchitis, and reduced lung function. NO_2 is known to irritate the respiratory system and can lead to increased hospital admissions for respiratory conditions (Blundell and Kokoza, 2022). Vulnerable populations, including children, the elderly, and individuals with pre-existing respiratory conditions, are particularly at risk. Beyond health impacts, NO_2 also contributes to environmental degradation. High concentrations of NO_2 are a precursor to acid rain, which can damage soil, water bodies, and vegetation (Nicholas and Ukoha, 2022). Additionally, NO_2 plays a role in the formation of ground-level ozone and particulate matter, further worsening air quality and contributing to climate change (Ilaboya *et al.,* 2024)..
Aerosol results presentation: Table 6 shows that 2019 had the lowest minimum value, while 2024 recorded the highest maximum value. The increase in aerosol levels in 2024 suggests a resurgence in emissions. The table presents aerosol concentration levels from 2019 to 2024, showing minimum, maximum, mean, and standard deviation values for each year. The data indicate that aerosol concentrations were predominantly negative from 2019 to 2021, with the mean values being -0.6291 in 2019, -0.7728 in 2020, and -0.5712 in 2021. However, from 2022 onward, there is a shift towards positive values, with the mean reaching 0.0202 in 2024. This transition suggests a significant change in aerosol composition,

measurement methods, or atmospheric conditions. The standard deviation values indicate variations in aerosol levels, with the highest variability observed in 2020 (0.0704) and the lowest in 2022 (0.0529), implying fluctuations in emissions or environmental conditions. The shift from negative to positive values may indicate an improvement in air quality, changes in pollution sources, or seasonal variations affecting aerosol distribution.

Table 6: Annual concentration of aerosol for 2019, 2020, 2021, 2022, 2023 and 2024

Aerosol	2019	2020	2021	2022	2023	2024
Minimum	-0.7082	-0.08732	-0.6728	-0.0653	-0.1582	-0.08352
Maximum	-0.4955	-0.6004	-0.4315	0.1387	0.0670	0.1477
Mean	-0.6291	-0.7728	-0.5712	0.0183	-0.0706	0.0202
Standard Deviation	0.0556	0.0704	0.0594	0.0529	0.0593	0.0532

Figure 17 illustrates significant drops sharply in 2020 due to the COVID-19 lockdown that restricted transportation, industrial activities, and human movement. A gradual increase is evident in 2021 and 2022, while 2023 saw a temporary drop and decline due to the fuel subsidy removal, which resulted in decreased fuel consumption. The rise in 2024 suggests increased fuel use and emissions as economic activities adjusted to fuel price changes.

Monthly distribution of aerosol: Table 7 depicts the month with the highest and lowest aerosol concentrations for each year, along with the mean and standard deviation. In 2019, February recorded the highest aerosol concentration at 0.367, while September had the lowest at -1.205. The mean was -0.6262, with a standard deviation of 0.4911. For 2020, February had the highest value at 0.704, while April had the lowest at -1.022. The mean was -0.7661, and the standard deviation was 0.6690. The significant drop in aerosol levels in April aligns with the COVID-19 lockdown. In 2021, December recorded the highest concentration at 0.828, while May had the lowest at -1.399. The mean was -0.5747, with a standard deviation of 0.6085. For 2022, January had the highest value at 0.962, while July recorded the lowest at -0.393.

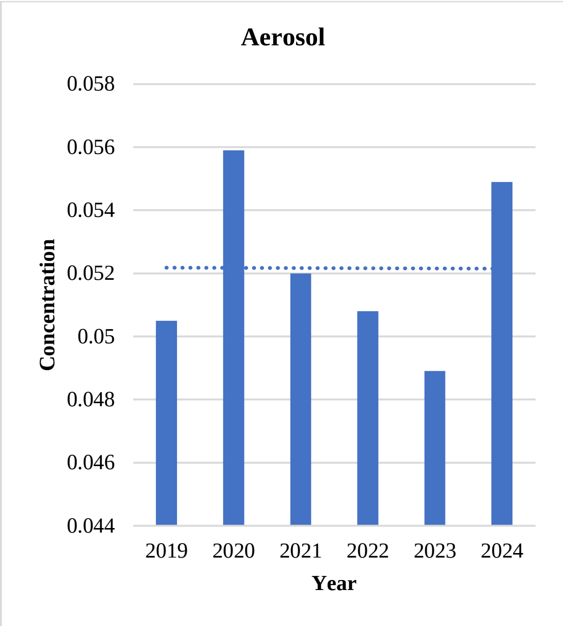

Fig. 17: Trend showing annual aerosol concentration (2019-2024)

Table 7: Monthly concentration of Aerosol for 2019, 2020, 2021, 2022, 2023 and 2024

Months	2019	2020	2021	2022	2023	2024
January	0.068	0.442	-0.28	0.962	0.969	1.09
February	0.367	0.704	-0.179	1.374	1.396	1.195
March	-0.275	-0.535	-0.673	0.683	-0.216	0.397
April	-0.497	-1.022	-1.173	-0.236	-0.126	-0.09
May	-0.921	-1.269	-1.399	-0.426	-0.413	-0.45
June	-0.826	-1.102	-1.376	-0.686	-0.628	-0.543
July	-0.907	-1.14	-0.38	-0.393	-0.655	-0.375
August	-0.823	-0.949	-0.626	0.019	-0.252	0.082
September	-1.205	-1.063	-0.682	-0.515	-0.45	-0.628
October	-1.134	-1.387	-0.704	-0.699	-0.717	-0.711
November	-0.998	-1.174	-0.252	-0.208	-0.437	-0.376
December	-0.363	-0.698	0.828	0.448	0.713	0.647
Mean	-0.6262	-0.7661	-0.5747	0.0269	-0.0680	0.0198
Standard deviation	0.4911	0.6690	0.6085	0.6830	0.6986	0.6662

The mean was 0.0269, with a standard deviation of 0.6830. In 2023, January had the highest value at 0.969, while July had the lowest at -0.655. The mean was -0.0680, with a standard deviation of 0.6986. For 2024, January recorded the highest concentration at 1.09, while August had the lowest at -0.628. The mean was 0.0198, with a standard deviation of 0.6662.

Spatial variations of aerosol concentration across the study years (2019-2024): The spatial variation of aerosol concentration in Figure 18 reveals that in 2019, Diobu, located in the northwestern part of Port Harcourt, had the highest concentration of aerosols, categorized as high, with a concentration of -0.4955. Aerosol had moderate concentrations spread evenly across the central region of Port Harcourt, including Port Harcourt City and Borokiri. The lowest concentrations were found in the southern parts of Port Harcourt and Old Bakana in the western part, with a concentration of -0.7082. The spatial variation of aerosol concentration in Figure 19 shows that in 2020, the aerosol distribution was similar to that of 2019, with a high concentration of -0.6004 and a low concentration of -0.8732.In Figure 20, the spatial variation of aerosol concentration for 2021 shows a distribution similar to that of 2019 and 2020, with a high concentration of -0.4315 and a low concentration of -0.6728. The spatial variation of aerosol concentration in Figure 21 shows that in 2022, the distribution was similar to previous years (2019, 2020, and 2021), with a high concentration of 0.1387 and a low concentration of -0.06534. In Figure 22, the spatial variation of aerosol concentration for 2023 reveals a distribution similar to the previous years (2019, 2020, 2021, and 2022), with a high concentration of 0.0670 and a low concentration of -0.1582. Finally, the spatial variation of aerosol concentration in Figure 23 for 2024 shows a distribution similar to that of 2019, 2020, 2021, 2022, and 2023, with a high concentration of 0.1477 and a low concentration of -0.0835.

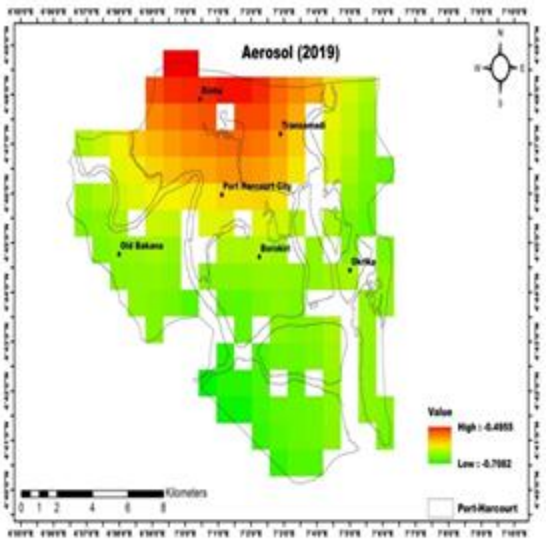

Fig. 18: Map showing Aerosol concentration for Port Harcourt in 2019

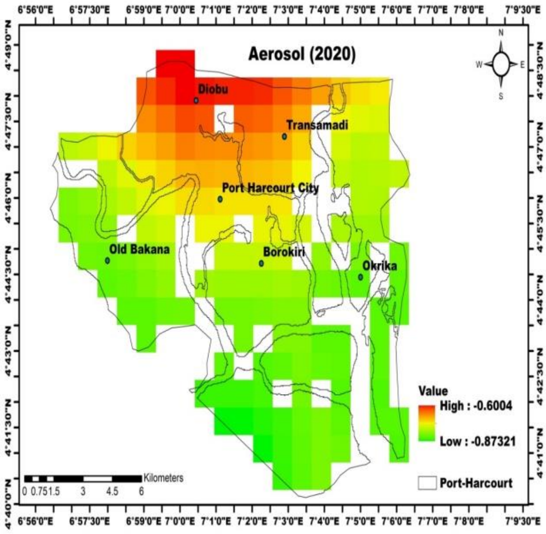

Fig. 19: Map showing Aerosol concentration for Port Harcourt in 2020

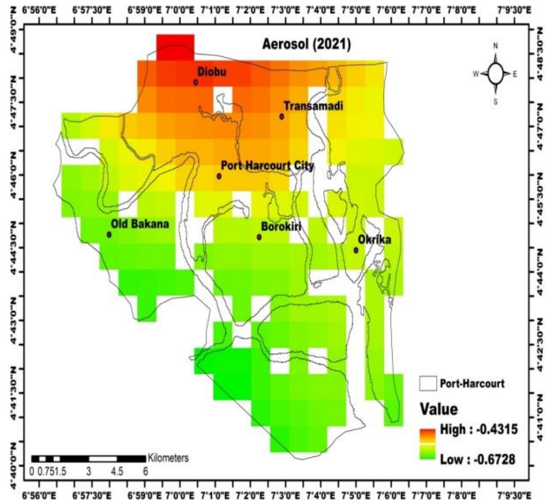

Fig. 20: Map showing Aerosol concentration for Port Harcourt in 2021

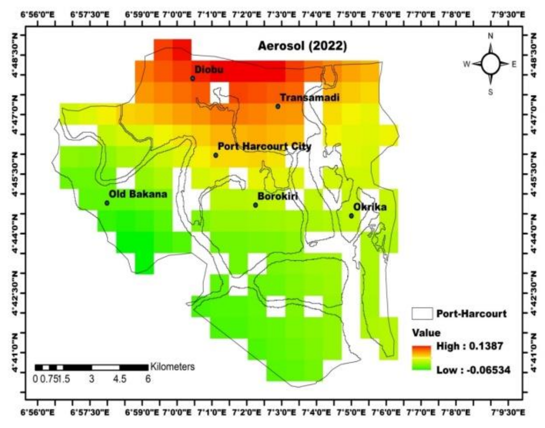

Fig. 21: Map showing Aerosol concentration for Port Harcourt in 2022

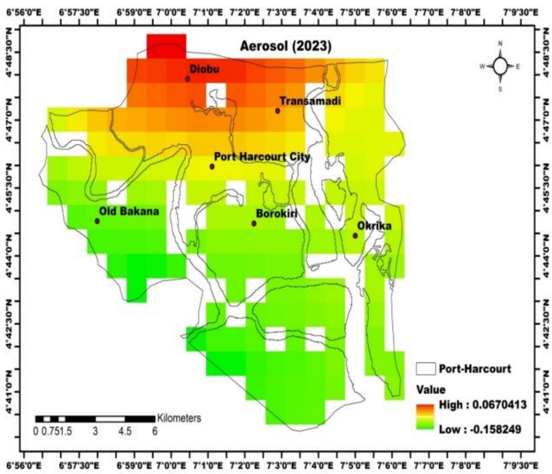

Fig. 22: Map showing Aerosol concentration for Port Harcourt in 2023

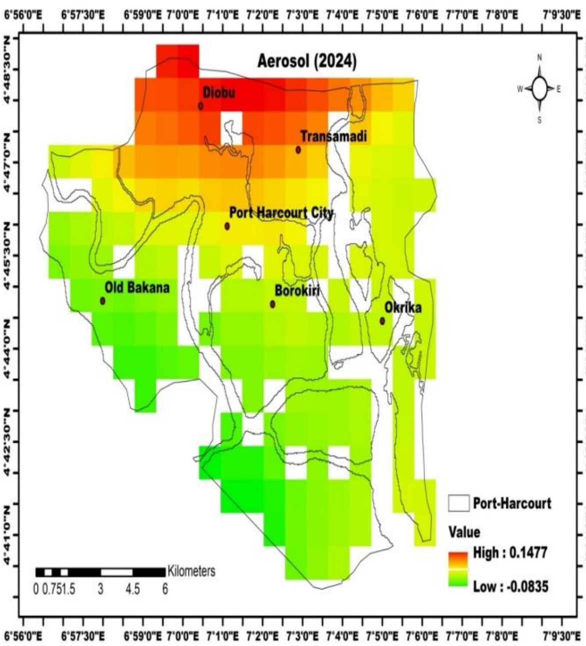

Fig. 23: Map showing Aerosol concentration for Port Harcourt in 2024

Aerosol distribution in Port-Harcourt across the study years: Aerosols are fine particles suspended in the air, originating from both natural and anthropogenic sources. They play a crucial role in air quality, climate regulation, and human health. The temporal and spatial distribution of aerosols in Port Harcourt over the years indicates varying concentration levels, largely influenced by industrial activities, vehicular emissions, and meteorological conditions. Analyzing aerosol data from 2019 to 2024, it is evident that peak concentrations were recorded mainly in the dry season (January to February), while the lowest values were observed during the rainy season (July to September). These fluctuations reflect the impact of seasonal variations, industrial emissions, and global events such as the COVID-19 lockdown in 2020.

From 2019 to 2024, there has been notable variability in aerosol concentrations in Port Harcourt. In 2019, February recorded the highest aerosol concentration at 0.367, while September had the lowest at -1.205. This trend continued in 2020, where February had the highest value at 0.704, whereas April experienced the lowest at -1.022. The sharp drop in April corresponds with the COVID-19 lockdown, during which industrial and vehicular activities significantly decreased, leading to a temporary improvement in air quality. Various similar studies, such as research by Zambrano-Monserrate *et al.* (2020), Saha *et al*. (2022), Kumari and Toshniwal (2020), Amaechi *et al.* (2024), and Pal *et al.* (2022) confirm that lockdown restrictions resulted in a temporary but significant improvement in air quality, particularly in urban areas.

In subsequent years, December 2021 saw the highest concentration at 0.828, while May recorded the lowest at -1.399. This aligns with patterns observed in previous years, where dry-season months tend to have higher aerosol levels. The trend shifted slightly in 2022, with January recording the highest concentration (0.962) and July the lowest (-0.393), showing a general increase in pollution levels compared to previous years. Similarly, in 2023 and 2024, January had the highest aerosol levels at 0.969 and 1.09, respectively, while the lowest values were recorded in July (-0.655) and August (-0.628). The steady rise in peak aerosol values suggests an increase in pollution sources, possibly due to industrial expansion and increased vehicular emissions.

For CO, a paired sample t-test showed that there was statistically significant difference in 2019 and 2020 CO exhibited the most frequent and significant variations, with notable differences observed in 2019–2020 (0.013), 2022–2023 (0.040), and a highly significant change in 2023–2024 (0.0001), suggesting major fluctuations in pollution sources or regulatory impacts. In contrast, NO_2 displayed sporadic significant variations, particularly in 2020–2021 (0.025) and 2022–2023 (0.020), while other years showed no substantial changes, implying relative stability or localized influences on emissions. Aerosol levels remained largely stable, with only a highly significant shift in 2021–2022 (0.007), possibly indicating an isolated environmental event or policy intervention affecting particulate matter concentrations. The most striking observation is the highly significant change in CO levels between 2023 and 2024 ($p = 0.0001$), which could indicate a major shift in pollution patterns, stricter regulations, industrial activities, or environmental factors influencing air quality.

Table 5: Statistical Significance of Air Quality Parameter Variations between Consecutive Years

Parameters	**2019 and 2020**	**2020 and 2021**	**2021 and 2022**	**2022 and 2023**	**2023 and 2024**
p-value of C0	p<0.05(0.013)	p>0.05(0.363)	p>0.05(0.058)	p<0.05(0.040)	p<0.01(0.0001)
p-value of $N0_2$	p>0.05(0.143)	p<0.05(0.025)	p>0.05(0.276)	p<0.05(0.020)	p>0.05(0.215)
p-valueof Aerosol	p>0.05(0.110)	p>0.05(0.367)	p<0.01(0.007)	p>0.05(0.295)	p>0.05(0.211)

$p < 0.01$ = high significant difference; $p < 0.05$ = significantly difference; $p > 0.05$ = no significant difference. (Source: Okoduwa and Amaechi, 2023)

Overall, these findings suggest that CO levels have undergone the most pronounced changes, while NO_2 and aerosols have experienced fewer fluctuations, highlighting the need for targeted interventions in controlling air pollution sources, particularly CO emissions, in the most affected years.

Conclusion: The government should enforce stricter emission regulations and promote cleaner technologies in industries and refineries. Gas flaring must be reduced through mandatory recovery systems, strict penalties, and incentives for flare-reduction technologies. Expanding public transport and encouraging electric or hybrid vehicles with tax incentives will help lower emissions. Seasonal policies like restricted industrial operations and alternative energy use should be implemented during high-pollution periods. Industrial zones should be relocated away from residential areas, and urban green spaces should be expanded to improve air quality. More air quality monitoring stations should be established for better pollution monitoring and management.

Declaration of Conflict of Interest: The authors declare no conflict of interest.

Data Availability: Data are available upon request from the corresponding author

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