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MONITORING CONCENTRATION LEVELS OF NITROGEN DIOXIDE AND SULFUR DIOXIDE IN AKWA IBOM STATE, SOUTH-SOUTH NIGERIA

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ABSTRACT

This study assesses the spatiotemporal variations in tropospheric nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) concentrations in Akwa Ibom State, Nigeria, from 2019 to 2024, using remotely sensed data from the Sentinel-5P satellite. The research employed Google Earth Engine for data extraction, ArcGIS for spatial analysis, and SPSS for statistical evaluation. Results indicate that NO_2 levels peaked in 2021, with a mean concentration of 0.0000610 mol/m², followed by a gradual decline through 2024, potentially due to reduced industrial activities and the removal of fuel (premium motor spirit) subsidy in 2023. SO_2 concentrations showed greater variability, with the highest maximum value in 2022 (0.0001084 mol/m²) and the highest mean in 2024 (0.0000200 mol/m²). Spatial analysis revealed persistently higher pollutant levels in commercial and industrial areas such as Uyo, Ikot Ekpene, and oil-producing zones. Statistical analysis using paired sample t-tests showed a highly significant difference in NO_2 concentrations between 2020 to 2021 ($p < 0.01$) and a significant difference between 2019 to 2024 ($p < 0.05$). A statistically significant difference in SO_2 concentrations was also observed between 2019 to 2024 ($p < 0.05$). However, no statistically significant differences were found between other consecutive years for NO_2, or for any year-to-year comparisons for SO_2 ($p > 0.05$). This study shows that while NO_2 levels have recently decreased, SO_2 remains variable, influenced by industrial operations and policy changes. These findings provide a basis for targeted air quality management and policy formulation in Akwa Ibom State.

KEYWORDS: *Air Quality, Remote Sensing*, *Sentinel-5P, Nitrogen dioxide, Sulfur dioxide*

INTRODUCTION

Air quality is a major global issue that harms human health, ecosystems, and the climate (Manisalidis *et al*., 2020; Arshad *et al*., 2024). Air pollution is caused by harmful gases and tiny particles released from both natural sources, like dust storms, and human activities, such as industrial processes, vehicle emissions, and burning fossil fuels for energy (Li, 2020; Munsif *et al*., 2021). These activities release pollutants like particulate matter, SO_2, nitrogen oxides (NO_x), and carbon monoxide (CO), which are dangerous to people and the environment (Latza *et al*., 2009; Ghorani-Azam *et al*., 2016; Khalaf *et al*., 2024; Arshad *et al*., 2024; Savioli *et al*., 2024). It also contributes to climate change, as aerosols and greenhouse gases like CO_2 trap heat in the atmosphere, leading to global warming (Spiegel and Maystre, 2021). Particulate matter from industries and vehicles affects cloud formation and rainfall patterns, causing unpredictable weather changes (Myhre *et al.*, 2014). Pollutants like NO_2 and SO_2 mix with water vapor to create acid rain, which damages crops, buildings, and aquatic life (Mehta, 2010; Liu *et al.*, 2022).

In Nigeria, a fast-growing economy in Africa, air pollution remains a serious problem, especially in urban and industrial areas (Amaechi and Biose, 2016). In the oil-producing regions, gas flaring worsens air quality (Obi *et al.*, 2021; Echendu *et al.*, 2022). Akwa-Ibom State, located in this region, is heavily affected by these activities, making it a suitable case study for monitoring NO_2 and SO_2 levels.

Akwa-Ibom is Nigeria's largest oil-producing state and possesses one of the nation's largest natural gas reserves (Diugwu *et al.*, 2013). Its oil-based economy and urban expansion contribute to elevated pollution levels, highlighting the need to study nitrogen dioxide and sulfur dioxide concentrations in the region. Air pollution in oil-producing areas is associated with severe health problems such as heart and lung diseases (Nriagu *et al.*, 2016), while vehicular emissions further worsen urban air quality (Abam and Unachukwu, 2009). The period from 2019 to 2024 is particularly significant, as global evidence indicates a notable reduction in NO_2 levels during the COVID-19 lockdowns (Muhammad *et al.*, 2020). Yet, there is limited research exploring how this affected air quality in Akwa-Ibom.

Traditional methods of air quality assessment are often expensive and logistically challenging, making it difficult to obtain detailed data on pollutant distribution over time and space. Increased industrial activity, urbanization, and illegal oil refining have further deteriorated air quality in Akwa-Ibom (Kanee *et al.*, 2021). However, few studies have used modern technologies such as remote sensing to track and analyze air quality changes in the area.

This study therefore examines the spatial and temporal variations in NO_2 and SO_2 levels in Akwa-Ibom from 2019 to 2024 using Sentinel-5P satellite data. The Sentinel-5P, launched by the European Space Agency, provides high-resolution information on atmospheric pollutants like NO_2, CO, and aerosols, offering a more effective way to monitor air quality compared to traditional ground-based methods (Okoduwa and Amaechi, 2023; Chandra and Singh, 2023; Amaechi *et al.*, 2024a). The study period also includes the COVID-19 pandemic, during which lockdowns significantly reduced industrial and vehicular emissions, providing a unique opportunity to observe variations in air quality (Amaechi *et al.*, 2024b). Despite rising awareness of the health impacts of air pollution in Nigeria, detailed long-term studies in Akwa-Ibom are still limited. Hence, this research aims to fill that gap by providing insights that will help policymakers identify pollution-prone areas and develop effective mitigation strategies.

The findings in this study will yield clear, data-driven insights for policymakers and environmental managers, helping to identify pollution hotspots and track trends across time. By providing an evidence-based understanding of air quality dynamics, the research supports long-term efforts to reduce emissions and safeguard environmental and public health in Akwa-Ibom State.

Study Area

Akwa Ibom State (Figure 1) is located in the southern part of Nigeria. Akwa Ibom is one of the thirty-six states in the country, with a population of over 3.5 million people (Mbat *et al*., 2013). The state was created on September 23, 1987, and it comprises 31 Local Government Areas, with Uyo serving as the capital. Geographically, Akwa Ibom lies between latitudes 4° 32′ N and 5° 33′ N, and longitudes 7° 25′ E and 8° 25′ E. It shares boundaries with Abia and Rivers States to the west, Cross River State to the east, Abia State to the north, and the Atlantic Ocean to the south (Ibok and Daniel, 2014). The state falls within the equatorial tropical region, and as such, it experiences a humid tropical climate with rainfall distributed throughout the year (Ekpoh, 2015). There are two main seasons wet and dry with the wet season lasting much longer, typically about ten to eleven months (Uduak *et al*., 2012). The rainfall pattern features a double peak (double maxima), with a short dry season in August (Ekpoh, 2015; Uduak *et al*., 2012). The average annual rainfall is around 3000 mm (Ubuoh *et al*., 2012). Temperature in the area is fairly constant, with daytime temperatures ranging between 27°C and 33°C. Night temperatures rarely drop below 15°C (Ekpoh, 2015). Relative humidity remains high, averaging between 70% and 80% throughout the year, except for a brief period during the dry season (Ekpoh, 2015; Ekpenyong, 2013). The region also contains abundant oil and gas deposits, which have attracted several marginal field operators such as Universal Energy Resources Limited and Frontier Oil Ltd (Ekpoh, 2015; Eze *et al*., 2017).

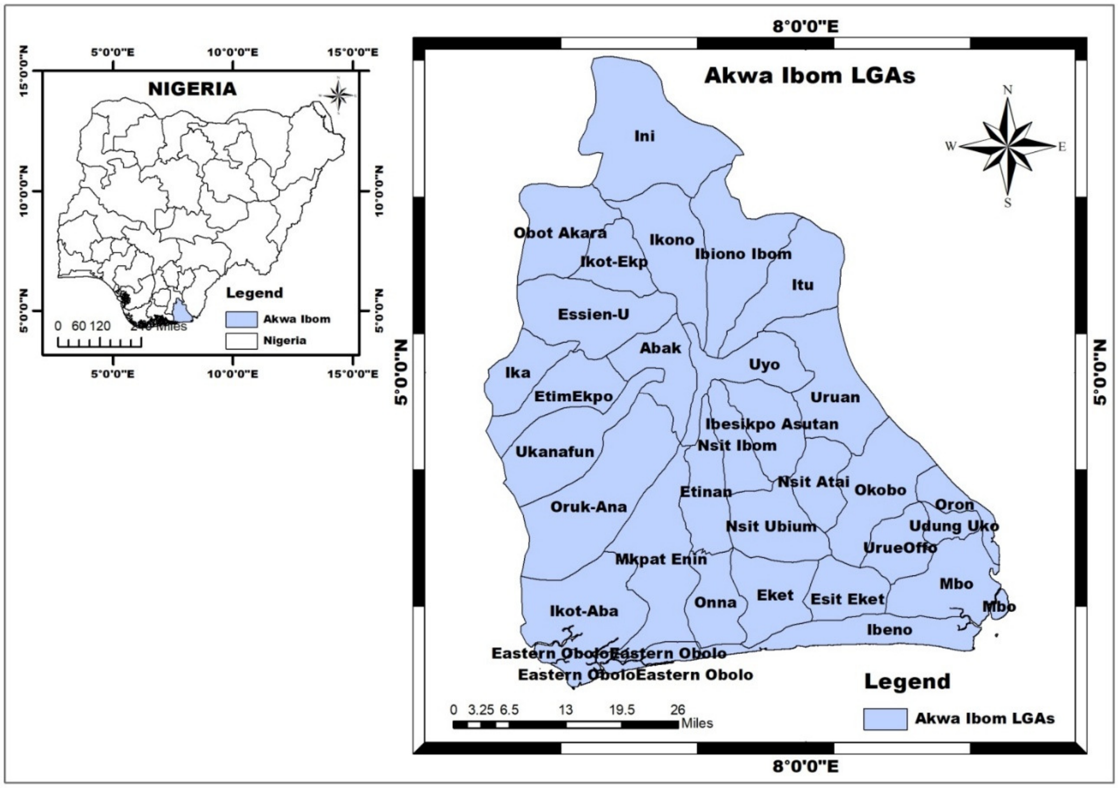

Fig. 1: Map of Akwa-Ibom State, South-South Nigeria.

MATERIALS AND METHODS

Data Type and Source

This study made use of secondary data type obtained from the utilization of Sentinel-5 Precursor (*Sentinel-5P*) satellite, which is designed to collect information related to air quality (Amaechi et al., 2024a). The remotely sensed data from the European Space Agency (ESA) database (ESA, 2019) were used to analyze air quality in Akwa Ibom State by measuring the concentrations of NO_2 and SO_2. To examine changes over time, data covering the period from 2019 to 2024 were used. The satellite is equipped with the TROPOMI (Tropospheric Monitoring Instrument) sensor, which provides high-resolution data on atmospheric pollutants, making it suitable for air quality research (Guanter *et al*., 2021; Okoduwa and Amaechi, 2023). TROPOMI has a sampling resolution of 7×7 km^2 and a swath width of 2,600 km. It uses four spectrometers that are each split into two electronic bands covering ultraviolet (UV), visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) regions with a radiometric accuracy ranging from 1.6% (SWIR) to 1.9% (UV) based on Earth's measured spectral reflectance (Zhao *et al*., 2020). TROPOMI works by detecting sunlight that is either reflected or scattered by the Earth's surface and atmosphere. This method enables detailed monitoring of various air pollutants such as NO_2, ozone (O_3), SO_2, carbon monoxide (CO), and aerosols. Sentinel-5P data were selected for this study because of their high spatial resolution and suitability for tracking air quality (ESA, 2019).

Data on NO_2 and SO_2 levels in Akwa Ibom were collected using JavaScript on the GEE platform, covering the period from 2019 to 2024. Monthly average concentrations of NO_2 and SO_2 were extracted for each year within this period. These datasets used are presented in Table 1. Studies have shown a strong correlation between Sentinel-5P data and measurements from ground-based monitoring stations, confirming the reliability of the satellite data (Grzybowski et al., 2023). The JavaScript code was used to generate raster datasets specific to the study area (Akwa Ibom), which were then saved to Google Drive. To make the data suitable for further analysis in Geographic Information System (GIS) software, the files were exported in GeoTIFF format. These raster datasets were later imported into ArcGIS for additional processing and spatial analysis.

Method of Data Analysis

This study used a combination of ArcGIS 10.7.1, GEE, Microsoft Excel, and the Statistical Package for the Social Sciences (SPSS) for the analysis of air quality data. The air quality data were first extracted from GEE and then exported to ArcGIS for further analysis. ArcGIS was used to process and analyze the data, especially for spatial visualization. For spatial analysis, the processed datasets (GeoTIFF) were imported into ArcGIS and visualized on maps to show the distribution of NO_2 and SO_2 across Akwa Ibom State for each year from 2019 to 2024. Different colour codes were used on the maps to represent concentration levels: red for high, yellow for medium, and green for low concentrations. To analyze trends over time, Microsoft Excel was used to examine the yearly changes in NO_2 and SO_2 concentrations. Graphs and tables were generated to clearly show how pollutant levels varied throughout the study period (2019 - 2024). The study focuses on the period from 2019 to 2024 because high-resolution atmospheric pollution data from Sentinel-5P only became fully available starting in 2019, as indicated in the Earth Engine data catalog. The focus on NO_2 and SO_2 was based on their importance as criteria indicators of urban air quality. These pollutants are closely linked to major emission sources in Akwa Ibom, such as gas flaring, industrial activities, and pipeline explosions (Fagorite *et al*., 2021; Tawari and Abowei, 2012). To conduct statistical analysis, SPSS was used to perform a paired sample t-test. This test was chosen because it compares the concentration levels of pollutants between consecutive years. The paired t-test helped to identify whether the year-to-year differences in NO_2 and SO_2 concentrations were statistically significant.

Table 1: NO_2 and SO_2 dataset used for this study

Band Name	Dataset	Unit	Min	Max	Description
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).
SO_2_column_number_density	OFFL/L3_SO_2	mol/m^2	-0.4051	0.2079	SO_2 vertical column density at ground level, calculated using the DOAS technique.

RESULTS AND DISCUSSION

Annual Concentration of NO_2 from 2019 to 2024

In 2019 (Table 2), NO_2 had a minimum annual concentration of 0.0000488 mol/m² and a maximum concentration of 0.0000617 mol/m². The average concentration for the year was 0.0000556 mol/m², with a standard deviation of 0.0000027 mol/m². By 2020, the minimum, maximum, and mean concentrations of NO_2 were 0.0000490 mol/m², 0.0000643 mol/m², and 0.0000561 mol/m² respectively, with a standard deviation of 0.0000030 mol/m². Compared to 2019, there was a slight increase in the annual NO_2 concentration, while the standard deviation also increased, indicating greater variability. In 2021, NO_2 concentrations ranged from 0.0000528 mol/m² to 0.0000720 mol/m², with an average of 0.0000610 mol/m² and a standard deviation of 0.0000038 mol/m². The overall increase in values during 2021 reveals a marked upward trend across the years.

For 2022, the recorded minimum, maximum, and mean NO_2 concentrations were 0.0000516 mol/m², 0.0000681 mol/m², and 0.0000599 mol/m² respectively, with a standard deviation of 0.0000031 mol/m². Although there was a slight decrease in concentration compared to 2021, the levels remained higher than those observed in 2019 and 2020, suggesting a minor reduction in emission sources. The standard deviation also declined slightly from the previous year. In 2023, NO_2 concentrations ranged between 0.000049 mol/m² and 0.0000656 mol/m², with a mean value of 0.0000581 mol/m² and a standard deviation of 0.0000033 mol/m². Both the minimum and maximum concentrations dropped further, signifying reduced peak emissions, while the mean concentration fell slightly below that of 2022. However, the standard deviation showed a slight increase compared to the preceding year. By 2024, the minimum and maximum annual NO_2 concentrations were 0.0000501 mol/m² and 0.0000633 mol/m² respectively, with a mean of 0.0000582 mol/m². The standard deviation, recorded at 0.0000024 mol/m², was the lowest across all years, indicating relatively stable NO_2 levels.

Figure 2 shows an overall upward trend in the annual mean concentration of NO_2 from 2019-2024. NO_2 concentrations slightly increased from 2019 to 2020, followed by a sharp rise in NO_2 concentration levels from 2020 to 2021, reaching the highest peak. A slight decline in mean concentration was observed from 2021 through 2023, after which there was a slight increase in 2024. In 2020, the concentration levels of NO_2 increased from 2019 possibly due to the ineffective implementation of the COVID – 19 lockdown policies. In 2023, the decline in NO_2 concentration may be attributed to the elimination of fuel (PMS) subsidy policy.

Table 2: Annual minimum, maximum, mean, and standard deviation values of NO_2 concentration from 2019 to 2024

NO_2	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Minimum	0.0000488	0.0000490	0.0000528	0.0000516	0.0000492	0.0000501
Maximum	0.0000617	0.0000643	0.0000720	0.0000681	0.0000656	0.0000633
Mean	0.0000556	0.0000561	0.0000610	0.0000599	0.0000581	0.0000582
Standard deviation	0.0000027	0.0000030	0.0000038	0.0000031	0.0000033	0.0000024

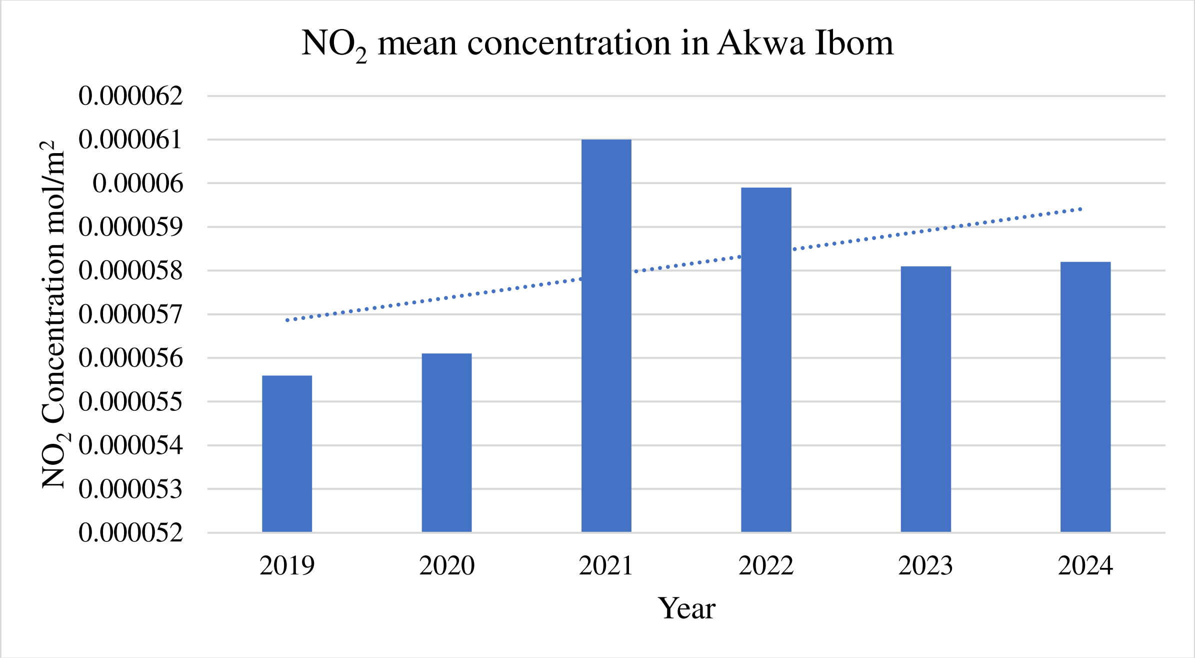

Fig. 2: Trend of annual concentration of NO_2 (2019-2024)

Spatial Distribution of NO_2 Concentration Over the Study Period (2019–2024)

Figures 3 to 8 shows the spatial distribution in NO_2 concentration across Akwa Ibom during the study period. The spatial variation of NO_2 concentrations in 2019 revealed that NO_2 concentration levels were noticeably higher in areas of Uyo which is the state capital, Ika, Obot Akara, Etim Ekpo, and part of Itu, with a recorded concentration of 0.0000617mol/m^2. Moderate levels of NO_2 were observed in Ini, Ikono, Abak, Ibiono Ibom, Etinan, Oruk-Ana, Nsit Ibom, Ibesikpo Asutan, Ukanafun, part of Mkpat Enin, Nsit Ubium, Nsit Atai, Ikot-Aba, Ikot Ekpene and Uruan. In contrast, lower NO_2 levels were observed in areas of Esit Eket, Eket, Ibeno, Mbo, Onna, Eastern Obolo, Okobo, Urue Offo and Udulng Uko, with a concentration of 0.0000488mol/m^2.

In 2020, the spatial variation of NO_2 concentrations follows the same pattern as seen in 2019. However, a slight rise was observed in both the higher and lower concentration levels of NO_2 with concentrations of 0.0000643mol/m^2 and 0.0000490mol/m^2 respectively. In 2021, the spatial distribution of NO_2 concentration levels was higher with a concentration of 0.0000720mol/m^2 in Uyo, and part of Itu. Moderate concentration levels were observed in Ibiono Ibom, Ikono, Abak, Essien-U, Ika, Etim Ekpo, Ikot Ekpene, Ini, Obot Akara, Ukanafun, Uruan, Ibesikpo Asutan, Nsit Ibom, Etinan, Oruk-Ana, Nsit Atai, Nsit Ubium and part of Mkpat Enin. While the lowest concentration of NO_2 (0.0000528mol/m^2) was observed in South, Southeastern region and Southwestern region including Ibeno, Mbo, Eastern Obolo, Ikot-Aba, Onna, Eket, Esit Eket, Urue Offo, Udung Uko, Oron and Okobo.

In 2022, the spatial variation of NO_2 concentrations revealed that NO_2 concentration levels were higher in the Central and Northwestern regions in Akwa Ibom State, covering areas such as Uyo, Ika, Obot Akara, and Ikot Ekpene, part of Essien-U and Itu with a concentration of 0.0000681mol/m^2. NO_2 had moderate concentrations across the Northern, Southern, Western and Eastern regions of Akwa Ibom which includes Ibiono Ibom, Ikono, Ini, Abak, Etim Ekpo, Ukanafun, Uruan, Nsit Ibom, Ibseikpo Asutan, Nsit Atai, Nsit Ubium, Etinan, Oruk-Ana, Mkpat Enin, Okobo and Ikot-Aba. Lower concentrations of 0.0000516mol/m^2 were observed in the Southern region including Ibeno, Mbo, Eastern Obolo, Onna, Eket, Esit Eket, Urue Offo, Udung Uko and Oron.

In 2023, the spatial variation of NO_2 concentrations follow a similar pattern as observed in 2022. However, there was a slight decrease in high and low concentrations of NO_2 which are 0.0000656mol/m^2 and 0.0000492mol/m^2 respectively. Finally in 2024, the spatial variation of NO_2 shows that higher concentration of 0.0000633mol/m^2 was noticed in Uyo the state capital, Obot Akara and part of Itu. Moderate levels of NO_2 were observed in Ini, Ikot Ekpene, Ikono, Ika, Etim Ekpo, Abak, Ibiono Ibom, Essien-U, Uruan, Nsit Ibom, Ibesikpo Asutan, Ukanafun, Oruk-Ana, Ikot-Aba, Mkpat Enin, Onna, Etinan, Nsit Ubium, Nsit Atai, Okobo, Oron, Eket and Eastern Obolo. Lower concentrations of 0.0000501mol/m^2 were observed in Southeastern region including Ibeno, Mbo, Udung Uko, Urue Offo and Esit Eket.

The distribution of NO_2 across Akwa Ibom State from 2019 to 2024 reveals a clear narrative shaped by human activity and policy. The spatial patterns were consistent where high concentrations were persistently found in the state capital, Uyo, and other urbanized and industrialized centres like Ikot Ekpene, Ika, and Obot Akara. This persistent NO_2 concentration in urban areas can be attributed to vehicular emissions and industrial combustion which serve as the primary anthropogenic sources of NO_2 in urban environment (Tawari and Abowei, 2012; Choudhary and Garg, 2013). These urban centers, with their high population density, traffic congestion, and commercial activity, act as direct point sources for this pollutant (Kaplan and Avdan, 2020).

Conversely, the lowest concentrations were consistently recorded in the southern and southeastern coastal regions, including Ibeno, Mbo, and Eastern Obolo. These areas are less densely populated and have fewer major industrial complexes. Their proximity to the Atlantic Ocean likely also enhances the dispersion and dilution of pollutants, leading to better air quality (Singh *et al.*, 2021; Das *et al.*, 2021; Cheng *et al.*, 2007; Gorai *et al.*, 2015 and Vaishali *et al.*, 2023).

On the other hand, the annual mean concentration presents a more dynamic picture. The annual mean concentration of NO_2 in 2020 changed highly significantly in 2021, but the years 2019, 2020, 2022, 2023 and 2024 did not change significantly even though changes in concentration was observed in each month of the years. The noticeable peak in NO_2 concentration levels observed in 2021 is particularly telling. It aligns with the global post-COVID-19 lockdown economic rebound, where industrial and vehicular activity surged to compensate for lost productivity (Kazemi-Garajeh *et al.*, 2023). The subsequent decline from 2022 onwards, and especially the notable drop in 2023, provides a powerful, real-world case study. This decline can be directly attributed to the Nigerian government's removal of the fuel (PMS) subsidy policy in mid-2023 (Amaechi *et al.*, 2023). The subsequent hike in fuel (PMS) prices acted as a discouragement, significantly reducing vehicular traffic and, by extension, the emissions from transportation which is a major source of NO_2. This demonstrates how macroeconomic policy can have an immediate and tangible impact on local environmental air quality.

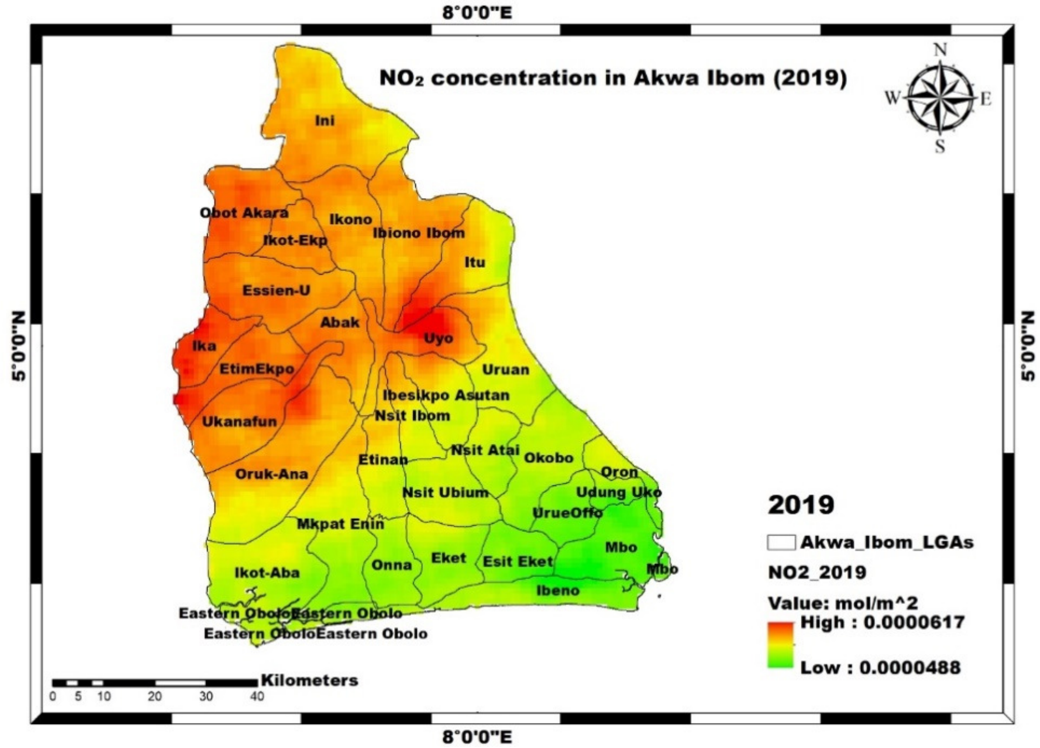

Fig. 3: Map illustrating the distribution of NO_2 concentration across Akwa Ibom in 2019

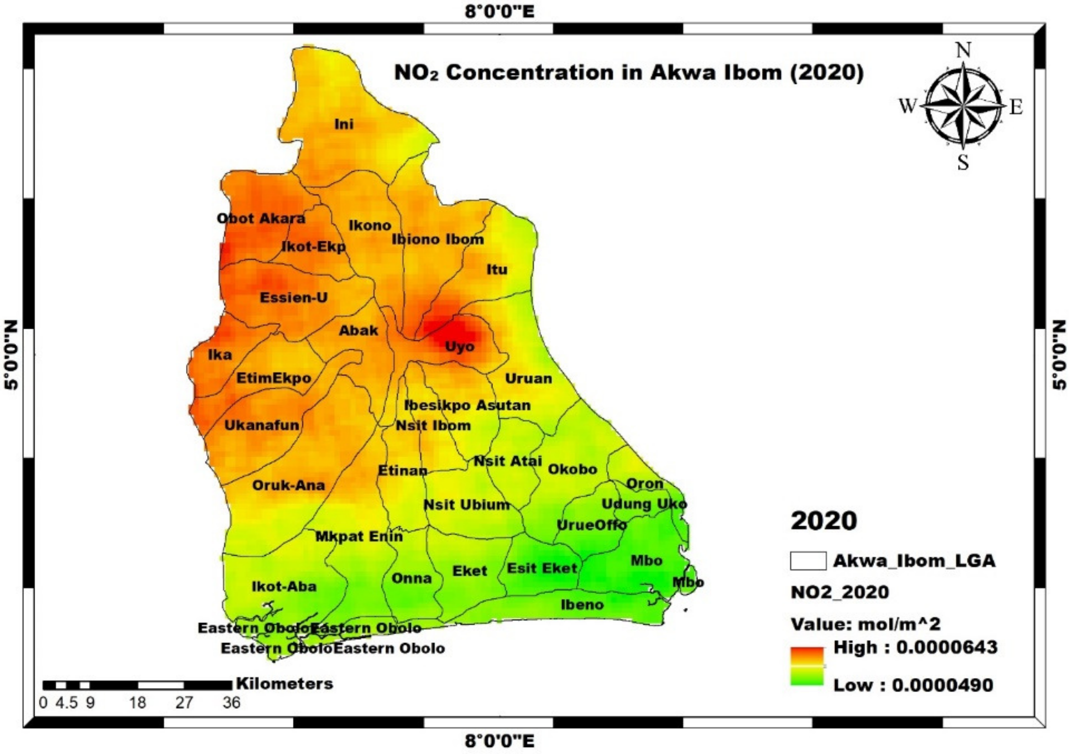

Fig. 4: Map illustrating the distribution of NO_2 concentration across Akwa Ibom in 2020

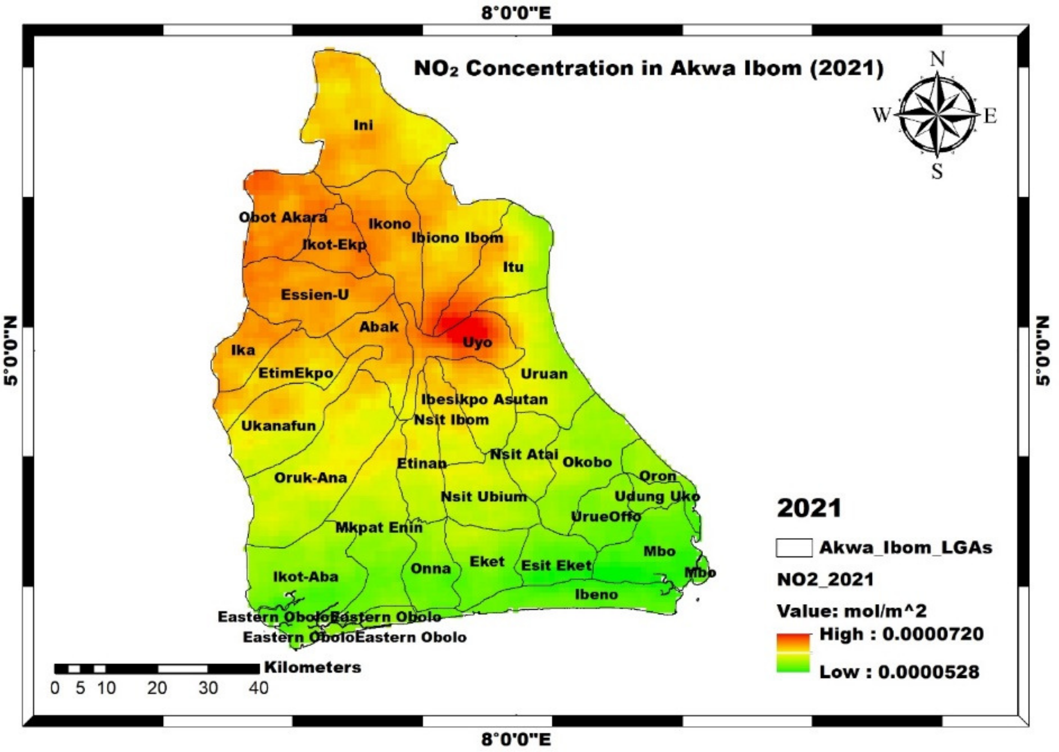

Fig. 5: Map illustrating the distribution of NO_2 concentration across Akwa Ibom in 2021

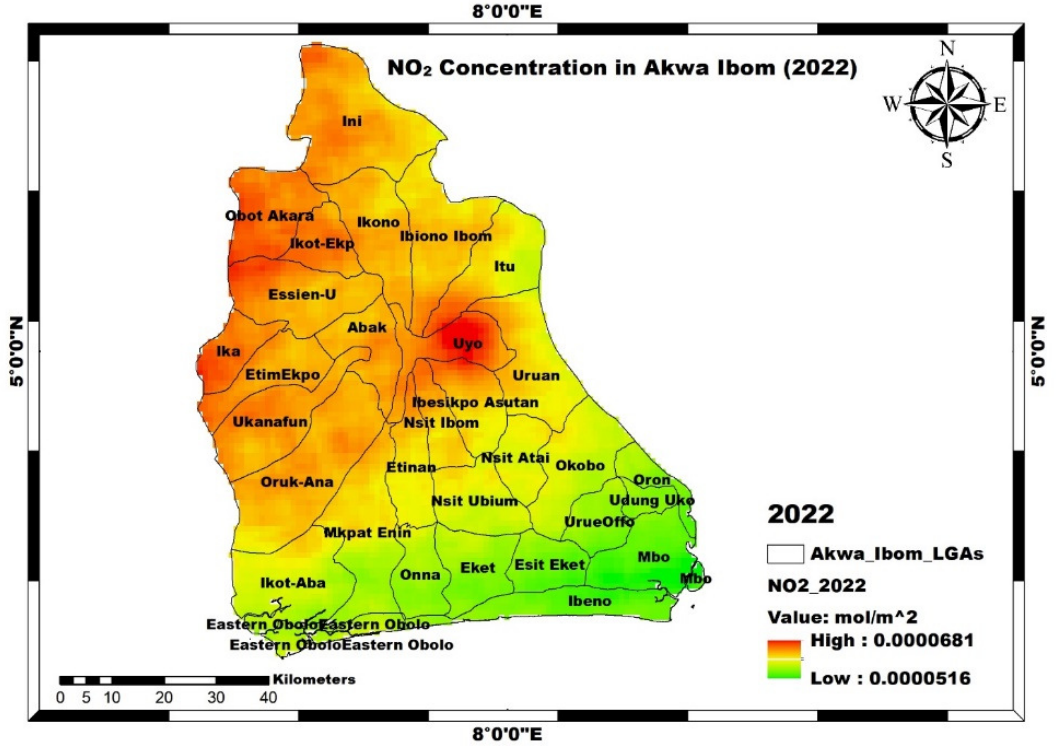

Fig. 6: Map illustrating the distribution of NO_2 concentration across Akwa Ibom in 2022

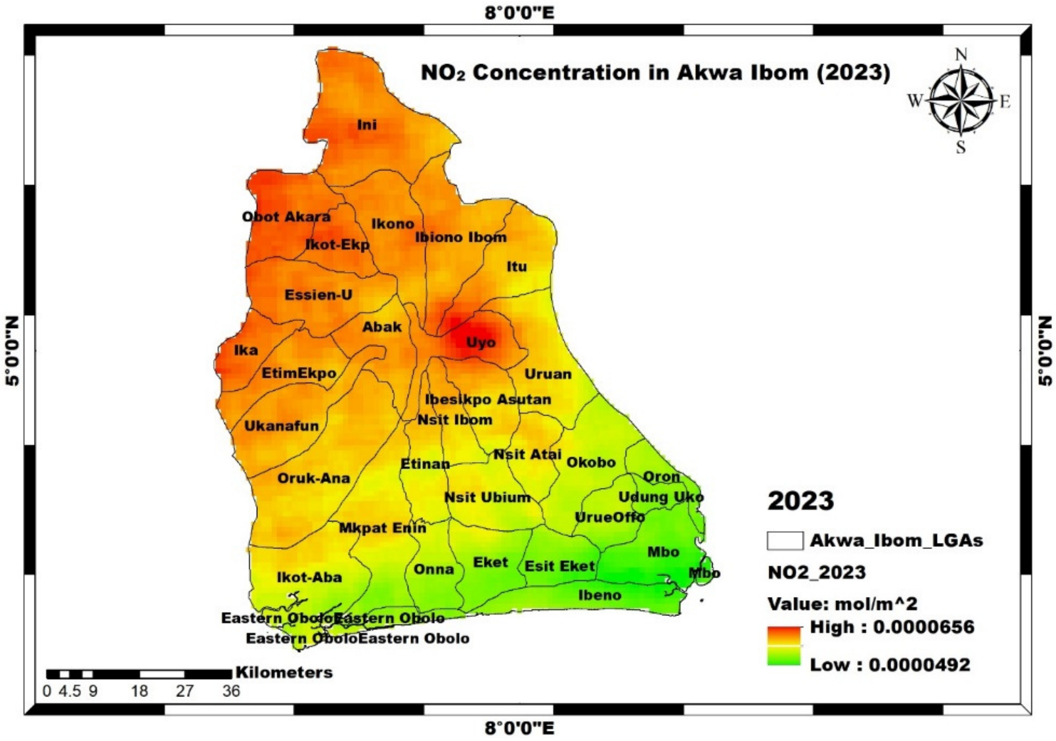

Fig. 7: Map illustrating the distribution of NO_2 concentration across Akwa Ibom in 2023

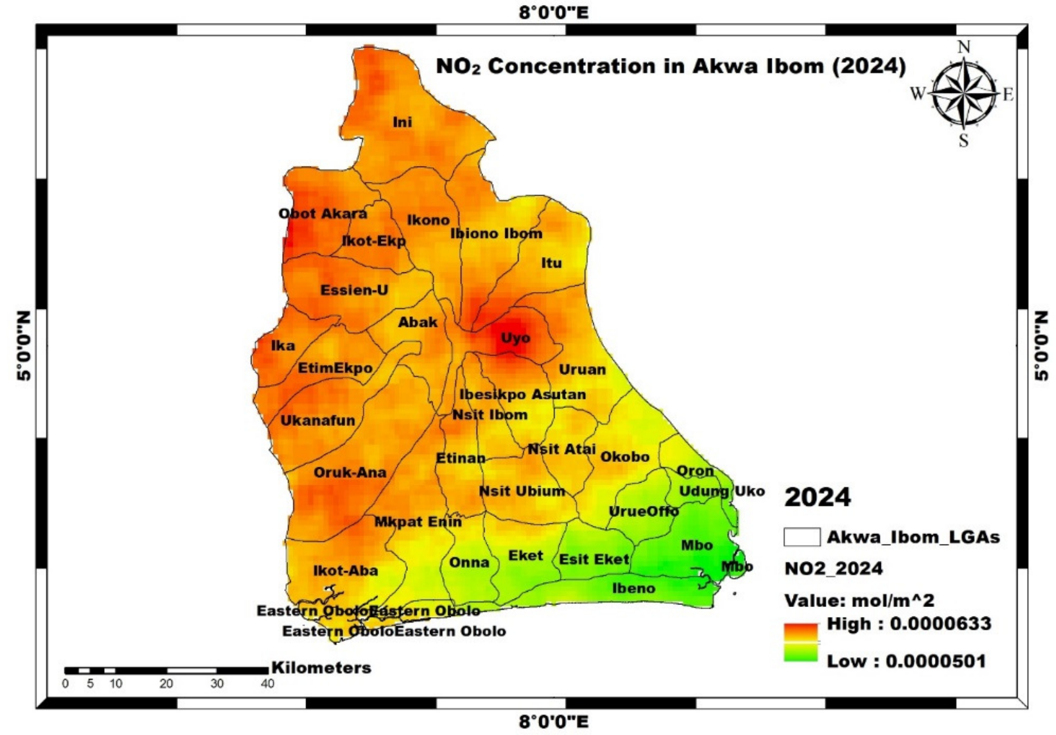

Fig. 8: Map illustrating the distribution of NO_2 concentration across Akwa Ibom in 2024

Annual SO_2 Concentration from 2019 to 2024

Table 3 presents the annual SO_2 concentrations. In 2019, the minimum concentration recorded was -0.0000974 mol/m², while the maximum reached 0.0000568 mol/m². The mean concentration for the year stood at -0.0000253 mol/m², with a standard deviation of 0.0000212 mol/m². The wide gap between the minimum and maximum values suggests significant fluctuations in SO_2 levels during the year. In 2020, SO_2 concentrations ranged from -0.0001097 mol/m² to 0.0000869 mol/m², with a mean of -0.0000142 mol/m² and a standard deviation of 0.0000288 mol/m². Compared to 2019, the minimum value decreased, reflecting more pronounced drops in SO_2 levels, while the maximum increased, indicating occasional spikes. The higher standard deviation in 2020 points to greater variability than the previous year.

For 2021, the minimum, maximum, and mean SO_2 concentrations were -0.0001253 mol/m², 0.0000932 mol/m², and -0.0000098 mol/m² respectively, with a standard deviation of 0.0000275 mol/m². The minimum concentration observed in 2021 was the lowest across the study period, showing deeper declines in SO_2 levels at certain times. The maximum concentration exceeded those of 2019 and 2020, while the standard deviation slightly reduced compared to 2020. In 2022, the annual SO_2 concentrations ranged from -0.0001017 mol/m² to 0.0001084 mol/m², with a mean value of 0.0000099 mol/m² and a standard deviation of 0.0000298 mol/m². Both the minimum and maximum concentrations remained among the highest across all years examined.

During 2023, the SO_2 concentrations varied between -0.0001030 mol/m² and 0.0000873 mol/m², with an average of -0.0000116 mol/m² and a standard deviation of 0.0000312 mol/m². The minimum value was slightly lower than in 2022, while the maximum declined below the previous year's peak, suggesting a possible reduction in emission sources. Notably, the standard deviation in 2023 was the highest of all years, reflecting increased variability in concentration levels. In 2024, the minimum SO_2 concentration was -0.0000540 mol/m², and the maximum reached 0.0001049 mol/m². The mean concentration rose to 0.0000200 mol/m² the highest recorded across the years while the standard deviation was 0.0000255 mol/m². The minimum concentration for 2024 was the highest overall, and the maximum ranked second after 2022. The standard deviation showed a slight reduction compared to 2023, indicating somewhat more stable conditions.

The annual mean trend of SO_2 as shown in Figure 9 shows an overall upward trend in SO_2 concentration. The figure illustrates that there was an increase in SO_2 concentration from 2019 to 2020, but remained in the negative range. In 2021, there was a further increase in concentration from the previous year 2020, but still remained in the negative range. In 2022 there was a noticeable increase in concentration into the positive range followed by a decline into the negative range in 2023. A sharp rise from the negative range to the positive range was observed in 2024, reaching the highest peak over the study years.

Table 3: Annual minimum, maximum, mean and standard deviation of SO_2 concentration from 2019 to 2024

SO_2	2019	2020	2021	2022	2023	2024
Minimum	-0.0000974	-0.0001097	-0.0001253	-0.0001017	-0.0001030	-0.0000540
Maximum	0.0000568	0.0000869	0.0000932	0.0001084	0.0000873	0.0001049
Mean	-0.0000253	-0.0000142	0.0000098	0.0000099	-0.0000116	0.0000200
Standard deviation	0.0000212	0.0000288	0.0000275	0.0000298	0.0000312	0.0000255

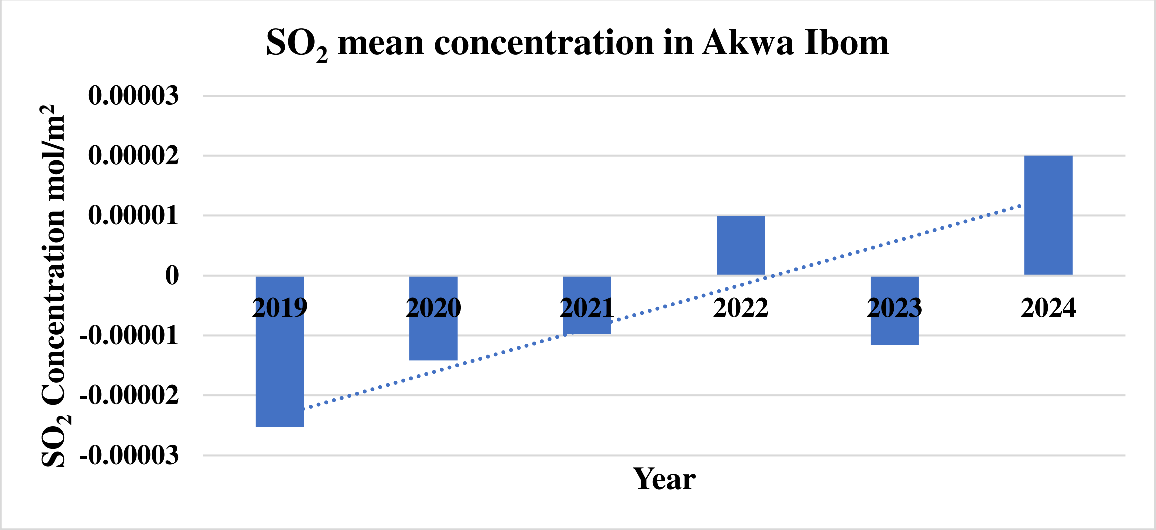

Fig. 9: Trend of annual concentration of SO_2 (2019-2024)

Spatial Distribution of SO_2 Concentration Over the Study Period (2019–2024)

Figures 10 to 15 show the spatial variations in SO_2 concentration levels across Akwa Ibom during the study period. The spatial variation of SO_2 from 2019-2024 showed pockets of elevated pollution likely due to specific local emission sources from the different local government areas. In 2019, the spatial variation of SO_2 revealed high concentrations of 0.0000568mol/m^2 of SO_2 in different parts of different local government areas including Ikot Ekpene, Ikono, Ibiono Ibom, Uruan, Nsit Atai, Onna, Ukanafun and Mkpat Enin. Moderate levels were observed in Mbo, Ibeno Esit Eket, Eket, Ikot-Aba, Oruk-Ana, Etinan, Nsit Ubium, Urue Offo, Udung Uko, Oron, Okobo, EtimEkpo, Uyo, Itu, Ini, Obot Akara, Essien-U, Ika, Eastern Obolo, Abak. While in areas like Obot Akara, Essien-U, Oruk-Ana, Uyo, Ini, Ibesikpo Asutan and Nsit Ibom have very low concentration of -0.0000974mol/m^2 in some parts of the LGAs.

In 2020, the spatial variation of SO_2 revealed high concentrations of 0.0000869mol/m^2 of SO_2 which also follows the same pattern of distribution as seen in 2019 in areas like Uyo, Itu, Ikono, Ikot-Ekpene, Ini, Ibesikpo Asutan, Nsit Atai, Nsit Ubium, Etinan, Mkpat Enin, Ikot-Aba, Eastern Obolo, Mbo and Ibeno. Moderate concentrations were observed in Ika, Uruan, Ibiono Ibom, Obot Akara, Essien-U, Etim Ekpo, Ukanafun, Oruk-Ana, Abak, Ini, Okobo, Onna, Eket, Esit Eket, Oron, Urue Offo and Udung Uko. While low concentrations of -0.000109mol/m^2 were in some parts of Obot Akara, Uyo, Nsit Ibom, Essien-U, Uyo, Abak, Oruk-Ana. In 2021, the spatial variation of SO_2 were higher with a concentration of 0.0000932mol/m^2 in areas like Oruk-Ana, Uruan, Urue Offo, Eastern Obolo, Okobo, Ikot-Ekpene, Itu, Ibeno, Obot Akara, Eket and Ini. Moderate levels of SO_2 were observed in areas such as Esit Eket, Mbo, Onna, Ikot Aba, Ukanafun, Ika, Etim Ekpo, Nsit Atai, Uyo, Ibesikpo Asutan, Nsit Ibom, Nsit Ubium, Etinan, Abak, Ibiono Ibom, Ikono and Essien-U. While lower concentrations of SO_2 with a concentration of -0.000125mol/m^2 were observed in parts of Nsit Atai, Nsit Ubium, Etim Ekpo, Etinan, Abak and Ika.

In 2022, the spatial variation of SO_2 revealed high concentration with a value of 0.000108mol/m^2 of SO_2 in some parts of the local government areas such as Ikot-Aba, Eastern Obolo, Etinan, Oruk-Ana, Uyo, Ibiono Ibom, Nsit Ibom, Esit Eket and Itu. Moderate levels were observed in areas such as Ini, Obot Akara, Ikot-Ekpene, Essien-U, Ikono, Abak, Ika, Etim Ekpo, Ukanafun, Mkpat Enin, Onna, Eket, Ibeno, Mbo, Urue Offo, Udung Uko, Oron, Okobo, Nsit Atai and Uruan. Low levels of SO_2 with a concentration of -0.000101mol/m^2 were observed in some parts of the different local government areas such as Ukanafun, Mkpat Enin, Ikot-Aba, Onna, Ika and Etinan. In 2023, the spatial concentration of SO_2 was high with a value of 0.0000873mol/m^2 in areas such as Ibeno, Eket, Eastern Obolo, Ikot-Aba, Onna, Mkpat Enin, Nsit Ubium, Mbo, Ibesikpo Asutan, Uruan, Uyo, Itu, Ini, Esit Eket and parts of Nsit Atai. Moderate levels were observed in Obot Akara, Ikot-Ekpene, Ikono, Ibiono Ibom, Abak, Essien-U, Ika, Etim Ekpo, Ukanafun, Oruk-Ana, Etinan, Nsit Ibom, Okobo, Urue Offo, Udung Uko and Oron. While lower concentrations of SO_2 with a value of -0.000103mol/m^2 were observed in some parts of different LGAs such as Nsit Atai, Nsit Ibom, Okobo, Ika, Etim Ekpo, Etinan, Ibiono Ibom and Essien-U.

Finally in 2024, the spatial variation of SO_2 shows that high concentration of 0.000104mol/m^2 was noticed in Oruk-Aka, Ikot-Aba, Eket, Uyo, Itu, Uruan, Mkpat Enin, Ibesikpo Asutan and some parts of Etinan. Moderate levels were noticed in areas such as Ini, Ikono, Obot Akara, Essien-U, Ika, Etim Ekpo, Ukanafun, Onna, Ibeno, Mbo, Okobo, Udung Eko, Oron, Nsit Atai. Lower concentrations with a value of -0.0000540mol/m^2 were noticed in areas such as Ikot-Ekpene, Abak and some parts of Ukanafun, Obot Akara, Essien-U, Etinan, Ikono, Ibiono Ibom, Oruk-Ana and Mkpat Enin.

In contrast to the relatively predictable patterns of NO_2, the distribution of SO_2 was clearly more complex, reflecting its different emission sources. SO_2 is predominantly emitted from specific industrial point sources such as fossil fuel combustion in power plants, refineries, petrochemical industries, and gas flaring (Saxena *et al*., 2019). This was evident in the spatial data, which showed highly variable of elevated SO_2 pollution that shifted across different local government areas from year to year. Unlike the stable urban hotspots of NO_2, these shifting SO_2 hotspots can be tied to the fluctuating operational schedules, maintenance periods, or output levels of specific industrial facilities.

SO_2 concentrations showed different seasonal variations with high concentrations regularly observed in December, except for 2020 and 2024. The peak concentration overall was recorded in March 2024 with a value of 0.0000800 mol/m^2. The high concentrations observed can be linked to increased vehicular activities (Okoduwa and Amaechi, 2023), and harmattan conditions. Low concentrations of SO_2 were consistent in March, except for 2019, 2020 and 2022, with the overall lowest concentration in July 2020 with a value of -0.0000855 mol/m^2. The slight increase in the annual mean concentration of SO_2 in 2020 can be attributed to the ineffective implementation of the COVID – 19 lockdown guidelines such as traffic reduction and industry closures during the pandemic in 2020 (Amaechi *et al*., 2024).

In addition, a study carried out by Ighodaro and Oriakhi (2011), found out that almost all household in Benin City has a generator and often utilize PMS and diesel on a daily basis, this may be a possible outcome in Akwa Ibom State. The increase in the annual mean concentration in 2021 and 2022 is likely due to the post-pandemic economic recovery, as industries, vehicular activities and businesses resumed their normal operations (Kazemi-Garajeh *et al*., 2023). The decline observed in 2023 can be attributed to the removal of fuel (PMS) subsidy policy which restricted the movement of vehicles due to the hike in fuel (PMS) prices (Okoduwa and Amaechi, 2023). The mean annual concentration of SO_2 was the highest in 2024, this could be due to the adaptation of the removal of fuel (PMS) subsidy policy in 2023 and the use of alternative fuel sources, leading to increase vehicular and industrial emissions (Amaechi *et al*., 2024c; Okorie and Wesseh, 2024).

The consistent observation of peak SO_2 concentrations in the dry season months, particularly December across multiple years, points to a strong seasonal influence. This could be due to several factors including, increased energy demand, higher operational capacity of industries during this period, or the practice of biomass burning, which can release SO_2. This aligns with established literature confirming that meteorological conditions and seasonal practices significantly influence the concentration and dispersion of air pollutants (Vaishali *et al*., 2023).

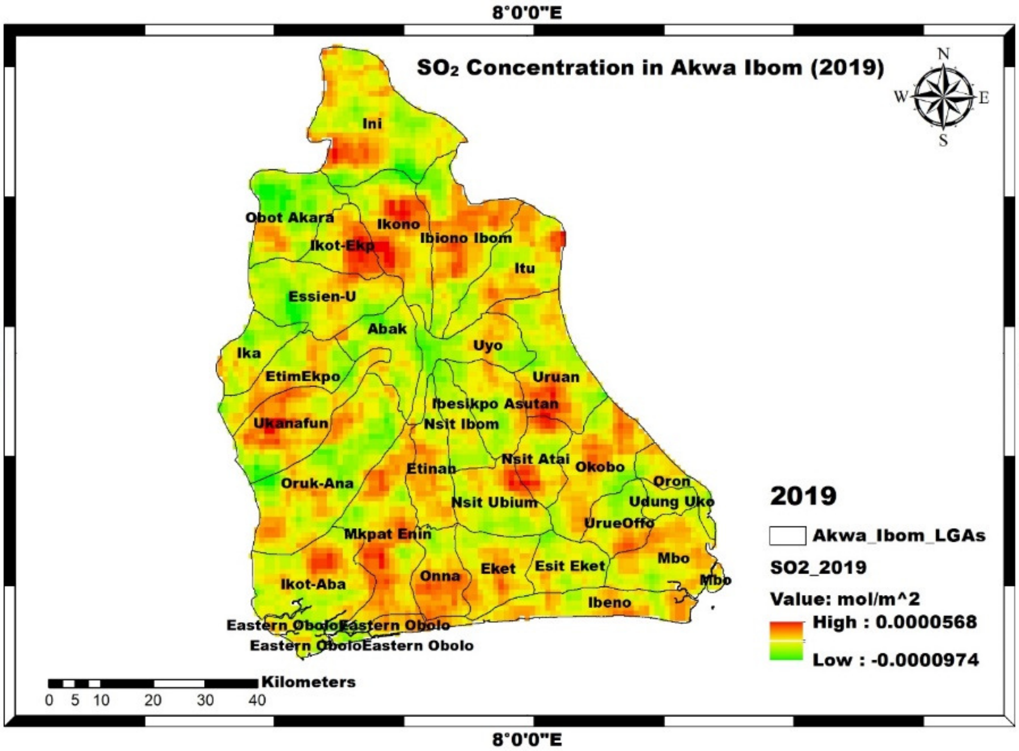

Fig. 10: Map illustrating the distribution of SO_2 concentration across Akwa Ibom in 2019

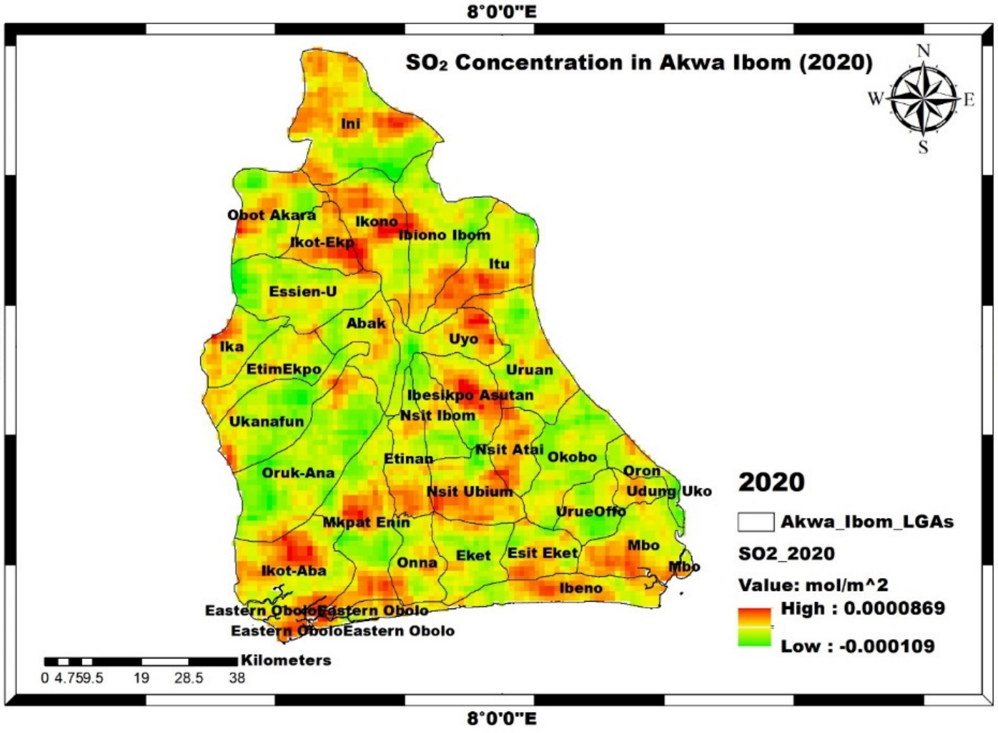

Fig. 11: Map illustrating the distribution of SO_2 concentration across Akwa Ibom in 2020

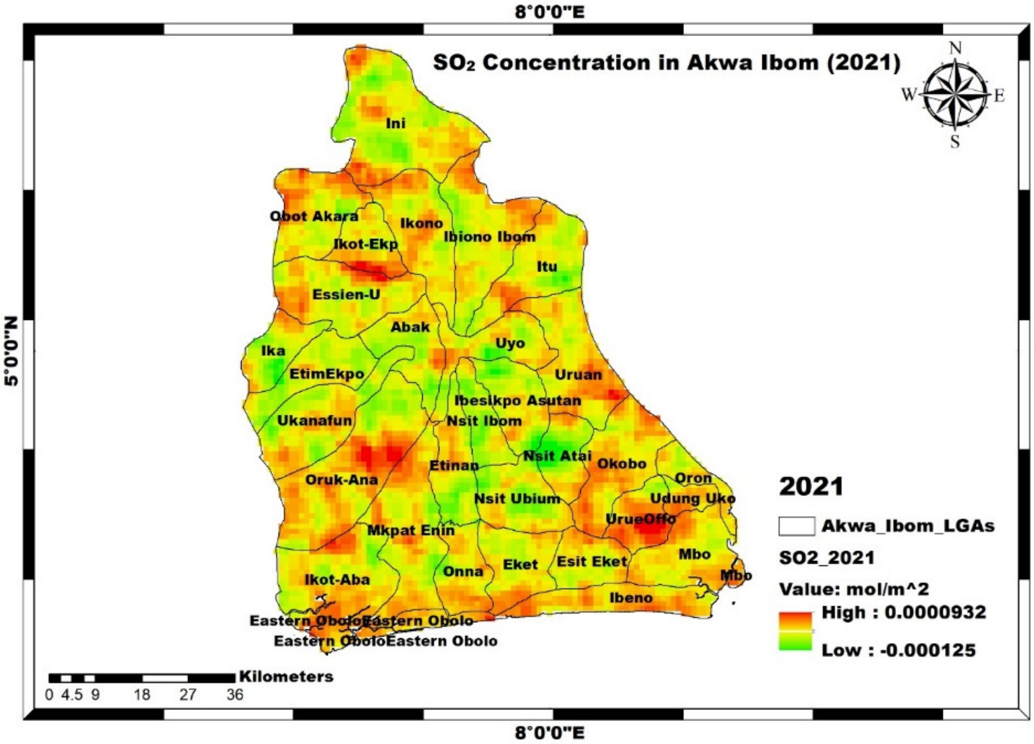

Fig. 12: Map illustrating the distribution of SO₂ concentration across Akwa Ibom in 2021

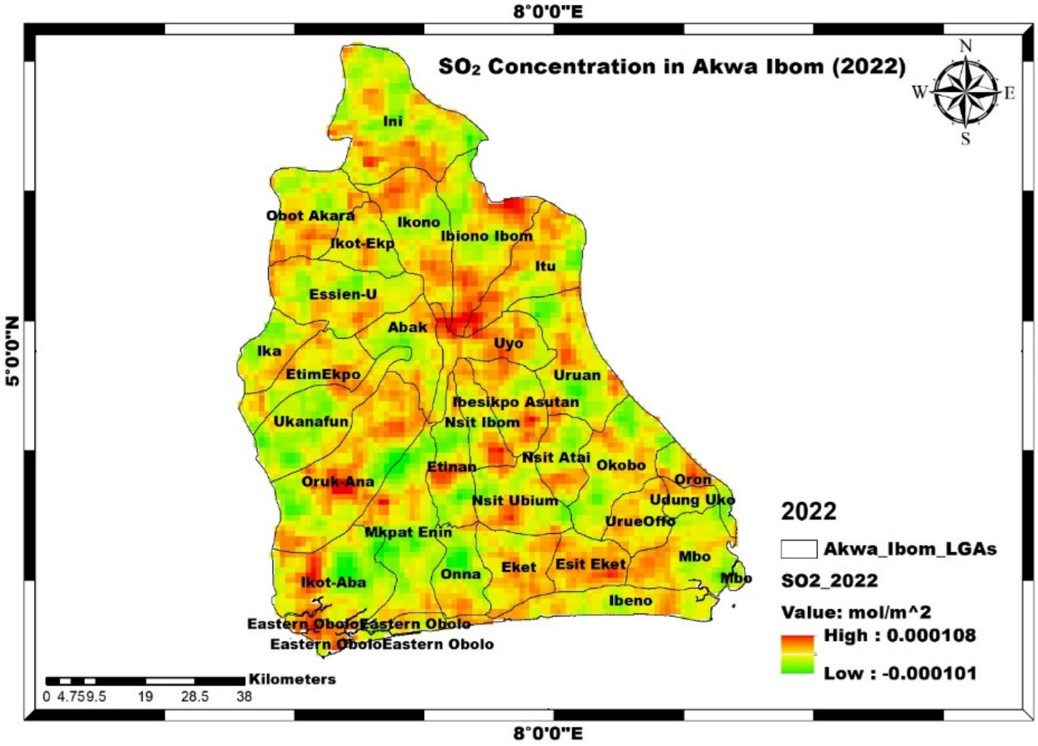

Fig. 13: Map illustrating the distribution of SO₂ concentration across Akwa Ibom in 2022

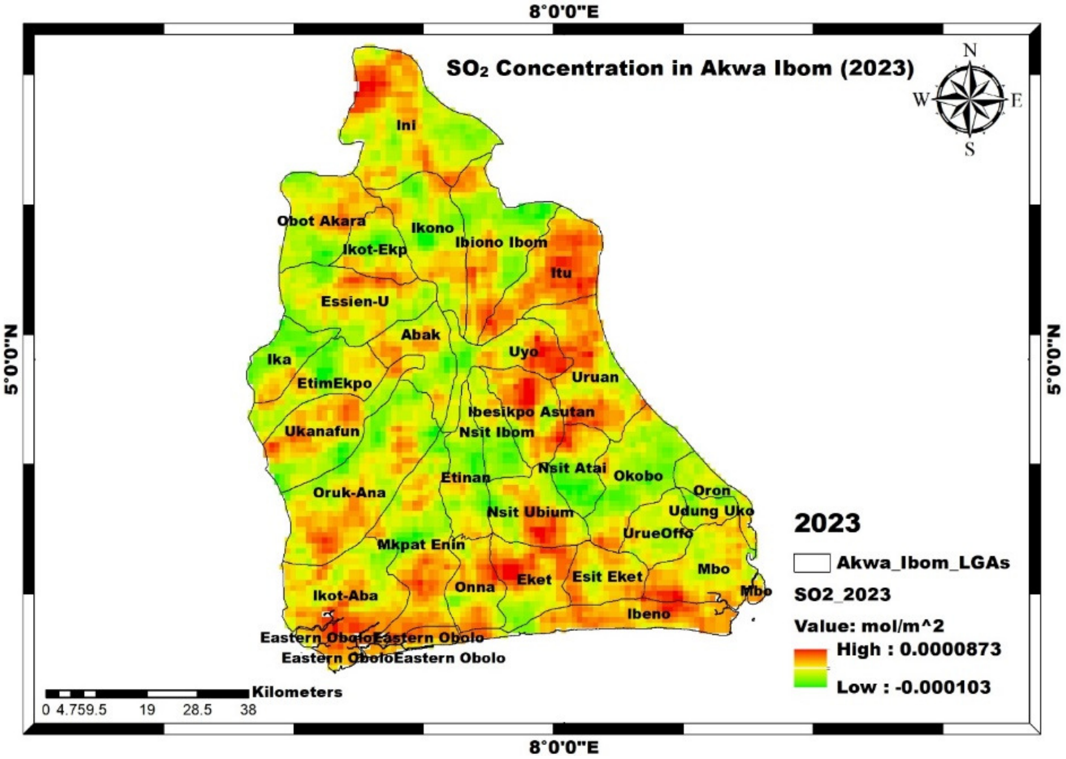

Fig. 14: Map illustrating the distribution of SO_2 concentration across Akwa Ibom in 2023

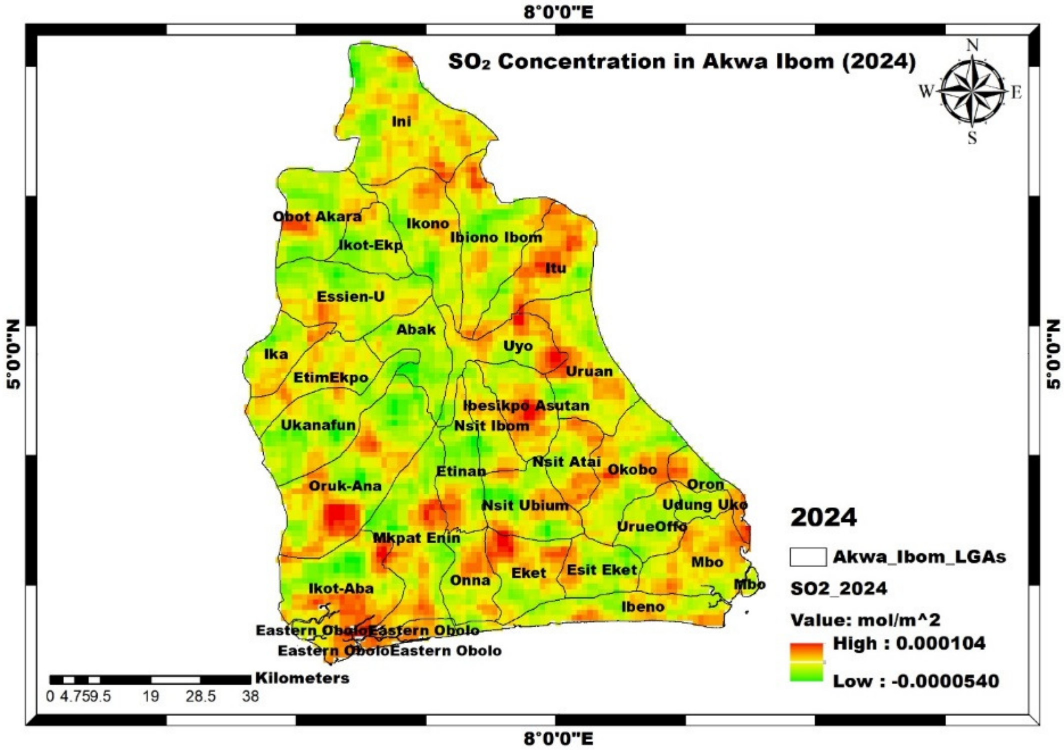

Fig. 15: Map illustrating the distribution of SO_2 concentration across Akwa Ibom in 2024

Analysis for Statistically Significant Difference

For NO_2 (Table 4), a paired sample t-test revealed a high statistically significant difference between 2020 to 2021 (p = <0.001) and statistically significant difference between 2019 to 2024 (p = 0.027). No statistically significant difference was observed between 2019 to 2020 (p = 0.737), 2021 to 2022 (p = 0.469), 2022 to 2023 (p = 0.523) and 2023 to 2024 (p = 0.900). For SO_2, there was no statistically significant difference between 2019 to 2020 (p = 0.322), 2020 to 2021 (p = 0.085), 2021 to 2022 (p = 0.430), 2022 to 2023 (p = 0.193) and 2023 to 2024 (p = 0.059). A high statistically significant difference was observed between 2019 to 2024 (p = <0.001).

Table 4: Significant difference between in the study years

Parameters	2019 – 2020	2020 – 2021	2021 - 2022	2022– 2023	2023 -2024	2019– 2024
NO_2	P = 0.737	P < 0.001	P = 0.469	P = 0.523	P = 0.900	P = 0.027
SO_2	P = 0.32	P 0.085	P = 0.430	P = 0.193	P = 0.059	P = 0.001

p < 0.01 = high significant difference; p ≤ 0.05 = significantly difference; p > 0.05 = no significant difference (Okoduwa and Amaechi, 2023)

CONCLUSION

This study has successfully mapped the spatiotemporal dynamics of NO_2 and SO_2 in Akwa Ibom State from 2019 to 2024. The findings confirm that air quality is significantly influenced by anthropogenic activities, with clear hotspots in commercial and industrial areas. The trends further reveal the tangible impact of macroeconomic policies and global events on the local environment. While year-to-year changes were not always statistically significant, the analysis revealed crucial, significant long-term trends. A statistically significant increase was found for NO_2 between 2019 and 2024, and a highly statistically significant increase was confirmed for SO_2 over the same period. Furthermore, a highly statistically significant spike in NO_2 from 2020 to 2021 provides concrete statistical evidence of the severe impact of the post-pandemic economic rebound on air quality. These significant findings move beyond mere fluctuation and indicate a pressing and worsening public health issue that demands urgent and sustained attention.

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