

Spatiotemporal Assessment of Particulate and Gaseous Air Pollutants in Northwestern Nigeria (2000–2024) Using Satellite-Derived Datasets

Lami Karimatu Abdullahi

Faculty of Basic Medical Sciences, Department of Chemistry, Baze university, Abuja

Corresponding Author's Email: karimatu2004@gmail.com

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ABSTRACT

Atmospheric pollution remains a persistent environmental and public health challenge in Northwestern Nigeria, driven by rapid urbanization, biomass burning, and industrial growth. This study assessed the spatial and temporal distribution of five key pollutants: Particulate Matter (PM_{2.5}), Aerosol Optical Depth (AOD), Nitrogen Dioxide (NO₂), Carbon Monoxide (CO), and Ozone across the region over a 24 year period from 2000 to 2024. Monthly satellite derived datasets were obtained from NASA's Giovanni platform using MERRA 2 and OMI/Aura products with spatial resolutions ranging from 0.25 degrees to 1.0 degree and a monthly temporal scale. Geographic Information System (GIS) software was applied to generate mean concentration maps, while temporal trends were analyzed using statistical tools. Results revealed significant spatial disparities in pollutant concentrations, with hotspots in urban and industrial areas such as Kaduna, Kano, and Kebbi, and lower levels in rural northern states including Sokoto and Katsina. Seasonal variations were evident, with higher pollution levels during the dry Harmattan months. Although some pollutants, particularly PM_{2.5} and NO₂, showed slight declines in recent years, air quality remains a pressing concern. The study concludes that sustained exposure to harmful pollutants poses risks to public health, especially in urban centers, underscoring the need for targeted policy action, cleaner energy adoption, and improved monitoring systems. Future research should focus on assessing the direct health impacts of long term exposure through epidemiological studies.

Keywords: Air Pollution, Spatiotemporal Analysis, Satellite Data, Northwestern Nigeria and Giovanni

1.0 INTRODUCTION

Air pollution has become an escalating global environmental and atmospheric concern, significantly impacting climate systems, biodiversity, urban sustainability, and human well-being (Afifa et al., 2024). According to the World Health Organization (WHO), ambient (outdoor) air pollution is responsible for approximately 4.2 million premature deaths annually, with the majority occurring in low- and middle-income countries where monitoring systems are either inadequate or nonexistent (Adamkiewicz et al., 2020). The 2023 State of Global Air report further confirms that over 90% of the world's population breathes air containing harmful levels of pollutants that exceed WHO guidelines (Dimitroulopoulou et al., 2023). This growing threat is not confined to megacities; rural and semi-urban areas are increasingly affected by agricultural practices, deforestation, waste burning, and transboundary pollution.

From an economic standpoint, air pollution **imposes substantial economic burdens globally** (Zheng et al., 2025). The World Bank (2022) estimates that the economic cost of air pollution exceeds \$8.1 trillion annually, accounting for approximately 6.1% of global GDP when healthcare costs, lost labor productivity, and

ecosystem degradation are considered. In many developing countries, the absence of strong regulatory enforcement, combined with rapid urbanization and energy demands, results in rising pollutant emissions from transport, industry, biomass combustion, and power generation (Chandra Voumik & Sultana, 2022). In sub-Saharan Africa, the air pollution crisis has grown more complex due to the convergence of natural and human-driven sources (Bello et al., 2022). The region experiences extensive seasonal biomass burning, increased vehicular emissions, rapid land use changes, and frequent Saharan dust intrusions, particularly during the Harmattan season (N'Datchoh et al., 2025). Despite this, data availability remains critically low, and monitoring efforts are limited. Nigeria, the region's most populous and economically dynamic nation, exemplifies this paradox: while urban and industrial growth is accelerating, institutional responses to air quality management remain fragmented and reactive (Abulude & Abulude, 2021).

Among Nigeria's six geopolitical zones, Northwestern Nigeria, comprising Kebbi, Sokoto, Zamfara, Katsina, Kano, Jigawa, and Kaduna states, stands out due to its climatic sensitivity, expanding population centers, and increasing environmental pressures (Salihu et al., 2018).

The region is influenced by distinct Sahelian climatic patterns, including long dry seasons, frequent dust storms, and low vegetation cover, all of which exacerbate air pollution dispersion and retention (Ozer, 2002). Additionally, growing urban centers like Kano and Kaduna have seen rapid industrialization and motorization, contributing significantly to atmospheric degradation (Kamana et al., 2024). Yet, despite the scale of these challenges, comprehensive long-term and spatially detailed studies on atmospheric pollution in Northwestern Nigeria remain scarce (Ofoefie et al., 2022). Most existing efforts have been limited in scope, focusing on short-term field measurements or localized studies (Dickin & Gabrielsson, 2023). This has left a critical gap in understanding the temporal evolution, seasonal patterns, and spatial disparities of pollution across the region (Ma et al., 2024).

To address this gap, the present study undertakes a spatiotemporal assessment of particulate and gaseous air pollutants in Northwestern Nigeria (2000–2024) using satellite-derived datasets. The research employs a suite of atmospheric indicators derived from long-term multi-sensor data archives to map pollution levels, track variability, and identify high-risk zones. The study explores how pollution patterns evolve with respect to seasons (wet and dry), geography (urban and rural), and time (2000 to 2024), offering insights into the underlying drivers and temporal shifts in pollutant accumulation.

The rationale for adopting satellite remote sensing stems from the paucity of ground-based monitoring stations in Nigeria, especially in the northern region. Remote sensing enables consistent, large-scale observation of atmospheric variables, providing high-resolution spatial insights over multiple years. By leveraging tools such as MODIS, OMI, and other satellite platforms available via the NASA Giovanni portal, this study offers an evidence-based approach to understanding atmospheric pollution trends in one of the country's most ecologically and economically important regions.

2.0 MATERIAL AND METHOD

Northwestern Nigeria comprises seven states that make up the Northwestern geopolitical zone: Kebbi, Sokoto, Zamfara, Katsina, Kano, Jigawa, and Kaduna. These states form the core of the study area, located between latitudes 9°00'N and 14°00'N and longitudes 3°00'E and 10°00'E, covering a significant portion of Nigeria's savannah and Sahel ecological zones (figure 1). The region shares an international border with the Republic of Niger to the north, while it is bounded by Northeastern Nigeria to the east, North-Central Nigeria to the south, and the Republic of Benin to the west via Kebbi State (Abdussalam et al., 2025). The region is

predominantly flat with scattered rocky outcrops and a gradual transition from semi-arid conditions in the south to arid conditions in the north (Babati et al., 2021). Soils are generally sandy or loamy with sparse vegetation, making the area highly susceptible to desertification, soil erosion, and land degradation (Musa et al., 2022).

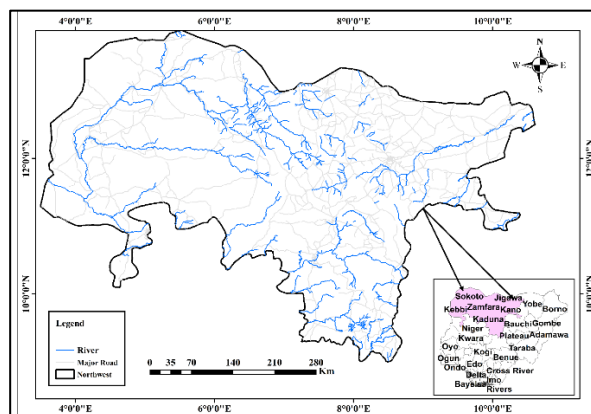


Figure 1: Map of the Study Area

Climatically, Northwestern Nigeria experiences a tropical continental climate, characterized by a rainy season (May–September) and a prolonged dry season (October–April). The Harmattan winds—dry, dust-laden northeasterly trade winds from the Sahara—dominate the dry months and significantly influence atmospheric pollution levels (Baba et al., 2022). Annual rainfall ranges from over 1,000 mm in southern Kaduna to less than 500 mm in Sokoto and northern Katsina, contributing to varied environmental and agricultural conditions. Socio-economically, the region is home to some of Nigeria's most populated and economically active cities, particularly Kano and Kaduna, which are major centers of commerce, transportation, and industry (Isa et al., 2023). These urban hubs face increasing pressure from rapid urbanization, vehicular traffic, biomass burning, and diesel-powered generators, all of which contribute to high levels of air pollution, especially in the dry season. In rural areas, traditional agricultural practices, including slash-and-burn farming and the widespread use of wood and charcoal for cooking, further add to the emission load. Limited vegetation cover and poor environmental regulations exacerbate pollutant retention and dispersion (Baba et al., 2022). The region lacks a reliable ground-based air quality monitoring network, making it necessary to rely on satellite-based datasets and remote sensing tools for long-term pollution analysis. These geographic, climatic, and socio-economic characteristics make Northwestern Nigeria highly vulnerable to air quality degradation and justify its selection as the focus of a spatiotemporal pollution assessment.

Table 1: Data, Data Source, and Resolution

S / N	Dataset Description	Parameter	Data Source	Spatial Resolution	Temporal Resolution	Timeframe	Additional Info
1	PM _{2.5} Mean Accumulated Map	PM _{2.5} Surface Mass Concentration (kg/m ³)	MERRA-2 (M2TMNX FLX v5.12.4)	0.5° × 0.625°	Monthly	Jan 2000 – Dec 2024	Averaged spatially across the entire timeframe
2	PM _{2.5} Time Series Area-Average Graph	PM _{2.5} Surface Mass Concentration (kg/m ³)	MERRA-2 (M2TMNX FLX v5.12.4)	0.5° × 0.625°	Monthly	Jan 2000 – Dec 2024	Area-averaged over Northwestern Nigeria
3	AOD Mean Accumulated Map	Aerosol Optical Depth (550 nm)	MERRA-2 (M2TMNX AER v5.12.4)	0.5° × 0.625°	Monthly	Jan 2000 – Dec 2024	Long-term spatial mean map
4	AOD Time Series Graph	Aerosol Optical Depth (550 nm)	MERRA-2 (M2TMNX AER v5.12.4)	0.5° × 0.625°	Monthly	Jan 2000 – Dec 2024	Area-averaged time series
5	NO ₂ Mean Accumulated Map	NO ₂ Tropospheric Column (mol/m ²)	OMI/Aura (OMNO2d v003)	0.25° × 0.25°	Monthly	Jan 2005 – Dec 2024	Mean monthly spatial map
6	NO ₂ Time Series Area-Average Graph	NO ₂ Tropospheric Column (mol/m ²)	OMI/Aura (OMNO2d v003)	0.25° × 0.25°	Monthly	Jan 2005 – Dec 2024	Monthly average over study area
7	CO Mean Accumulated Map	CO Total Column Amount (mol/m ²)	MERRA-2 (M2TMNX FLX v5.12.4)	0.5° × 0.625°	Monthly	Jan 2000 – Dec 2024	Mean concentration map
8	CO Time Series Graph	CO Total Column Amount (mol/m ²)	MERRA-2 (M2TMNX FLX v5.12.4)	0.5° × 0.625°	Monthly	Jan 2000 – Dec 2024	Regional monthly trend
9	Ozone Concentration Map	Ozone Total Column (Dobson Units)	OMI/Aura (OMDOAO 3e v003)	1.0° × 1.0°	Monthly	Jan 2005 – Dec 2025	Spatial monthly average
10	Ozone Time Series Graph	Ozone Total Column (Dobson Units)	OMI/Aura (OMDOAO 3e v003)	1.0° × 1.0°	Monthly	Jan 2005 – Dec 2025	Monthly area-averaged trend

2.1 Data Processing

The data processing phase of this study involved a systematic and rigorous approach to acquiring, cleaning, and preparing monthly air quality datasets for analysis. All data were sourced from the NASA Giovanni (Geospatial Interactive Online Visualization and Analysis Infrastructure) portal, an advanced online tool developed by NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC). Giovanni offers access to a wide range of satellite-based and reanalysis datasets and was chosen due to its accuracy, spatial-temporal coverage, and suitability for environmental research. The datasets selected for this study include monthly measurements of PM_{2.5} surface mass concentration, Aerosol Optical Depth (AOD) at 550 nm, Nitrogen Dioxide (NO₂) tropospheric column

density, Carbon Monoxide (CO) total column, and Ozone total column (Table 1). These five parameters were prioritized because they represent the most widely used indicators of anthropogenic and natural air pollution, are strongly linked to public health impacts, and are consistently available across long-term satellite records. Other pollutants such as SO₂, VOCs, or PM₁₀ were excluded primarily due to limited temporal coverage, weaker satellite retrieval reliability, or redundancy with the chosen parameters.

Data acquisition was carried out by specifying each dataset's temporal range and geographical coverage directly within Giovanni. For PM_{2.5}, AOD, and CO, data spanning from January 2000 to December 2024 were selected. For NO₂ and Ozone, data were extracted from January 2005 to December 2025 to match the availability

of satellite missions like Aura-OMI. The spatial extent was defined using a bounding box covering the states in Northwestern Nigeria—namely Sokoto, Kebbi, Zamfara, Katsina, Kano, Jigawa, and Kaduna. By using Giovanni's built-in spatial sub-setting tool, the data were limited to only this region, ensuring that the analysis was focused and context-specific.

The spatial resolution of the datasets was approximately $0.1^\circ \times 0.1^\circ$ (about 10 km at the equator), which provides sufficient detail for regional-scale assessments but may miss localized variations in pollution. Satellite-derived products inherently contain uncertainties related to sensor calibration, retrieval algorithms, cloud cover interference, and atmospheric scattering effects. These uncertainties were acknowledged in interpreting results. While no direct ground-based validation data were available for Northwestern Nigeria, the selected datasets (e.g., MERRA-2, OMI, and AIRS) are widely peer-reviewed and validated globally, making them suitable proxies for large-scale pollution assessments.

Following acquisition, the datasets were processed to generate both spatial and temporal products. For spatial analysis, monthly data were aggregated across the entire study period to produce mean accumulated concentration maps. This process involved averaging the monthly values for each grid cell over the years, resulting in a visual representation of long-term pollution intensity across the region. These maps enabled the identification of persistent pollution hotspots and spatial disparities in air quality.

For temporal analysis, area-averaged time series graphs were created. Giovanni computed the mean value of each parameter across all grid cells within Northwestern Nigeria for every month in the study period. This produced detailed time series plots that illustrated how concentrations of $PM_{2.5}$, AOD, NO_2 , CO, and Ozone fluctuated over time, thereby supporting trend detection, seasonal variation analysis, and impact assessment. Special attention was given to the Harmattan season (December–February), during which episodic Saharan dust storms and transboundary pollution events are prevalent. These effects were incorporated into the seasonal interpretation of time series patterns, acknowledging their role in driving peaks in particulate matter and aerosol loading.

The data outputs were exported in formats suitable for advanced analysis and visualization. Numerical data were saved as Comma-Separated Values (CSV) files, while spatial maps were downloaded as NetCDF (.nc) files for compatibility with Geographic Information

System (GIS) software such as QGIS and ArcGIS. Time series graphs were downloaded as high-resolution PNG images for documentation, while their numerical equivalents were used for plotting custom graphs in Microsoft Excel.

To ensure data quality and reliability, only peer-reviewed and validated datasets were used. These include the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), the Ozone Monitoring Instrument (OMI) aboard NASA's Aura satellite, and the Atmospheric Infrared Sounder (AIRS) where applicable. Although Giovanni provides preprocessed data, additional preprocessing steps were applied: missing monthly values were flagged and excluded from trend calculations, extreme outliers (values beyond ± 3 standard deviations) were inspected and retained only if climatologically consistent, and no artificial smoothing was applied to avoid biasing natural variability. Furthermore, all datasets were analyzed using a consistent temporal resolution, monthly averages, to ensure comparability across parameters. By adhering to this uniform structure, the study maintained methodological rigor and avoided biases associated with mixed-resolution datasets.

2.2 Method

The method of data analysis for this study was structured to comprehensively assess both the spatial and temporal characteristics of key air pollutants across Northwestern Nigeria, using monthly datasets obtained from NASA's Giovanni platform. The focus was on five atmospheric parameters: $PM_{2.5}$ surface mass concentration, Aerosol Optical Depth (AOD), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), and Ozone total column concentration. The spatial analysis was conducted first to understand the geographic distribution and concentration patterns of each pollutant across the study area, followed by a detailed temporal trend analysis to evaluate seasonal variability and long-term trends.

For the spatial analysis, mean accumulated concentration maps were generated for each pollutant using monthly data over the respective study periods (2000–2024 for $PM_{2.5}$, AOD, and CO; 2005–2025 for NO_2 and Ozone). These maps, downloaded in NetCDF format from the Giovanni platform, were processed using Geographic Information System (GIS) software such as QGIS and ArcGIS. Each map was clipped to the administrative boundaries of Northwestern Nigeria to ensure relevance to the study region. The pollutant values were classified using the natural breaks (Jenks) classification method, which groups data into classes based on inherent patterns in the dataset. This enabled the visualization of spatial

disparities and the identification of hotspots, areas with consistently high pollutant concentrations.

Following the spatial assessment, the temporal analysis was conducted using the monthly area-averaged values for each pollutant over the study periods. The time series data were exported from Giovanni in CSV format and analyzed using Microsoft Excel and Python programming tools (particularly the Pandas and Matplotlib libraries). Descriptive statistical measures, including mean, standard deviation, maximum, minimum, and coefficient of variation were calculated to summarize the variability in each pollutant over time. Line plots of monthly concentrations were generated to visualize trends, highlight seasonal fluctuations, and detect any anomalies. These visualizations helped determine whether pollutant levels were increasing, decreasing, or remaining stable over time.

To quantitatively assess long-term changes, linear regression analysis was applied using the Ordinary Least Squares (OLS) method. This allowed for the estimation of trend lines and the calculation of slope coefficients, indicating whether concentrations were rising or falling over the years. The statistical significance of these trends was evaluated using p-values and R^2 values, which provided insight into the reliability and strength of the observed patterns. In addition, seasonal decomposition of time series (STL) was performed on selected parameters such as $PM_{2.5}$ and AOD to separate the overall trend, seasonal cycles, and residual components. This technique enabled a clearer understanding of the underlying seasonal behavior of these pollutants, such as increases during dry harmattan periods and reductions during the wet season.

Cross-parameter comparisons were also undertaken to identify potential correlations or co-occurrence between pollutants. For instance, trends in AOD were analyzed alongside $PM_{2.5}$ to explore the relationship between aerosol loading and surface particulate matter, while NO_2 and CO trends were compared to assess contributions from vehicular and biomass burning emissions. All findings from the temporal and spatial analyses were integrated to provide a holistic view of air quality dynamics across Northwestern Nigeria. The results were interpreted in light of local climatic conditions, land use patterns, and anthropogenic activities, offering actionable insights for environmental management, public health protection, and policy formulation.

3.0 RESULTS AND DISCUSSION

3.1 $PM_{2.5}$ Concentration and Trends

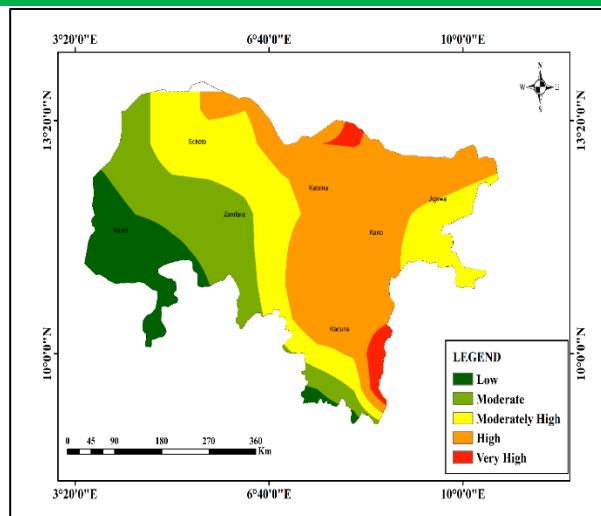


Figure 2: $PM_{2.5}$ mean accumulated map from 2000 to 2024

Figure 2 shows the $PM_{2.5}$ mean accumulated map from 2000 to 2024 for Northwestern Nigeria. The findings reveal significant spatial variations in particulate matter concentration across the region, highlighting areas of environmental concern. The map classifies the region into five zones, Low, Moderate, Moderately High, High, and Very High, based on long-term average $PM_{2.5}$ concentrations. The southeastern part of Kaduna State, represented in red, falls within the “Very High” pollution category. This high level is likely attributable to rapid urbanization, dense population, industrial activities, and heavy vehicular emissions within and around the Kaduna metropolis. Similarly, the central parts of Kano and northern sections of Kaduna and Katsina show “High” to “Moderately High” $PM_{2.5}$ levels, reflecting the impact of urban-based emissions, poor waste disposal practices, and widespread open burning. These urban centers are among the most economically active in the region, and their pollution profiles mirror the intensity of human activities. In contrast, states like Kebbi, western Zamfara, and parts of Sokoto are dominated by “Low” to “Moderate” pollution levels. These areas are largely rural with less industrial activity, lower population density, and reduced vehicular traffic, contributing to cleaner ambient air. However, moderate pollution levels in some parts of Sokoto and Zamfara suggest possible influences from desert dust during the Harmattan season and the use of biomass fuels for domestic purposes.

When compared to existing studies, the findings align closely with the work of Mahmud et al. (2023), which identified northern urban centers such as Kano and Kaduna as pollution hotspots due to high anthropogenic emissions and seasonal dust events. The World Bank (2020) also reported elevated $PM_{2.5}$ exposure levels in these same locations, particularly during the dry season

when particulate concentration surges due to Saharan dust influx. However, unlike earlier studies such as Owoade et al. (2021), which reported a more uniform PM_{2.5} distribution across the region, the current analysis provides a more detailed spatial resolution and longer temporal coverage, offering a nuanced understanding of pollution intensity and distribution (Omogbe Nosa & Omorede, 2025). The implications of these findings are far-reaching. Long-term exposure to high PM_{2.5} levels is associated with severe health risks, including respiratory infections, cardiovascular diseases, and increased mortality. Populations in areas like Kaduna, Kano, and Katsina are particularly vulnerable, emphasizing the need for urgent air quality interventions. To address this, policy actions should prioritize emission control in urban centers, promote cleaner cooking and transport technologies, enforce industrial regulations, and invest in real-time air quality monitoring systems. Strengthening public awareness and integrating environmental health into urban planning are also critical to mitigating the harmful impacts of particulate matter across Northwestern Nigeria.

Temporal Trends

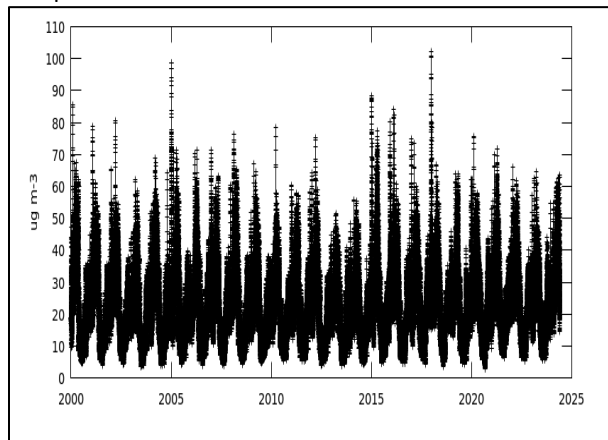


Figure 3: PM_{2.5} time series area average graph for Northwestern Nigeria from 2000 to 2024

Figure 3 shows the PM_{2.5} time series area average graph for Northwestern Nigeria from 2000 to 2024 illustrates a clear seasonal and inter-annual fluctuation in ambient particulate matter concentration over the 24-year period. The values, expressed in micrograms per cubic meter ($\mu\text{g}/\text{m}^3$), consistently range between $10 \mu\text{g}/\text{m}^3$ and over $100 \mu\text{g}/\text{m}^3$, with noticeable peaks occurring annually, particularly during the dry season months, and troughs during the wet season. This pattern is strongly indicative of seasonal variations, primarily influenced by meteorological factors and human activities.

The pronounced annual spikes in PM_{2.5} concentrations can be attributed to the Harmattan season, which

typically spans from November to March. During this period, dry and dusty winds from the Sahara Desert contribute significantly to elevated particulate matter levels. These seasonal dust storms are often intensified by biomass burning, open waste burning, and increased road dust, especially in urban centers. The lower PM_{2.5} values, typically observed between June and September, correspond to the rainy season, during which precipitation helps to wash out atmospheric particles, resulting in cleaner air. There is also a notable variation in peak intensities over the years, with years like 2005, 2013, and 2015 showing exceptionally high PM_{2.5} values that exceed $100 \mu\text{g}/\text{m}^3$. These peaks may be linked to extreme weather conditions, intensified urban emissions, or regional dust events. In contrast, some years after 2016 show slightly reduced peak levels, possibly due to gradual environmental regulation, climate variability, or changes in land use and emission sources. However, despite these occasional dips, the overall trend does not indicate a strong long-term decline, implying that air quality challenges remain persistent across Northwestern Nigeria.

3.2 Aerosol Optical Depth (AOD) Patterns

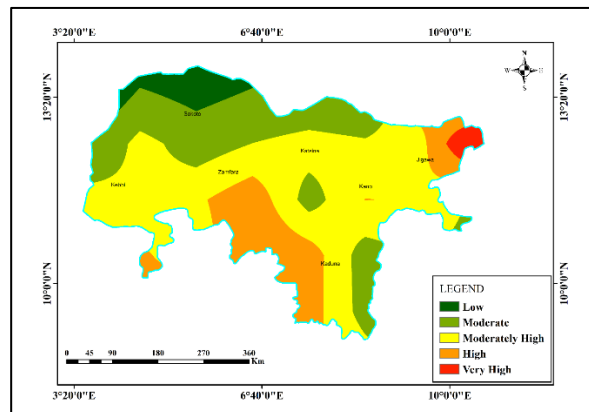


Figure 4: The mean accumulated Aerosol Optical Depth (AOD) map for Northwestern Nigeria from 2000 to 2024

Figure 4 shows the mean accumulated Aerosol Optical Depth (AOD) map for Northwestern Nigeria from 2000 to 2024 provides a spatial representation of atmospheric aerosol loading across the region over a 24-year period. AOD is a key indicator of the number of light-extinguishing aerosols (such as dust, smoke, and pollution particles) suspended in the atmosphere. Higher AOD values correspond to denser aerosol concentrations, which can impact air quality, climate, and human health. According to the map, aerosol concentrations vary significantly across the region, with levels classified as Low, Moderate, Moderately High, High, and Very High. The map reveals that Jigawa State, particularly its northeastern part, experiences the highest AOD values,

designated as “Very High” on the map. This could be due to its geographical proximity to the Sahel and Sahara Desert, making it more prone to dust intrusion, especially during the Harmattan season. This region also experiences significant dry-season farming and biomass burning, which contribute to aerosol emissions. Parts of Kaduna and Zamfara, as well as southern Kebbi, are classified under the “High” AOD category, likely influenced by a combination of anthropogenic sources such as vehicular emissions, unregulated industrial activity, and agricultural residue burning. In contrast, central Kano, parts of Katsina, and surrounding zones fall into the “Moderately High” and “Moderate” categories. These areas are urbanized but may benefit from localized rainfall and urban greenery that help reduce particulate buildup. The lowest AOD levels are observed in northern Sokoto and parts of Katsina, where aerosol concentrations are classified as “Low” to “Moderate.” These regions are more rural and less industrialized, and although they are exposed to desert dust, the lower population density and reduced human activity may help in keeping AOD levels relatively lower. The spatial pattern observed is consistent with previous studies, including Ibe et al. (2025), who also reported higher aerosol loading in the northeastern corridor of Northwestern Nigeria, especially in Jigawa and parts of Kaduna. These studies highlighted the role of seasonal dust storms and dry-season biomass burning in influencing AOD patterns. Onyeuwaoma et al. (2015), using MODIS AOD data, also found similar spatial distributions, noting that higher AOD levels correlate with regions experiencing longer dry seasons and intense agricultural burning.

Temporal Trends

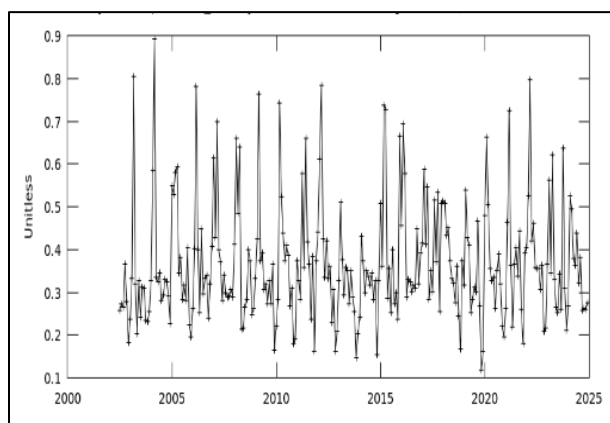


Figure 5: Time series graph of Aerosol Optical Depth (AOD) over northwestern Nigeria from 2000 to 2024

Figure 6 shows the time series graph of Aerosol Optical Depth (AOD) over northwestern Nigeria from 2000 to 2024 shows a detailed picture of the aerosol variability

and atmospheric clarity in the region over the past two and a half decades. AOD is a key parameter for understanding the extent of aerosol particles, such as dust, smoke, and pollution, in the atmosphere. Values closer to zero indicate a clearer atmosphere, while higher values suggest more aerosols and reduced visibility. From the graph, AOD values typically range between 0.2 and 0.85, with sharp fluctuations indicating periodic aerosol events. The early 2000s, particularly between 2003 and 2007, experienced frequent and intense spikes in AOD, some approaching values as high as 0.8. These peaks are likely linked to intensified Harmattan seasons, when dry and dusty northeasterly trade winds carry large volumes of Saharan dust into the region. Additionally, agricultural burning and biomass combustion, common in rural parts of northwestern Nigeria, may have contributed to elevated aerosol levels.

Between 2008 and 2015, the pattern continued with high variability, but the frequency of extreme peaks appears slightly reduced. Post-2015, the AOD values seem to stabilize somewhat, showing fewer extreme highs and exhibiting a mild declining trend, particularly between 2016 and 2019. This reduction may be attributed to improved vegetation cover in localized areas, changing land use practices, better environmental awareness, or favorable meteorological conditions such as increased precipitation that suppressed dust suspension. Nevertheless, the sharp spikes seen again in 2020 and 2022 indicate that while there may be a general decline, intense aerosol events continue to occur, likely due to episodic climate events or persistent human-induced activities like deforestation, bush burning, and urban emissions. These recurring peaks emphasize the region’s continued vulnerability to atmospheric pollution and the influence of transboundary dust transport.

Comparatively, these findings are consistent with Onyeuwaoma et al. (2015), who noted high AOD values in northern Nigeria during the dry season (November to March), reaching peak values above 0.7. The similarity in seasonal trends and peak intensities supports the interpretation that Harmattan remains a dominant factor influencing aerosol loading in the region. Likewise, Balarabe et al. (2016) found that northwestern Nigeria records higher AOD levels than the southern parts of the country, attributing this to its proximity to the Sahara and the frequency of land-surface disturbances. Their analysis using MODIS satellite data also reported declining AOD trends in some areas after 2015, which aligns with the observed pattern in this time series graph. However, a contrasting perspective is provided by Ibrahim et al. (2022), who reported a rising AOD trend across the wider Sahel region, driven by increasing desertification, urbanization, and land degradation. The

difference in findings could result from regional disparities, northwestern Nigeria may have benefited from specific local interventions or vegetation recovery not occurring uniformly across the broader Sahel zone.

3.3 NO₂ Distribution and Dynamics

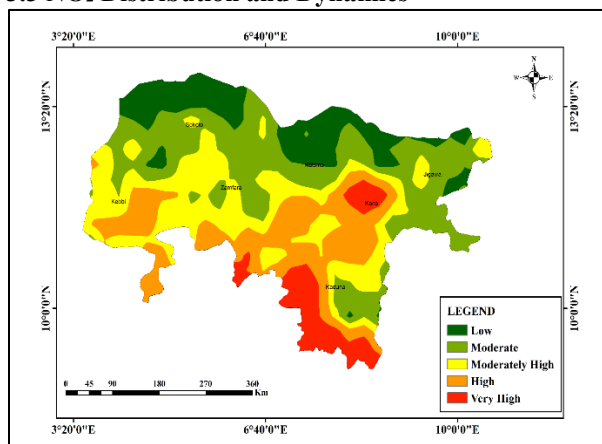


Figure 6: NO₂ (Nitrogen Dioxide) mean accumulated map of northwestern Nigeria from 2000 to 2024

The NO₂ (Nitrogen Dioxide) mean accumulated map of northwestern Nigeria from 2000 to 2024 presents a detailed and revealing picture of long-term spatial patterns in atmospheric pollution across the region. The results show a marked concentration gradient, with NO₂ levels increasing from the northern parts of the regions such as Sokoto, Katsina, and Jigawa, towards the central and southern areas, especially in Kano and Kaduna states. These southern zones are characterized by “High” to “Very High” NO₂ accumulation, while northern parts remain in the “Low” to “Moderate” categories. This distribution reflects both population density and the intensity of anthropogenic activities, with more urbanized and industrialized states bearing higher pollution burdens.

Kano, located in the central zone, emerges as a major NO₂ hotspot. This finding is consistent with its status as one of the most industrialized and densely populated cities in Nigeria. The high concentration of NO₂ here is likely driven by factors such as heavy vehicular traffic, widespread use of fossil fuel-powered generators, industrial manufacturing, and urban congestion. Similarly, the southern part of Kaduna also shows “Very High” levels, which may be attributed to industrial zones around the state capital, growing peri-urban expansion, and agricultural biomass burning practices. These two areas serve as focal points of economic activity in the region, making them primary contributors to NO₂ emissions over time. Moderately high NO₂ levels are observed in transitional zones like Zamfara and Kebbi,

where semi-urban expansion and mixed land use (agriculture, small-scale industry, and increasing transportation networks) are gradually increasing emission loads. These areas act as buffers between the high NO₂ zones and the relatively clean, low-emission zones further north. In contrast, the far northern areas such as Sokoto, Katsina, and parts of Jigawa, maintain lower NO₂ accumulation due to lower population densities, fewer urban centers, minimal industrial activities, and less reliance on fossil fuels for energy and transport. These regions are more agrarian and less economically urbanized, resulting in less air pollution over time.

The results also suggest that long-term cumulative emissions have continued to build up particularly in urban centers over the 24-year period, indicating a lack of significant interventions to reduce emissions during this time. The spatial concentration and intensity of NO₂ over these urban hubs have not only remained persistent but likely worsened in periods of rapid urban expansion. This is corroborated by the temporal overlap with the rise in population, unregulated construction, increased transportation demands, and energy crises that pushed households and industries to rely heavily on diesel and petrol generators. From a climatological and environmental perspective, the accumulation of NO₂ over time contributes to poor air quality, reduced visibility, and the potential formation of secondary pollutants such as tropospheric ozone. NO₂ also plays a role in altering regional atmospheric chemistry and may influence local weather patterns, particularly in densely polluted areas where heat retention and smog formation become more prevalent.

The broader implication of these results is that the region's urban environments are becoming increasingly hazardous for human health. Prolonged exposure to elevated NO₂ levels is associated with respiratory infections, reduced lung development in children, increased risk of asthma, cardiovascular stress, and premature death. Urban dwellers in Kano and Kaduna are therefore at greater risk compared to rural populations. The absence of stringent air quality monitoring and regulation systems in Nigeria further amplifies the danger, as communities remain unaware of the pollutants they are exposed to on a daily basis. The results of this spatial analysis align with previous studies, such as Tyovenda et al. (2021), which also reported high NO₂ concentrations in urban centers of northern Nigeria due to fossil fuel combustion from traffic, generators, and industrial emissions. The concentration of NO₂ in major cities like Kano is particularly concerning, as long-term exposure to this pollutant has been linked to serious

health problems, including respiratory conditions such as asthma, bronchitis, and reduced lung function, especially in vulnerable populations like children and the elderly. Additionally, NO₂ exposure increases the risk of cardiovascular diseases and can contribute to premature mortality. Environmental impacts are also significant; nitrogen dioxide is a precursor to acid rain, which can damage crops, soils, and aquatic systems, while also contributing to the formation of ground-level ozone and fine particulate matter that further degrade air quality.

Temporal Trends

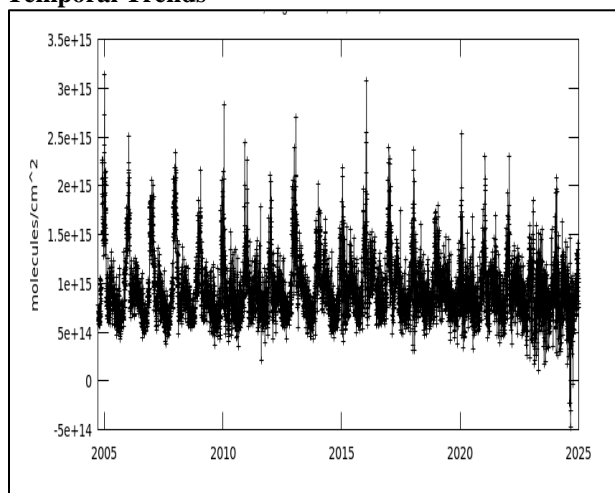


Figure 7: Time series graph of NO₂ (Nitrogen Dioxide) over northwestern Nigeria from 2005 to 2024

The NO₂ (Nitrogen Dioxide) time series area average graph for northwestern Nigeria from 2005 to 2024 presents a detailed picture of long-term atmospheric pollution dynamics in the region. The data show that NO₂ concentrations, measured in molecules per square centimeter, exhibited substantial variability over time, with frequent peaks and troughs indicating fluctuations in emission levels likely tied to seasonal patterns, human activity, and meteorological influences. In the early part of the period, especially between 2005 and 2012, there were repeated high peaks. These peaks suggest significant NO₂ loading, likely resulting from rapid urban expansion, high fossil fuel consumption (especially from vehicular emissions and generator use), and increased industrial activities in urban centers like Kano and Kaduna. This period coincides with Nigeria's population growth and rising energy demand, much of which was met by diesel and petrol-powered generators due to unstable electricity supply.

Following this high-activity phase, the graph shows a noticeable moderation in NO₂ levels around 2013–2016, although values remain elevated and spikes continue. This phase could reflect a period of slight economic and infrastructural adjustment, including a push for

environmental regulations and greater awareness of air pollution's health impacts. There may also have been regional climatic effects, such as heavier rainfall seasons that help disperse pollutants, or policy-driven changes, such as an increase in solar energy adoption in parts of the region. Despite this moderation, occasional spikes persisted especially in 2015 and 2018, indicating episodic pollution events tied to dry seasons, bush burning, or diesel generator usage.

A more defined downward trend appears from around 2019 onward, where the frequency and magnitude of NO₂ spikes decrease significantly. This trend may reflect multiple factors. Firstly, increased penetration of renewable energy technologies, especially solar mini-grids and home solar systems in rural and semi-urban areas, may have reduced dependency on generator emissions. Secondly, the COVID-19 pandemic in 2020–2021 led to reduced industrial operations, restricted travel, and lower fuel combustion, all of which could have contributed to a temporary but significant drop in NO₂ emissions. The continuation of lower levels beyond the pandemic period hints at more structural changes in fuel use, transportation behavior, or possibly improved air dispersion patterns. From a climatological standpoint, the recurring seasonal cycles seen in the graph, with higher NO₂ levels typically peaking during the dry season months (November–March), are consistent with reduced atmospheric dispersion and increased emissions during Harmattan periods, when cooler, stable air traps pollutants closer to the ground. These seasonal dynamics align with findings from Emekwuru and Ejohwomu (2023), who documented seasonal NO₂ variability in northern Nigeria, with higher values during dry months and lower values during the rainy season. The declining trend after 2018 also supports the conclusion of Abaje et al. (2020), who reported improving air quality in some parts of northern Nigeria based on satellite and model data, attributing this to increased policy interest in environmental health, renewable energy promotion, and cleaner fuel campaigns.

3.4 Carbon Monoxide (CO) Trends

Spatial Distribution

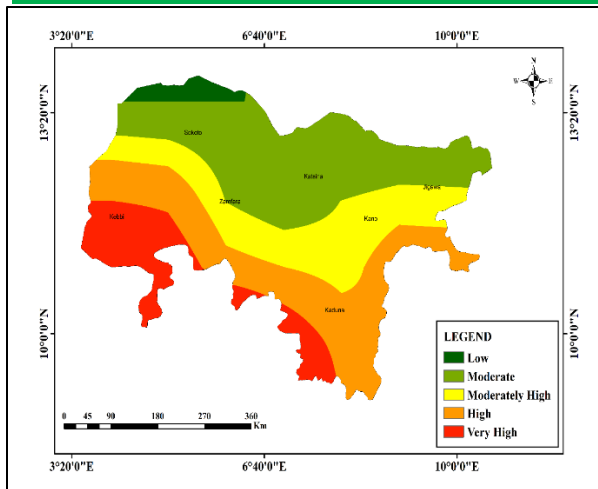


Figure 8: Carbon Monoxide (CO) concentration map for northwestern Nigeria from 2000 to 2024

The mean accumulated Carbon Monoxide (CO) concentration map for northwestern Nigeria from 2000 to 2024 (figure 8) reveals distinct spatial variations in atmospheric CO levels across the region. The map categorizes CO intensity into five levels: Low, Moderate, Moderately High, High, and Very High, represented by a gradient from green in the north to deep red in the south. Northern states such as Sokoto, Katsina, and parts of Jigawa fall within the Low to Moderate CO categories, suggesting relatively cleaner air and lower emissions. These areas are predominantly rural, with sparse population density, limited vehicular traffic, and minimal industrialization, all of which contribute to lower CO concentrations. Conversely, southern parts of the region, particularly southern Kebbi and Kaduna, exhibit High to Very High CO accumulation. These elevated levels are likely driven by increased urbanization, higher traffic volumes, industrial activities, and widespread use of biomass burning for agriculture, which is common in the area during dry seasons. The spatial gradient observed may also be influenced by meteorological and topographic factors, such as air stagnation or limited vertical mixing, which can cause pollutants to accumulate near the ground in the southern zones. These findings are consistent with previous studies such as Baba (2025), which reported elevated CO levels in Kaduna, using satellite datasets.

Temporal Variation

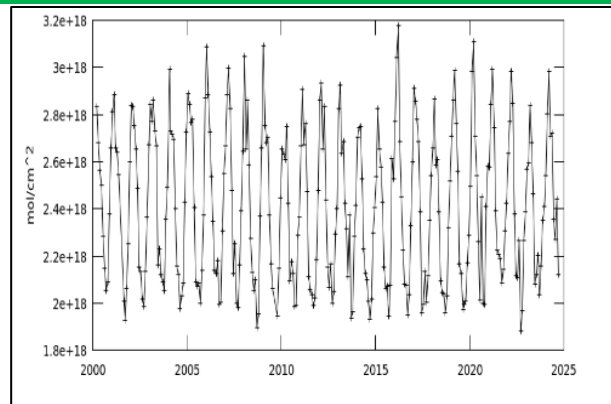


Figure 9: The time series graph depicting area-averaged Carbon Monoxide (CO) concentrations over northwestern Nigeria from 2000 to 2024

The time series graph depicting area-averaged Carbon Monoxide (CO) concentrations over northwestern Nigeria from 2000 to 2024 (figure 9) offers valuable insights into the region's atmospheric pollution dynamics over a 25-year period. Measured in molecules per square centimeter (mol/cm^2), the data exhibits strong and regular seasonal oscillations, with CO values ranging approximately between $1.8 \times 10^{18} \text{ mol}/\text{cm}^2$ and $3.2 \times 10^{18} \text{ mol}/\text{cm}^2$. Each year shows a distinctive pattern: a sharp rise in CO levels during the dry season (typically November through March) and a pronounced decline during the rainy season (around May to September). This cyclical behavior reflects the interaction between climatic seasonality and anthropogenic activities, which are the dominant forces influencing atmospheric CO levels in this region.

The dry season peaks correspond with periods of intense biomass burning, a common practice in northwestern Nigeria for land clearing and post-harvest waste disposal. In addition, the harmattan season, characterized by dry, dusty winds from the Sahara, leads to atmospheric stability and low vertical mixing, which traps pollutants like CO near the surface. The widespread use of fossil fuel-powered generators, due to unreliable electricity supply in both urban and rural areas, also contributes significantly to CO emissions during this period. These sources, coupled with increased vehicular emissions and industrial activity, elevate atmospheric CO concentrations, resulting in the consistent annual spikes observed in the graph. In contrast, the wet season troughs are explained by improved atmospheric cleansing through rainfall washes out pollutants, and convective weather systems enhance vertical dispersion, significantly lowering CO levels.

Importantly, the graph reveals that while seasonal fluctuations in CO levels are pronounced and persistent, there is no strong long-term increasing or decreasing trend across the entire study period. This suggests that while CO-emitting activities (urban growth, transportation, generator use) may have increased, they may be counterbalanced by improvements in fuel efficiency, growing environmental awareness, or favorable meteorological conditions that enhance pollutant dispersion. Nonetheless, some short-term anomalies such as pronounced spikes around 2003, 2015, and 2020 likely point to episodic events such as intense droughts, heightened fire activity, or regional-scale atmospheric stagnation that temporarily enhanced CO accumulation. When compared with existing studies, this temporal pattern aligns closely with findings from Baba (2025), who used satellite-based analysis to study air quality trends in Kaduna. Their results also highlighted the strong seasonal dependence of CO concentrations, particularly in the savannah and Sahel zones, where biomass burning and harmattan conditions amplify dry-season pollution levels.

3.5 Ozone Concentration and Behaviour Spatial Variability

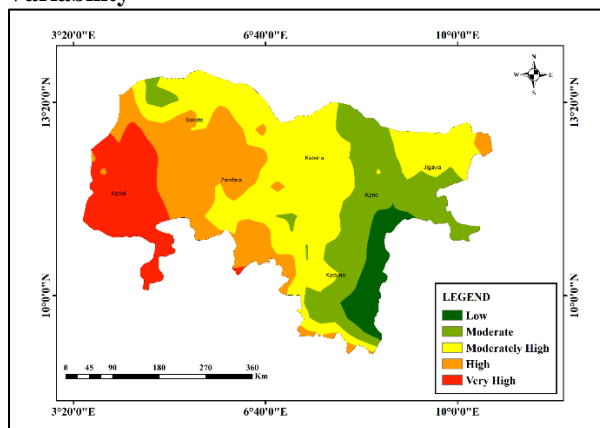


Figure 10: The Ozone Concentration Map of Northwestern Nigeria from 2005 to 2025

The ozone concentration map of Northwestern Nigeria illustrates a clear spatial variation in ground-level ozone pollution across the seven states in the region (Kebbi, Sokoto, Zamfara, Katsina, Kano, Jigawa, and Kaduna) (Figure 10). The map categorizes ozone levels into five classes: low, moderate, moderately high, high, and very high. Notably, Kebbi State exhibits very high ozone concentrations, as indicated by the red shading. This shows intense levels of air pollution in the area, possibly driven by high emissions from vehicular traffic, agricultural burning, or industrial activity, compounded by strong sunlight that accelerates the photochemical reactions leading to ozone formation. Such elevated

levels of ozone are hazardous, posing significant health risks such as respiratory irritation, worsening of asthma, and other cardiovascular complications.

Adjacent to Kebbi, Sokoto and parts of Zamfara show high ozone concentrations (orange areas), which indicate persistent air quality issues likely influenced by regional dust storms, biomass burning, and limited vegetation cover. These conditions enhance the presence of ozone precursors like nitrogen dioxide (NO₂) and volatile organic compounds (VOCs), which react under sunlight to form ozone. Moderately high concentrations (yellow zones) are observed across Katsina, Jigawa, and parts of Zamfara, suggesting the presence of moderate pollution sources, potentially from semi-urban activities, domestic fuel usage, and vehicular emissions. Interestingly, Kano and Kaduna States, despite being more urbanized and industrially active, show low to moderate ozone concentrations (dark and light green areas). This could be attributed to several factors, including better pollution control measures, higher vegetation cover, or meteorological conditions such as wind patterns that help disperse ozone and its precursors. It also highlights the complex interaction between primary pollutants, land use, and atmospheric chemistry, where areas with significant emissions may not always correspond with high ozone levels due to varying environmental conditions.

From a public health and environmental standpoint, the observed spatial disparities in ozone levels raise concern. High and very high ozone concentrations in the western states of the region could result in increased respiratory illnesses and reduced agricultural productivity. This situation underscores the urgent need for localized air quality management strategies. These could include stricter control of emissions, promotion of cleaner energy alternatives, urban greening initiatives, and community awareness campaigns. Monitoring efforts should also be strengthened, integrating other pollutants like PM_{2.5} and NO₂ for a comprehensive understanding of air pollution dynamics across the Northwestern region.

Temporal Trends

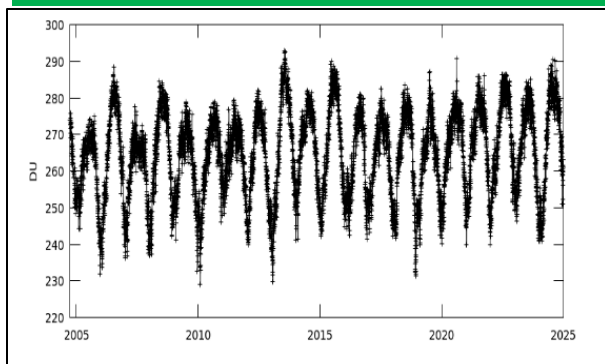


Figure 11: The ozone time series graph for Northwestern Nigeria from 2005 to 2025

The ozone time series graph for Northwestern Nigeria from 2005 to 2025 (figure 11) provides important insights into atmospheric dynamics and air quality patterns across the region. The data, measured in Dobson Units (DU), indicates that ozone concentrations have fluctuated cyclically between approximately 230 DU and 290 DU over the 20-year period. These variations follow a consistent seasonal trend, characterized by distinct annual peaks and troughs, which reflect the climatic rhythm of the region dominated by the dry season (October to April) and the wet season (May to September). During the dry season, ozone levels rise significantly, often reaching values above 270 DU. This can be attributed to several interlinked factors. Firstly, the region experiences intense solar radiation and low humidity, which promote the photochemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs), leading to the formation of ground-level ozone. Secondly, biomass burning a common practice during the dry season for land clearing and agricultural purposes releases substantial quantities of ozone precursors into the atmosphere. Additionally, transboundary dust transport from the Sahara Desert, particularly during the Harmattan, introduces aerosols that can modify atmospheric chemistry and enhance ozone formation. The combined effect of these factors explains the seasonal peaks observed in the graph.

In contrast, ozone levels tend to decline during the wet season, often falling below 250 DU. The presence of frequent rainfall, increased humidity, and thicker cloud cover during this period limits solar radiation and photochemical activity. Moreover, wet deposition processes help in cleansing the atmosphere by removing pollutants and ozone precursors. This results in a drop-in ozone formation, accounting for the seasonal troughs evident in the graph. What is particularly notable from the graph is the absence of a significant long-term upward or downward trend, suggesting that the total column ozone over Northwestern Nigeria has remained relatively stable. This is a positive indication in terms of stratospheric ozone protection, as it suggests there has

been no substantial depletion of the ozone layer over the region. However, the year-to-year variability evidenced by slight changes in the amplitude of ozone peaks and troughs highlights the influence of dynamic environmental and anthropogenic factors. These may include variations in the extent of biomass burning, changes in land use, fluctuations in vehicular emissions, or broader climate anomalies such as El Niño events or shifts in the Intertropical Convergence Zone (ITCZ).

The observed pattern corresponds with findings from several regional studies. For example, Rabiú et al. (2025) reported similar seasonal oscillations in ozone levels across West Africa, attributing them to the region's unique combination of climatic and anthropogenic influences. Brooks & Legrand (2000) also highlighted that the Sudan-Sahel ecological zone, which includes Northwestern Nigeria, consistently experiences elevated ozone levels during the dry season due to both natural (dust, solar intensity) and human (burning, emissions) factors. These studies support the assertion that ozone behavior in the region is not random but closely tied to environmental cycles and human activities.

Although this graph represents total column ozone, primarily found in the stratosphere (where it protects life from harmful UV radiation), the seasonal peaks may coincide with increased levels of ground-level (tropospheric) ozone, a harmful pollutant with significant health and ecological implications. Elevated ground-level ozone is linked to respiratory distress, asthma, reduced lung function, cardiovascular stress, and can also negatively impact plant health and crop yields. Therefore, while the stability of stratospheric ozone is reassuring, it does not negate the potential risks posed by ground-level ozone, especially during the dry season when photochemical activity is heightened. Given these findings, it is essential for policymakers, environmental health officials, and researchers to adopt a multi-level monitoring approach. This should include not only satellite-based observation of total ozone but also ground-based monitoring of surface-level pollutants, including ozone, NO_2 , $\text{PM}_{2.5}$, and CO. Implementing dry-season emission controls, promoting clean energy alternatives, and raising public awareness about air pollution and its effects could play a vital role in reducing ozone precursor emissions and protecting both public health and the environment.

4.0 CONCLUSION

This study provided a comprehensive spatiotemporal assessment of particulate and gaseous air pollutants in Northwestern Nigeria (2000–2024) using satellite-derived datasets, focusing on five key parameters: $\text{PM}_{2.5}$, AOD, NO_2 , CO, and Ozone. The research revealed

marked spatial disparities and temporal fluctuations in pollutant concentrations, driven by both anthropogenic activities and seasonal climatic variations. The spatial analysis showed that pollution hotspots consistently align with major urban and industrial centers, particularly Kaduna, Kano, and parts of Kebbi, which exhibited high to very high levels of PM_{2.5}, NO₂, and CO. In contrast, northern rural areas such as Sokoto and Katsina recorded relatively low concentrations, reflecting less intense human activity.

Seasonal assessments demonstrated recurring patterns of elevated pollutant levels during the dry Harmattan season (November–March), influenced by biomass burning, fossil fuel usage, dust transport, and reduced atmospheric dispersion. Conversely, the wet season consistently brought declines in pollutant levels due to rainfall, higher humidity, and atmospheric cleansing processes. While no strong long-term trends were observed in CO and ozone levels, PM_{2.5} and NO₂ exhibited slight decreases in recent years, potentially reflecting environmental awareness, renewable energy adoption, or pandemic-related activity reductions. However, episodic pollution spikes, especially during extreme dry seasons, continue to threaten regional air quality. Furthermore, the study confirms that ground-level ozone formation is heavily influenced by sunlight, precursor emissions, and seasonal photochemical activity, particularly in western states like Kebbi and Sokoto.

Collectively, these findings underscore the public health risks and environmental implications of persistent atmospheric pollution in the region. Urban populations face higher risks of respiratory and cardiovascular illnesses, while agricultural productivity may also be impacted due to elevated ozone and particulate levels. To build on this work, future research should explore the direct health impacts of long-term pollutant exposure on local populations through epidemiological studies. More importantly, policymakers and environmental agencies must prioritize targeted interventions, such as stricter emission controls, improved urban planning, and the promotion of clean energy to safeguard both public health and environmental sustainability in Northwestern Nigeria.

References

Abaje, I. B., Bello, Y., & Ahmad, S. A. (2020). A Review of Air Quality and Concentrations of Air Pollutants in Nigeria. *Journal of Applied Sciences and Environmental Management*, 24(2), 373–379. <https://doi.org/10.4314/jasem.v24i2.25>

Abdussalam, A. F., Isa, Z., Babati, A., Baba, B. M., Eberemu, A., Suleiman, A. S., & Abubakar, A. O. (2025). Multivariate bias correction of ERA5 climatic

data for assessing climate - related road vulnerabilities in Nigeria. *Discover Geoscience*. <https://doi.org/10.1007/s44288-025-00151-4>

Abulude, F. O., & Abulude, I. A. (2021). Monitoring Air Quality in Nigeria: The Case of Center for Atmospheric Research-National Space Research and Development Agency (CAR-NASRDA). *Aerosol Science and Engineering*, 5(4), 478–498. <https://doi.org/10.1007/s41810-021-00116-3>

Adamkiewicz, G., Liddie, J., & Gaffin, J. M. (2020). The Respiratory Risks of Ambient/Outdoor Air Pollution. *Clinics in Chest Medicine*, 41(4), 809–824. <https://doi.org/10.1016/j.ccm.2020.08.013>

Afifa, Arshad, K., Hussain, N., Ashraf, M. H., & Saleem, M. Z. (2024). Air pollution and climate change as grand challenges to sustainability. *Science of The Total Environment*, 928, 172370. <https://doi.org/10.1016/j.scitotenv.2024.172370>

Baba, B. M., Isa, Z., Abdussalam, A. F., & Abu-Hanifa Babati. (2022). Influence Of Climate Indices On Vegetation Dynamics In Kamuku National Park, Nigeria Using Coupled Model Intercomparison Project Phase 6 (CMIP6). *FUDMA Journal of Sciences*, 6(4), 160–173. <https://doi.org/https://doi.org/10.33003/fjs-2022-0604-1059> 8 FJS

Baba, S. U. (2025). Assessing the Influence of Urban Development Projects on Air Quality Through Carbon Dioxide Monitoring in Kaduna Metropolis. *International Journal of Science for Global Sustainability*, 11(1), 51–63. <https://doi.org/10.57233/ijsgs.v11i1.782>

Babati, A., Saleh, Y. I., Isa, Z., Baba, B. M., Dabo, A. A., & Yahya, M. I. (2021). Simulation Of Groundwater Level In River Mallam Sule Catchment Area Of Potiskum , Yobe State Using SWAT. *Science World Journal*, 16(3), 363–368.

Balarabe, M., Abdullah, K., & Nawawi, M. (2016). Seasonal Variations of Aerosol Optical Properties and Identification of Different Aerosol Types Based on AERONET Data over Sub-Sahara West-Africa. *Atmospheric and Climate Sciences*, 06(01), 13–28. <https://doi.org/10.4236/acs.2016.61002>

Bello, M. O., Erdogan, S., & Ch'Ng, K. S. (2022). On the convergence of ecological footprint in African countries: New evidences from panel stationarity tests with factors and gradual shifts. *Journal of Environmental Management*, 322, 116061. <https://doi.org/10.1016/j.jenvman.2022.116061>

Brooks, N., & Legrand, M. (2000). Dust Variability over Northern Africa and Rainfall in the Sahel (pp. 1–25). https://doi.org/10.1007/0-306-48086-7_1

Chandra Voumik, L., & Sultana, T. (2022). Impact of urbanization, industrialization, electrification and renewable energy on the environment in BRICS: fresh

- evidence from novel CS-ARDL model. *Heliyon*, 8(11), e11457. <https://doi.org/10.1016/j.heliyon.2022.e11457>
- Dickin, S., & Gabrielsson, S. (2023). Inequalities in water, sanitation and hygiene: Challenges and opportunities for measurement and monitoring. *Water Security*, 20, 100143. <https://doi.org/10.1016/j.wasec.2023.100143>
- Dimitroulopoulou, S., Dudzińska, M. R., Gunnarsen, L., Hägerhed, L., Maula, H., Singh, R., Toyinbo, O., & Haverinen-Shaughnessy, U. (2023). Indoor air quality guidelines from across the world: An appraisal considering energy saving, health, productivity, and comfort. *Environment International*, 178, 108127. <https://doi.org/10.1016/j.envint.2023.108127>
- Emekwuru, N., & Ejohwomu, O. (2023). Temperature, Humidity and Air Pollution Relationships during a Period of Rainy and Dry Seasons in Lagos, West Africa. *Climate*, 11(5), 1–18. <https://doi.org/10.3390/cli11050113>
- Ibe, O. C., Nwofor, O. K., & Okoro, U. K. (2025). Evaluation of aerosol loading and its relationship with geopotential height in Nigeria's Guinea Coast. *Bulletin of the National Research Centre*, 49(1), 11. <https://doi.org/10.1186/s42269-025-01303-9>
- Ibrahim, E. S., Ahmed, B., Arodudu, O. T., Abubakar, J. B., Dang, B. A., Mahmoud, M. I., Shaba, H. A., & Shamaki, S. B. (2022). Desertification in the Sahel Region: A Product of Climate Change or Human Activities? A Case of Desert Encroachment Monitoring in North-Eastern Nigeria Using Remote Sensing Techniques. *Geographies*, 2(2), 204–226. <https://doi.org/10.3390/geographies2020015>
- Isa, Z., Abdussalam, A. F., Sawa, B. A., Ibrahim, M., Isa, U. A., & Babati, A.-H. (2023). Identifying major climate extreme indices driver of stream flow discharge variability using machine learning and SHaply Additive Explanation. *Sustainable Water Resources Management*, 9(4), 119. <https://doi.org/10.1007/s40899-023-00897-0>
- Kamana, A. A., Radoine, H., & Nyasulu, C. (2024). Urban challenges and strategies in African cities – A systematic literature review. *City and Environment Interactions*, 21, 100132. <https://doi.org/10.1016/j.cacint.2023.100132>
- Ma, X., Zou, B., Deng, J., Gao, J., Longley, I., Xiao, S., Guo, B., Wu, Y., Xu, T., Xu, X., Yang, X., Wang, X., Tan, Z., Wang, Y., Morawska, L., & Salmond, J. (2024). A comprehensive review of the development of land use regression approaches for modeling spatiotemporal variations of ambient air pollution: A perspective from 2011 to 2023. *Environment International*, 183, 108430. <https://doi.org/10.1016/j.envint.2024.108430>
- Mahmud, K., Mitra, B., Uddin, M. S., Hridoy, A.-E. E., Aina, Y. A., Abubakar, I. R., Rahman, S. M., Tan, M. L., & Rahman, M. M. (2023). Temporal assessment of air quality in major cities in Nigeria using satellite data. *Atmospheric Environment*, X, 20, 100227. <https://doi.org/10.1016/j.aeaoa.2023.100227>
- Musa, A. S., Atiyong, B. R., Isa, Z., Tanko, A. L., & Babati, A. (2022). Spatio-Temporal Variations Of Soil Salinity In Gusau Local Government Area, Zamfara State, Nigeria. *Fudma Journal Of Sciences*, 6(5), 109–114. <https://doi.org/10.33003/fjs-2022-0605-1108>
- N'Datchoh, T. E., Liousse, C., Roblou, L., & N'Dri, A. B. (2025). Biomass Burning over Africa: How to Explain the Differences Observed Between the Different Emission Inventories? *Atmosphere*, 16(4), 440. <https://doi.org/10.3390/atmos16040440>
- Ofoezie, E. I., Eludoyin, A. O., Udeh, E. B., Onanuga, M. Y., Salami, O. O., & Adebayo, A. A. (2022). Climate, Urbanization and Environmental Pollution in West Africa. *Sustainability*, 14(23), 15602. <https://doi.org/10.3390/su142315602>
- Omoregbe Nosa, O., & Omorede, O. (2025). Spatial and Temporal Distribution of Outdoor Particulate Matter (PM 2.5) Levels for Locations within Two Local Government Areas in Edo State, Southern Nigeria. *Indonesian Journal of Social and Environmental Issues (IJSEI)*, 6(1). <https://doi.org/10.47540/ijsei.v6i1.1421>
- Onyeuwaoma, N. D., Nwofor, O. K., Chineke, T. C., Eguaroje, E. O., & Dike, V. N. (2015). Implications of MODIS impression of aerosol loading over urban and rural settlements in Nigeria: Possible links to energy consumption patterns in the country. *Atmospheric Pollution Research*, 6(3), 484–494. <https://doi.org/10.5094/APR.2015.054>
- Owoade, O. K., Abiodun, P. O., Omokungbe, O. R., Fawole, O. G., Olise, F. S., Popoola, O. O. M., Jones, R. L., & Hopke, P. K. (2021). Spatial-temporal Variation and Local Source Identification of Air Pollutants in a Semi-urban Settlement in Nigeria Using Low-cost Sensors. *Aerosol and Air Quality Research*, 21(10), 200598. <https://doi.org/10.4209/aaqr.200598>
- Ozer, P. (2002). Dust variability and land degradation in the Sahel. *Belgeo*, 2, 195–210. <https://doi.org/10.4000/belgeo.16124>
- Rabiu, A. B., Ogunjo, S. T., Akerele, A., & Dare-Idowu, O. E. (2025). Long-term variability study of total column ozone over Nigeria using multi-sensor reanalysis measurements. *Discover Geoscience*, 3(1), 75. <https://doi.org/10.1007/s44288-025-00186-7>
- Salihu, T., Olukunle, J. O., Adenubi, O. T., Mbaaji, C., & Zarma, M. H. (2018). Ethnomedicinal plant species commonly used to manage arthritis in North-West Nigeria. *South African Journal of Botany*, 118, 33–43. <https://doi.org/10.1016/j.sajb.2018.06.004>



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Tyovenda, A. A., Ayua, T. J., & Sombo, T. (2021). Modeling of gaseous pollutants (CO and NO₂) emission from an industrial stack in Kano city, northwestern Nigeria. *Atmospheric Environment*, 253, 118356.

<https://doi.org/10.1016/j.atmosenv.2021.118356>

World Bank. (2022). The Global Health Cost of PM_{2.5} Air Pollution: A Case for Action Beyond 2021. In *The Global Health Cost of PM_{2.5} Air Pollution: A Case for Action Beyond 2021*. The World Bank. <https://doi.org/10.1596/978-1-4648-1816-5>

Zheng, B., Chen, J., & Zhang, Q. (2025). Air pollution control and health economic burdens: Evidence from a megacity in China from 2014 through 2022. *Environmental Research*, 264, 120392. <https://doi.org/10.1016/j.envres.2024.120392>