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Spatio-Temporal Monitoring of Carbon Monoxide and Aerosol: a Case Study of North Eastern Nigeria

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Abstract: Air pollution remains a major environmental and public health concern in sub-Saharan Africa, with carbon monoxide (CO) and aerosols posing significant health risk.This study aims to monitor and assess the tropospheric concentration of carbon monoxide (CO) and aerosols across the North Eastern region of Nigeria. Sentinel-5 Precussor data was accessed and processed using Google Earth Engine, while Geographic Information Systems (GIS) were employed for spatial analysis and visualization. Statistical analyses were applied to examine interannual variability and significant differences across years. Results indicate clear seasonal and spatial variability in both pollutants. CO concentrations peaked consistently during the dry-season months, with the highest monthly values recorded between January and March, reaching up to 0.049 mol/m², while the lowest values occurred during the peak wet-season months of August and September (0.03 - 0.032 mol/m²). Aerosol concentrations also showed elevated values during the dry season, with the highest monthly levels occurring between December and February (0.31 to 1.434), while lower concentrations were observed during the wet season, reaching minima of −1.427 in September and −1.345 in August. Interannually, the overall trend for both CO and aerosol concentrations exhibited an increasing pattern, with 2020 and 2024 recording the highest concentrations of CO, while aerosol concentrations reached their peak levels in 2022 and 2023, respectively. Paired sample statistical tests revealed significant differences between selected years ($p < 0.05$), indicating notable temporal changes in pollutant levels. Spatially, the highest CO concentrations are predominantly concentrated in the southern part of the region, particularly across Adamawa and Taraba States. In contrast, Borno and Yobe States consistently recorded elevated aerosol concentrations throughout the study period. The findings highlight critical pollution periods and hotspots, providing valuable insights for targeted mitigation strategies and public health interventions in North Eastern Nigeria.

1. Introduction

Air pollution represents a significant environmental challenge worldwide, impacting both developed and developing nations. This issue has intensified as a result of rapid population growth, urbanization, and the excessive exploitation of natural resources, establishing air pollution as a critical global concern (Mannucci and Franchini, 2017; Wassie, 2020; Ernyasih *et al*., 2023). Studies reveal that the environment and human health are negatively impacted by both short-term and long-term exposure to gaseous pollutants such carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and aerosols. These pollutants not only pose serious health risks but also contribute to climate change, which threatens local and international communities (Fazakas *et al*., 2024; Singh *et al*., 2021; Manisalidis *et al*., 2020; Sharma *et al*., 2013; Kaur and Pandey, 2021). Higher concentrations of these pollutants are found in urban and suburban regions, especially in expanding cities, which results in hazardous air quality situations that frequently surpass World Health Organisation (WHO) regulations (WHO, 2022).

CO, a colourless, odourless, and highly toxic atmospheric pollutant produced from the incomplete combustion of carbon-based fuels such as petrol, diesel, wood, charcoal, and biomass has immediate and severe implications for human health due to its high affinity for hemoglobin, forming carboxyhemoglobin and reducing the blood's oxygen-carrying capacity (Mitchell and Sweeney, 2018; Vural *et al*., 2024; Nañagas *et al*., 2022; Chenoweth *et al*., 2022; Adesina *et al*., 2024). The United State Environmental Protection Agency (EPA) establishes a safe limit for carbon monoxide (CO) under the National Ambient Air Quality Standards (NAAQS) at 9 ppm (10 mg/m³) over an 8-hour period. However, even minor increases in CO levels can lead to serious health consequences. Studies have shown that a 1 mg/m³ rise in CO levels corresponds to a 0.91% increase in daily mortality rates (Chen *et al*., 2021), while a similar increase in China resulted in a 2.08% rise in Years of Life Lost (YLL) (*Wang* et al.*, 2020*).

Atmospheric aerosols are minute solid and liquid particles suspended in the air, originating from both natural and anthropogenic sources. Natural sources of these particles includes desert dust, sea salt, volcanic emissions, and biogenic particles, while anthropogenic sources stem from fossil fuel combustion, biomass burning, industrial processes, and vehicular emissions (Duarte, 2020; Riabova 2025; Marval and Tronville, 2022). Aerosols exert profound influences on air quality, regional climate, and human health by altering cloud microphysics, atmospheric circulation, and radiative forcing which influences global temperature, in addition to penetrating the respiratory system and exacerbating cardiopulmonary diseases (Garcia *et al*., 2023; Arfin *et al*., 2023)

Africa contributes to global atmospheric CO and aerosol concentrations primarily due to extensive biomass burning, charcoal production, agricultural residue burning, and traditional cooking methods. Seasonal savanna fires across West, East, and Southern Africa release enormous amounts of these pollutants into the atmosphere, influencing local and regional air quality (Kumar *et al*., 2022; Bockarie 2023; Keita *et al*., 2021 Almsatar, 2020).

Nigeria is one of the major African countries experiencing increasing CO and aerosol concentrations yearly (Abaje *et al*, 2020; Okedere *et al*., 2021). The North Eastern states of Nigeria, which are Adamawa, Bauchi, Borno, Gombe, Taraba, and Yobe are particularly susceptible to the effects of CO and aerosol concentrations, due to a combination of socio-economic, climatic, and environmental factors (Aliyu and Botai, 2018; Abaje *et al*., 2020). The Widespread use of biomass fuels, frequent bush burning, increasing urbanization, generator dependence due to unstable electricity supply, and expanding transport networks all contribute significantly to emissions of these pollutants (Nasr and Eissa, 2025). Additionally, the region's proximity to the Sahel and Sahara Desert influences atmospheric dynamics such as Harmattan winds, dust loading, and boundary layer fluctuations, affecting pollutant dispersion and CO atmospheric lifetime (Lucky *et al*., 2022; Bauer *et al*., 2019; Wang *et al*., 2020). Aerosol optical depth and surface particulate concentrations sky rockets during the dry season due to increased dust entrainment, reduced atmospheric moisture, and enhanced boundary-layer stability, leading to strong scattering and absorption, reduced visibility, possible climate and health impacts, thereby intensifying exposure risks for local populations, (Offor *et al*., 2016; Adeniran *et al*., 2018; Nikkath and Selvi, 2024; Awoleye *et al*., 2025)

Recent Environmental studies have shown an increasing deployment of Geographic Information Systems (GIS) and Remote Sensing (RS) in enabling spatial analysis, mapping, and visualization of pollutant distribution patterns across multiple locations (Nuvolone et al., 2011; Verma *et al*., 2023; Ahamad *et al*., 2022). Remote sensing, through satellite-based sensors such as the TROPOspheric Monitoring Instrument aboard Sentinel-5P offers high-resolution measurements of air pollutant concentrations. These pollutants includes NO_2, formaldehyde, SO_2, CH_4, CO and aerosols (Omokpariola *et al*., 2024; Audu *et al*., 2025; Amaechi *et al*., 2024). GIS and Remote sensing enables the derivation of regional variations, detection of pollution hotspots, analysis of long-term trends, comprehension of the effects of land use, meteorological conditions, and anthropogenic activities on air quality (Dheekwal *et al*., 2025). The usefulness of these tools in evaluating pollution trends, seasonal fluctuations, and regional patterns has been shown in a number of Nigerian research (Okoduwa and Amaechi, 2023; Enuneku *et al*., 2025)

Given the lack of extensive ground-based monitoring networks in the North East and Nigeria as a whole, the integration of GIS and Remote Sensing offers an effective and efficient method for conducting a holistic monitoring of carbon monoxide and aerosols across the region. This approach provides a more comprehensive understanding of pollutant behavior, atmospheric transport mechanisms, and spatial–temporal variability, thereby supporting effective environmental planning, air quality management, and public health interventions (Korchenko *et al*., 2019; Ahamad *et al*., 2022). This study is therefore timely and essential, as it applies modern geospatial tools to evaluate and monitor CO and aerosol concentrations across states that make up the North Eastern Geopolitical zone of Nigeria. This study aims to monitor and assess the tropospheric concentration of CO) and aerosols across the North Eastern region of Nigeria.

2. Methodology

2.1 Study Area

The Sahelian region of northeastern Nigeria is located between latitudes 6°N and 14°N and longitudes 11°E and 15°E (Hassan *et al*. 2017). This region comprises six states: Adamawa, Bauchi, Borno, Gombe, Taraba, and Yobe (Figure 1). It borders Cameroon, Chad, and Niger, reflecting its proximity to the Sahel and the Lake Chad Basin. The region covers an area of 273,563 km², with a population estimated at over 30 million people (National Bureau of Statitistics, 2022). This semi-arid region has a tropical climate with distinct wet and dry seasons. The wet season spans from June to September, with average annual rainfall ranging from 466 mm to 1,075 mm (Hassan *et al*. 2017). Temperatures often exceed 40 °C during the dry season, which lasts from October to May (Ibrahim *et al.* 2022). Geographically, the Northeast is the largest geopolitical zone in Nigeria, covering nearly one-third of the country's total area (Akinymi *et al.,* 2022).

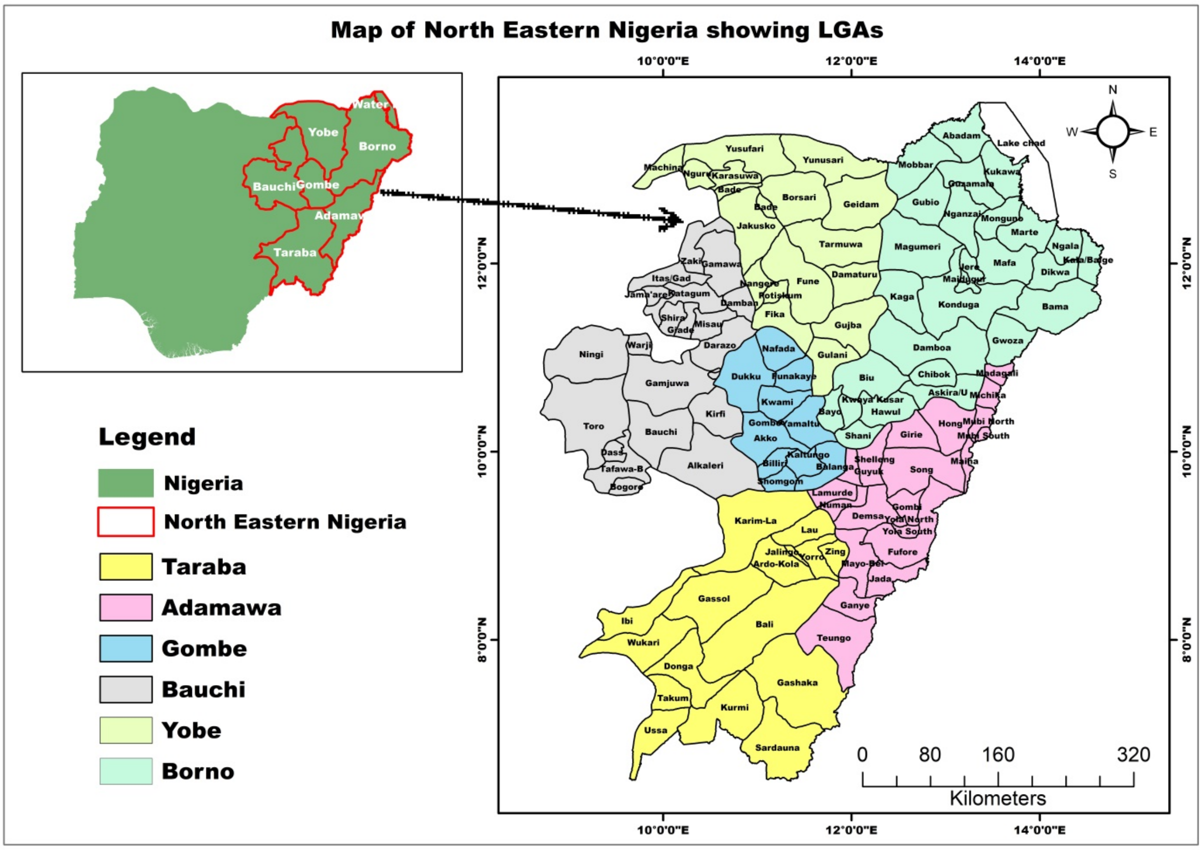

Figure 1. Map of study area

2.2 Data source and collection

This study relied on secondary satellite data obtained from the Sentinel-5 Precursor (Sentinel-5P) and processed on the Google Earth Engine (GEE) platform to assess CO and aerosol concentrations in the North Eastern region of Nigeria. Sentinel-5P, launched by the European Space Agency (ESA) in 2017 under the Copernicus Programme, is designed for global atmospheric monitoring. It carries the TROPOspheric Monitoring Instrument (TROPOMI), which provides high resolution measurements of major atmospheric pollutants including aerosols, NO_2, CO, sulfur dioxide (SO_2), methane (CH_4), and ozone (O_3). The satellite offers daily global coverage and operates across multiple spectral bands, enabling accurate detection of pollutant concentrations. Sentinel-5P data have been widely applied in air-quality monitoring (Vîrghileanu *et al*., 2020, Okoduwa and Amaechi, 2023; Sharifi and Felegari, 2022; Reshi *et al*., 2024; Enuneku *et al*., 2025).

2.3 Data Processing and Method of Analysis

Figure 2 illustrate the flow of the method used in this study. GEE, a cloud-based geospatial processing platform was used to process the Sentinel-5P datasets. Data spanning 2019 to 2025 were extracted and analyzed to quantify aerosol and CO concentrations in the North Eastern region of Nigeria. GEE enabled efficient data filtering, computation, and spatial mapping to reveal temporal trends and spatial distributions of pollutants across both locations. Previous studies have shown that integrating Sentinel-5P with GEE supports effective atmospheric pollution monitoring by detecting both temporal and spatial variations that inform environmental management decisions (Sharifi and Felegari, 2022; Makineci *et al*., 2023). The study period of 2019–2025 was selected because

Sentinel-5P data are consistently available and of high resolution during these years, capturing seasonal dynamics and the influence of anthropogenic activities on air quality. Further preprocessing was conducted in ArcGIS 10.7.1, which was used to create the spatial distribution of all pollutants. The maps were classified into three pollutant concentration levels, high (red), moderate (yellow), and low (green), to illustrate air-quality variations across the seven-year period. Microsoft Excel was used to generate graphical representations of observed trends. A paired sample t-test was also applied using the Statistical packages for the Social Sciences (SPSS) to evaluate whether differences in pollutant concentrations between consecutive years are statistically significant. This test is appropriate for the study because pollutant levels across years are interrelated. The formula for paired sample t test is expressed as:

$$t = \frac{\sum d}{\frac{\sqrt{n(\sum d^2) - (\sum d)^2}}{n-1}} \qquad \textbf{Equ. 1}$$

Where d: difference per paired value

N: number of samples

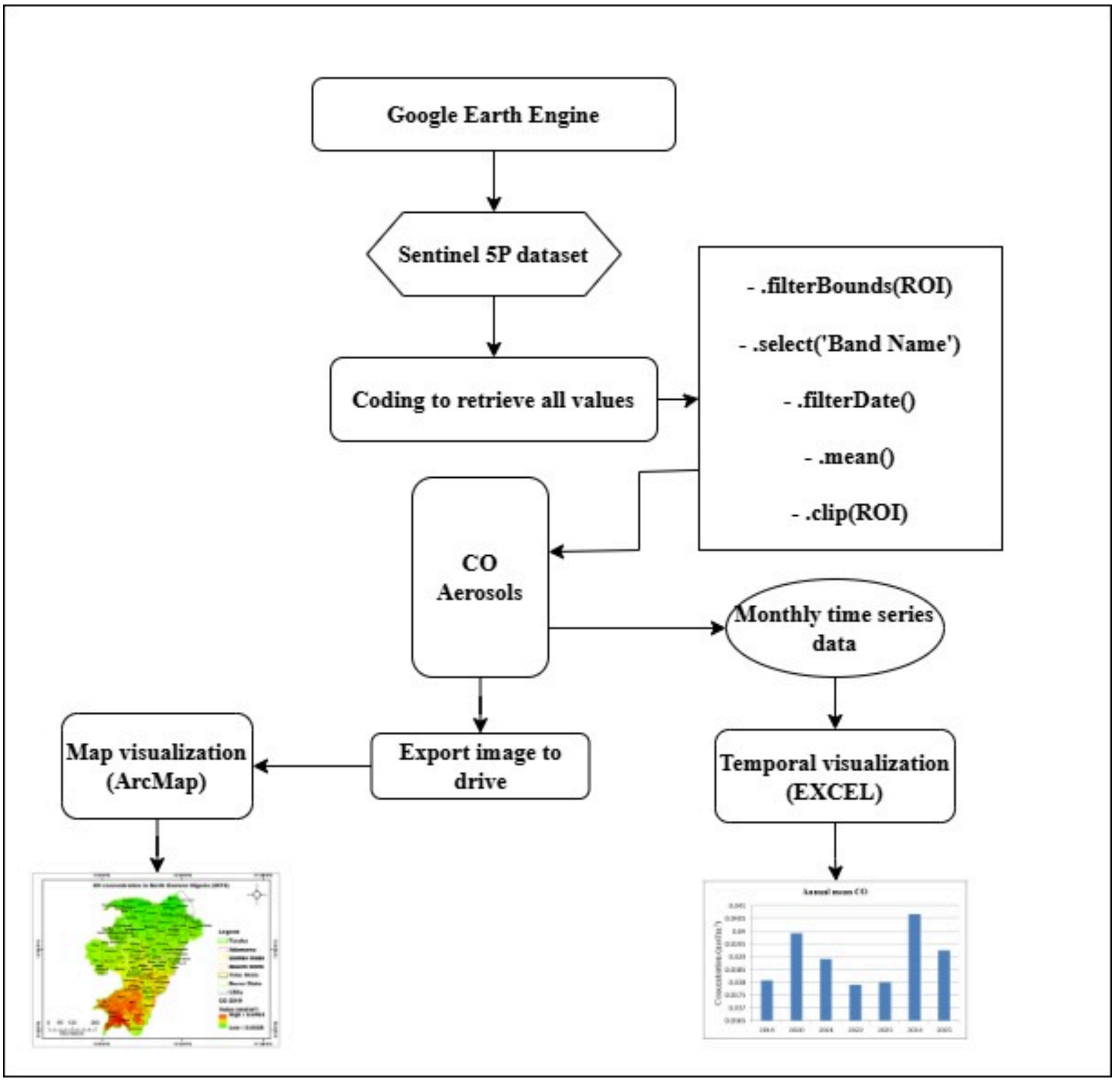

Figure 2. Research methodology flowchart

3. Results and Discussion

3.1 Monthly variations of CO in North Eastern Nigeria (2019 – 2025)

The monthly variations of CO concentrations across North Eastern Nigeria from 2019 to 2025 (Table 1), reveal a pronounced seasonal pattern, with elevated concentrations during the dry season and lower values during the wet season. Across all years, CO concentrations generally increased from November through March, coinciding with the dry season period. Peak concentrations were frequently observed between February and March, with maximum values reaching 0.049 mol/m² in 2020 and 2024, and 0.048 mol/m² in 2021. Higher dry-season CO concentrations are commonly associated with increased combustion activities such as biomass burning, widespread generator use, and vehicular emissions, combined with reduced atmospheric dispersion (Andreae and Merlet, 2001; Seinfeld and Pandis, 2016). In northern Nigeria, dry-season meteorological conditions may limit pollution dispersion and rainfall-driven removal processes, allowing CO to accumulate near the surface (Jacob and Winner, 2009).

A consistent decline in CO concentrations is evident from April through September, corresponding to the wet season. During this period, monthly CO values across all years generally ranged between 0.03 mol/m² and 0.037 mol/m², with the lowest concentrations consistently recorded in September. This seasonal reduction reflects the influence of increased rainfall, enhanced wet scavenging, and improved atmospheric ventilation during the wet season, which collectively reduce ambient CO concentrations (Seinfeld and Pandis, 2016). Interannual variability is also evident within the dataset. Years such as 2020 and 2024 exhibited relatively higher CO concentrations during peak dry-season months, suggesting periods of intensified emission activities or meteorological conditions favorable to pollutant accumulation. Conversely, slightly lower peak values observed in years such as 2019 and 2023 may be associated with reduced emission intensity or short-term climatic variability influencing atmospheric transport and dilution. The overall interannual trend in CO concentrations from 2019 to 2025 is illustrated in Figure 3.

Table 1. Monthly variations of CO in North Eastern Nigeria (2019 – 2025)

Month	CO 2019	CO 2020	CO 2021	CO 2022	CO 2023	CO 2024	CO 2025
January	0.0430	0.0400	0.0420	0.0410	0.041	0.039	0.043
February	0.0460	0.0490	0.0440	0.0430	0.041	0.045	0.049
March	0.0450	0.0490	0.0480	0.0460	0.045	0.049	0.046
April	0.0450	0.0450	0.0430	0.0450	0.043	0.045	0.043
May	0.0410	0.0420	0.0380	0.0390	0.04	0.045	0.04
June	0.0350	0.0370	0.0350	0.0350	0.034	0.038	0.037
July	0.0340	0.0340	0.0370	0.0350	0.034	0.038	0.037
August	0.034	0.039	0.038	0.037	0.036	0.043	0.038
September	0.031	0.032	0.033	0.03	0.032	0.035	0.033
October	0.032	0.032	0.034	0.031	0.034	0.035	0.032
November	0.035	0.039	0.037	0.035	0.038	0.037	0.035
December	0.036	0.041	0.038	0.038	0.038	0.039	0.038
Mean	0.0381	0.0399	0.0389	0.0379	0.038	0.0407	0.0393

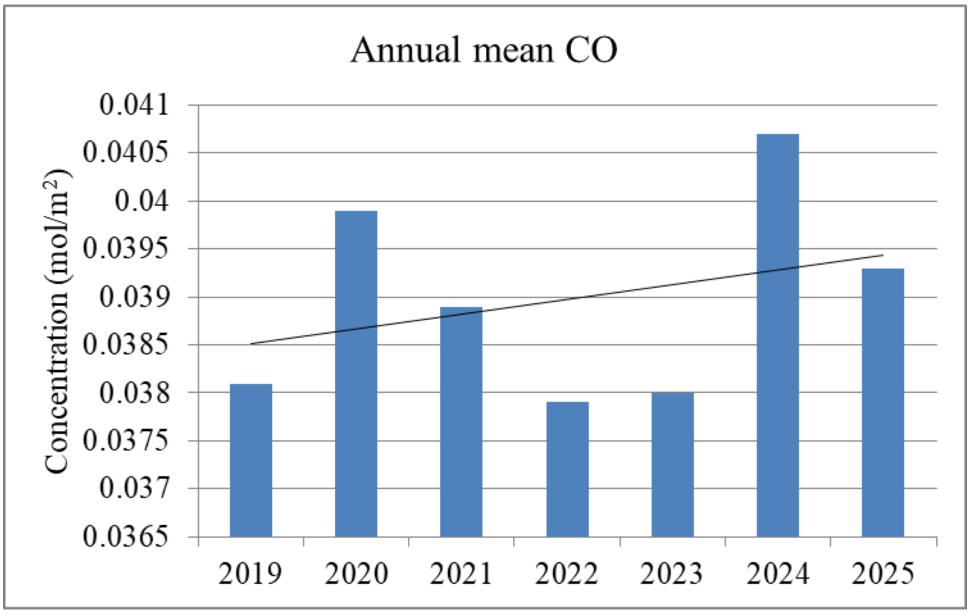

Figure 3. Trend of CO from 2019 – 2025 in the North eastern region of Nigeria

3.2 Monthly variations of Aerosol in North Eastern Nigeria (2019 – 2025)

The monthly variations of aerosol concentrations across North Eastern Nigeria from 2019 to 2025 (Table 2), exhibit pronounced seasonal and interannual fluctuations. Across the study period, higher aerosol values were generally observed during the early months of the year, particularly between January and March, while markedly lower values dominated the mid-year months from July to September. In 2019, aerosol concentrations were positive during the first four months, increasing from 0.092 in January to a peak of 0.280 in March, before declining sharply from May onwards. Negative values dominated from May through December, with the lowest levels occurring between August and October. A similar seasonal pattern was observed in 2020, although aerosol values remained predominantly negative throughout the year, with the most pronounced reductions recorded during the core wet-season months of July to September, where values dropped below −1.28.

The year 2021 displayed a mixed seasonal response, with negative aerosol values prevailing during the first half of the year, followed by a gradual transition to positive values from October to December, culminating in a relatively high value of 0.929 in December. In contrast, 2022 was characterized by substantially elevated aerosol concentrations during the early dry-season months, with exceptionally high values recorded between January and March. The peak aerosol concentration of 1.573 observed in March 2022 represents the highest monthly value recorded across the entire study period. From June onwards, aerosol values declined steadily, becoming negative during July to September before increasing again towards the end of the year.

In 2023 and 2024, a similar seasonal structure persisted, with positive aerosol values dominating the dry-season months from January to May, followed by a transition to negative values during the peak wet-season months of July to September. Aerosol concentrations in both years recovered during the final quarter, with positive values re-emerging between October and December, particularly in 2023. The year 2025 followed a comparable seasonal pattern, with positive aerosol values recorded from January to June, peaking in February at 0.811, before declining sharply into negative values between July and September and increasing again towards the end of the year.

These seasonal variations reflect the strong influence of regional meteorological processes on aerosol level in North Eastern Nigeria. Elevated dry-season aerosol concentrations are closely associated with Harmattan dust transport from the Sahara Desert, increased biomass burning, and reduced atmospheric removal processes, while wet-season declines are driven by enhanced rainfall, wet scavenging, and increased atmospheric mixing (Prospero and Lamb, 2003; Seinfeld and Pandis, 2016). The observed interannual variability further suggests that differences in dust intensity, combustion activity, and meteorological conditions play a significant role in modulating aerosol concentrations from year to year. The annual trend of aerosol concentrations from 2019 to 2025 is illustrated in Figure 4.

Table 2. Monthly variations of aerosol in North Eastern Nigeria (2019 – 2025)

Month	Aerosol 2019	Aerosol 2020	Aerosol 2021	Aerosol 2022	Aerosol 2023	Aerosol 2024	Aerosol 2025
January	0.092	-0.044	-0.643	0.956	0.787	0.866	0.662
February	0.25	0.24	-0.169	1.434	1.073	1.117	0.811
March	0.28	0.016	-0.084	1.573	0.572	1.193	0.64
April	0.252	-0.205	-0.561	0.906	0.866	0.78	0.646
May	-0.234	-0.514	-0.985	0.852	0.542	0.77	0.744
June	-0.429	-0.334	-0.828	0.322	0	0.698	0.085
July	-0.751	-1.218	-0.218	-0.187	-0.261	-0.338	-0.512
August	-1.162	-1.345	-0.545	-0.495	-0.325	-0.61	-0.524
September	-1.016	-1.427	-0.133	-0.441	-0.148	-0.523	-0.461
October	-1.244	-1.324	0.066	-0.022	0.529	-0.322	-0.194
November	-0.979	-1.143	0.352	0.222	0.217	0.107	0.175
December	-0.612	-0.731	0.929	0.434	0.648	0.31	0.576
Mean	-0.463	-0.669	-0.235	0.463	0.375	0.337	0.221

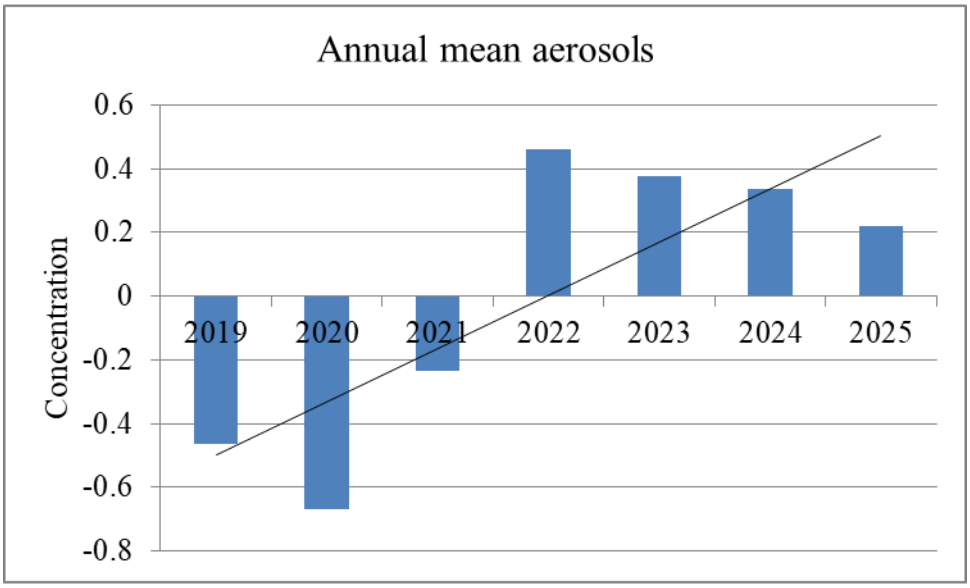

Figure 4. Annual mean aerosol concentration from 2019 – 2025 in the North eastern region of Nigeria

3.3 *Analysis for statistical significant difference*

A paired sample t-test was conducted to examine whether there were statistically significant differences in mean CO and aerosol concentrations between successive years and between the baseline year (2019) and the most recent year (2025) across North Eastern Nigeria. For CO, the paired sample t test results indicate varying levels of statistical significance across the study period (Table 4). A statistically significant difference was observed between 2019 and 2020 ($p = 0.02$), indicating a measurable change in CO concentrations between these two years. In contrast, no significant difference was detected between 2020 and 2021 ($p = 0.20$), suggesting relative stability in CO levels during this interval. The comparison between 2021 and 2022 shows a statistically significant difference ($p = 0.05$), while the difference between 2022 and 2023 was not statistically significant ($p = 0.80$), indicating limited year-to-year variability during this period. A highly significant difference was recorded between 2023 and 2024 ($p = 0.004$), reflecting a pronounced change in CO concentrations that may be associated with shifts in emission intensity or meteorological conditions influencing pollutant accumulation. Variations in atmospheric stability and interannual meteorology are known to affect trace gas concentrations such as CO (Jacob, 1999; Seinfeld and Pandis, 2016). The difference between 2024 and 2025 was not statistically significant ($p = 0.12$), suggesting a return to relative stability. However, the long-term comparison between 2019 and 2025 reveals a statistically significant difference ($p = 0.05$), indicating that CO concentrations have changed appreciably over the full duration of the study.

For aerosol concentrations, the paired sample t test results reveal stronger temporal variability. A highly significant difference was observed between 2019 and 2020 ($p = 0.002$), indicating a substantial year-to-year change in aerosol level. No statistically significant difference was found between 2020 and 2021 ($p = 0.10$), suggesting limited variability during this interval. A statistically significant difference was again recorded between 2021 and 2022 ($p = 0.02$), followed by non-significant differences between 2022 and 2023 ($p = 0.50$), 2023 and 2024 ($p = 0.80$), and 2024 and 2025 ($p = 0.20$), indicating relative stability in aerosol concentrations during the later years. Notably, the long-term comparison between 2019 and 2025 shows a highly significant difference ($p < 0.001$), demonstrating a pronounced cumulative change in aerosol concentrations over the study period. Aerosols are particularly sensitive to interannual variability in dust transport, biomass burning intensity, and meteorological conditions, which explains their stronger long-term variability relative to gaseous pollutants such as CO (Prospero and Lamb, 2003; Wilks, 2011). Overall, the paired sample t test results confirm that both CO and aerosol concentrations exhibit statistically significant temporal changes across selected years.

Table 3. Levels of significant difference between years (95% Confidence Interval)

Parameters	2019 and 2020	2020 and 2021	2021 and 2022	2022 and 2023	2023 and 2024	2024 and 2025	2019 and 2025
CO	0.02	0.20	0.05	0.80	0.004	0.12	0.05
Aerosol	0.002	0.10	0.02	0.50	0.80	0.20	< 0.001

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

3.5 Spatial distribution of CO in North Eastern Nigeria

The spatial distribution of CO across North-Eastern Nigeria from 2019 to 2025 (Figures 5 (A-F)) exhibits a stable and persistent north–south gradient, reflecting differences in emission intensity, land use, and population distribution across the region. Throughout the study period, CO concentrations remain consistently lowest across the northern Sahelian states of Borno and Yobe, increase moderately across Bauchi and Gombe States, and reach their highest values in the southern states of Adamawa and Taraba, where persistent spatial hotspots are repeatedly observed.

Previous satellite-based and global atmospheric studies have demonstrated that CO concentrations are strongly controlled by the spatial distribution of incomplete combustion sources, with rural and sparsely populated regions consistently exhibiting lower levels (Edwards *et al*., 2006). The persistently low CO concentrations across Borno and Yobe States are consistent with the limited presence of major anthropogenic emission sources in the northern Sahelian zone. These areas are characterised by limited industrial and commercial activity, resulting in reduced emissions from transport and residential fuel combustion

Bauchi and Gombe States consistently function as transitional zones within the regional CO gradient, exhibiting predominantly low to moderate concentrations throughout the study period. This spatial behaviour reflects their intermediate level of urban development and transport activity relative to both the northern Sahelian belt and the southern states. Studies using satellite observations and emission inventories show that semi-urban and developing regions typically display moderate CO levels associated with growing vehicular traffic and residential combustion, but without the intensity observed in major urban centres (Duncan *et al*., 2016; Edwards *et al*., 2006).

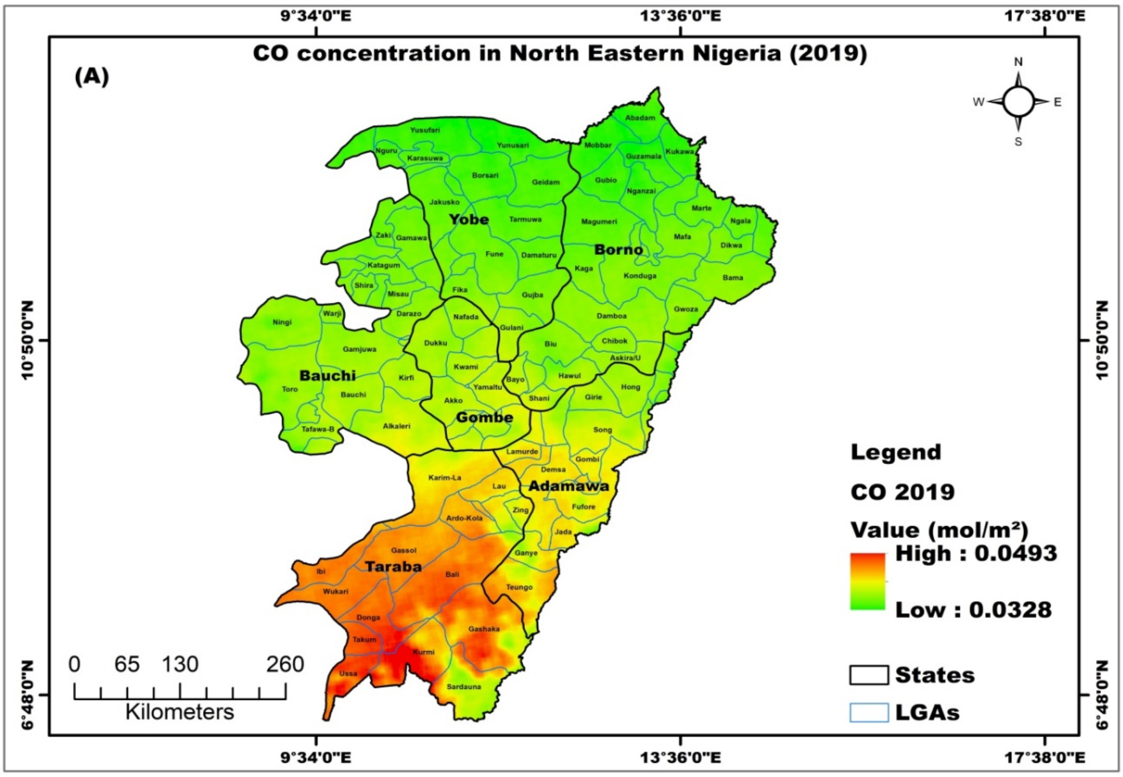

Figure 5a. Spatial distribution of CO in North Eastern Nigeria (2019)

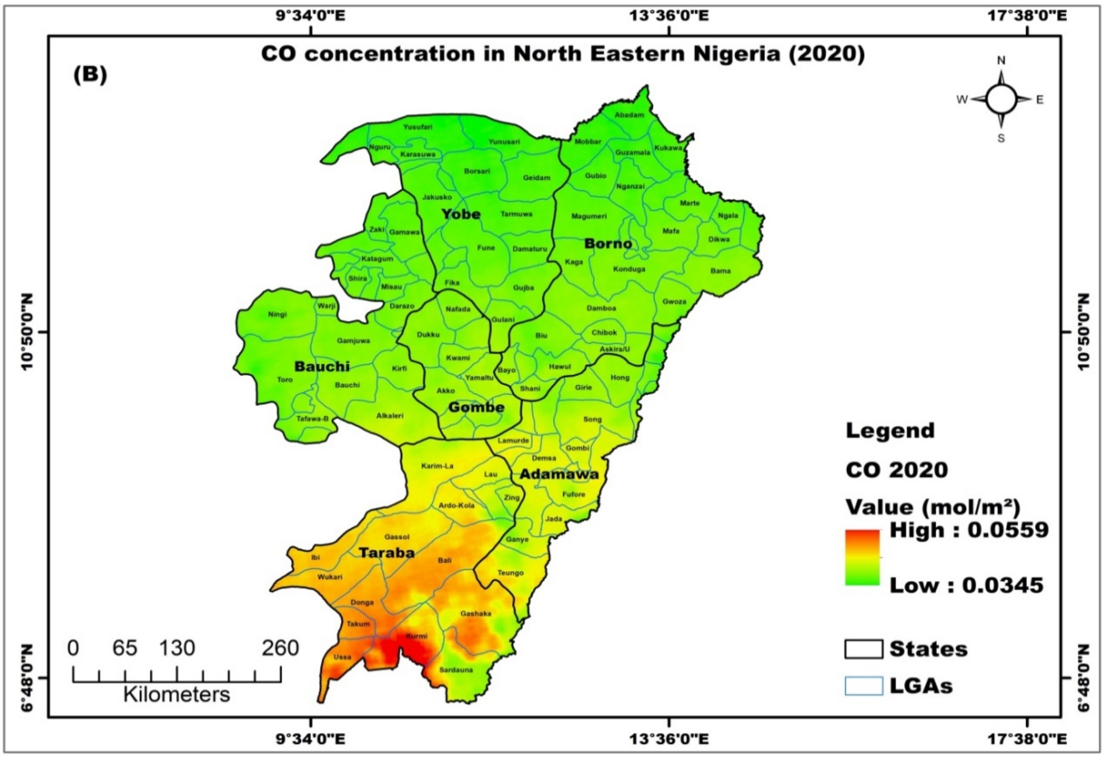

Figure 5b. Spatial distribution of CO in North Eastern Nigeria (2020)

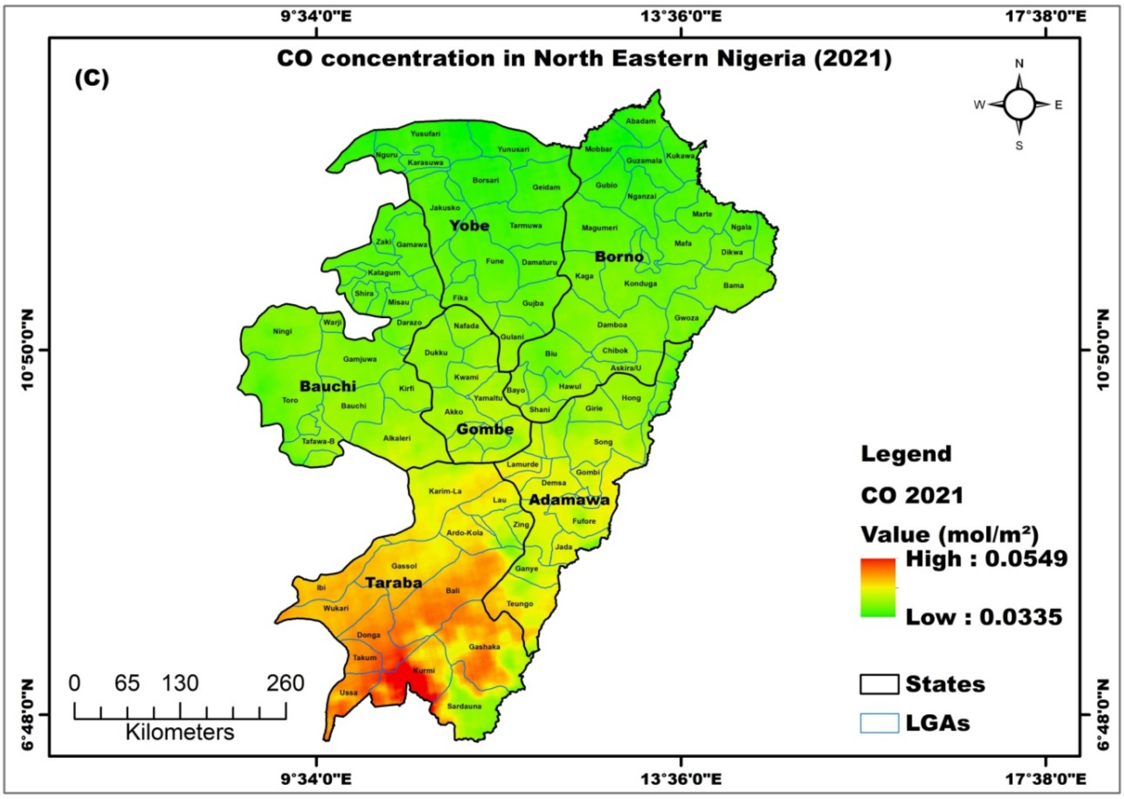

Figure 5c. Spatial distribution of CO in North Eastern Nigeria (2021)

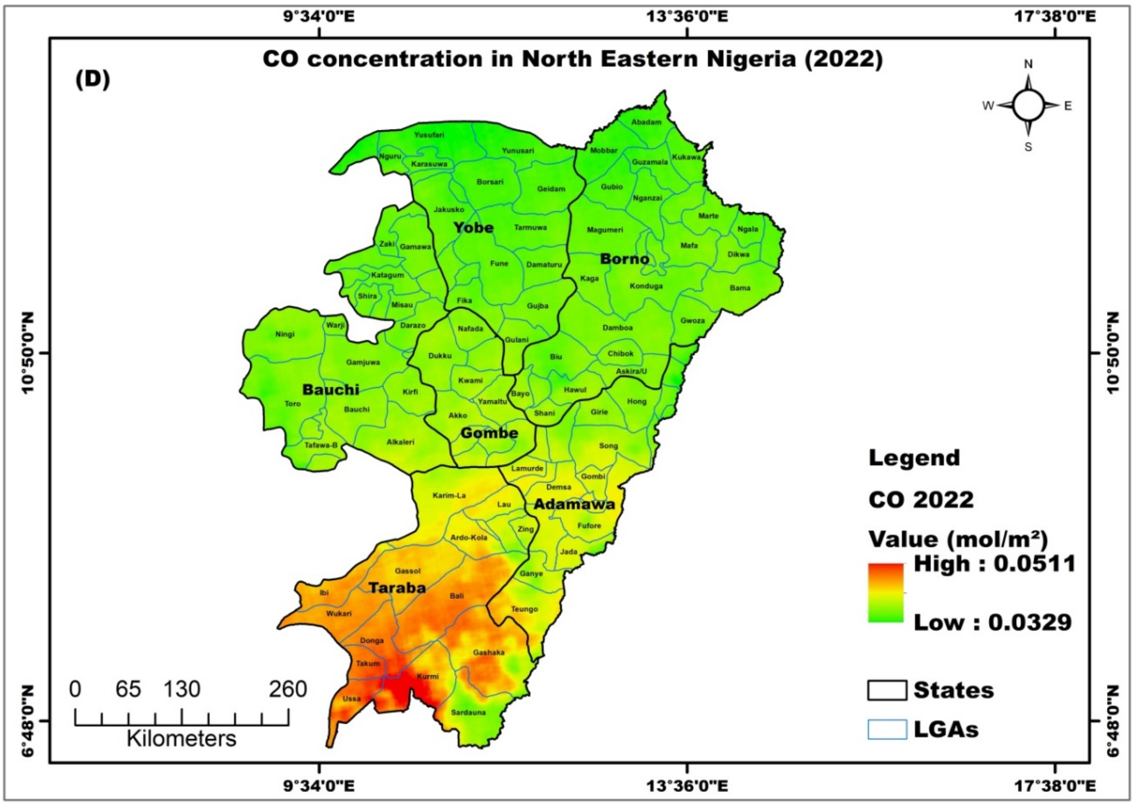

Figure 5d. Spatial distribution of CO in North Eastern Nigeria (2022)

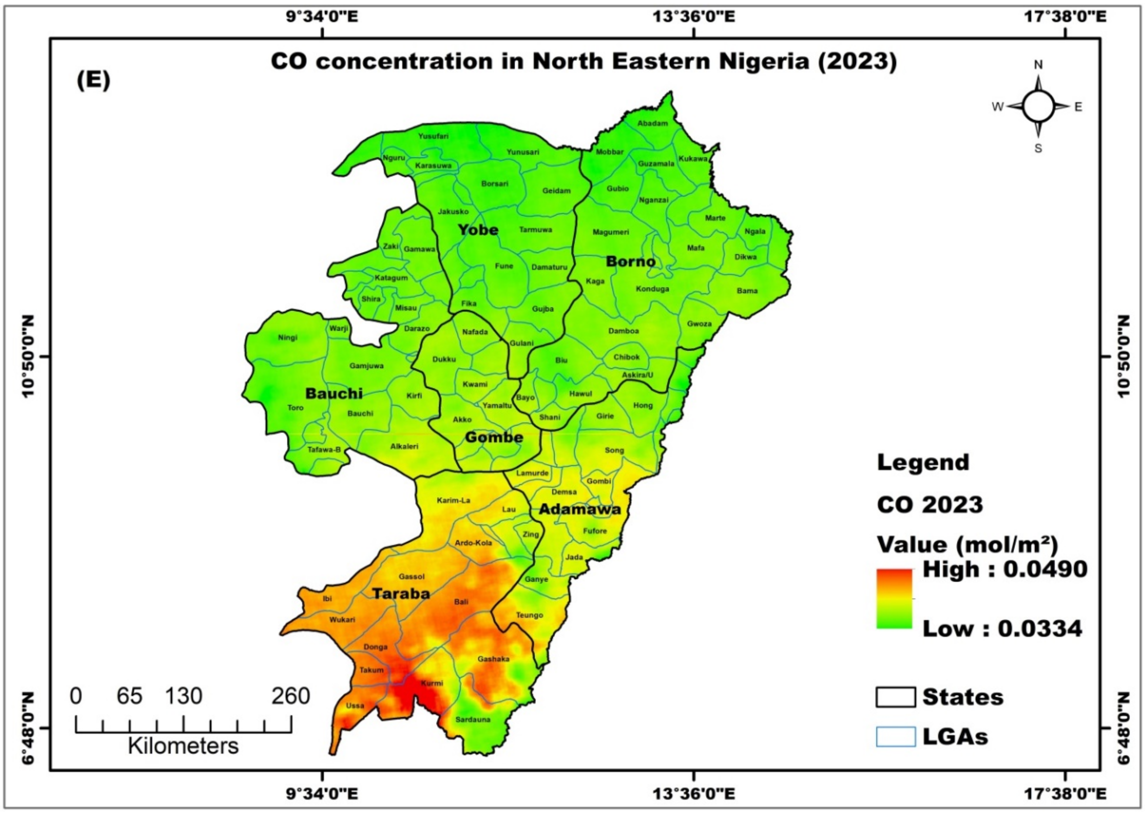

Figure 5e. Spatial distribution of CO in North Eastern Nigeria (2023)

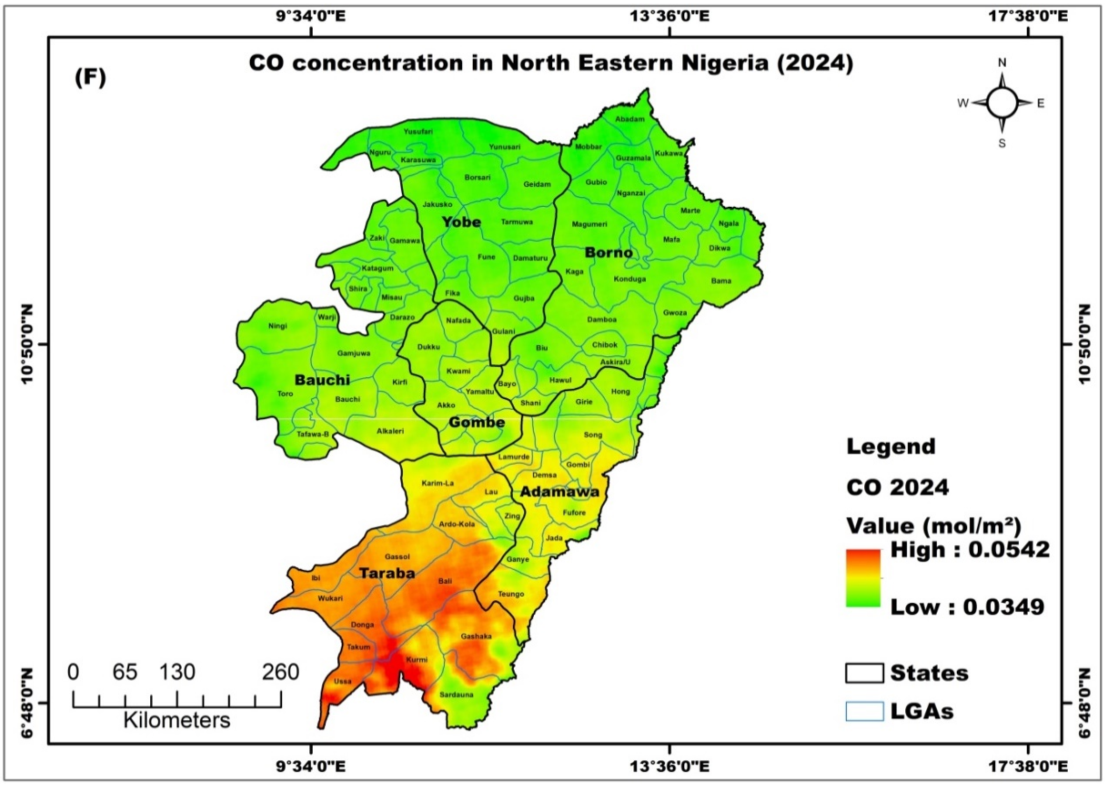

Figure 5g. Spatial distribution of CO in North Eastern Nigeria (2024)

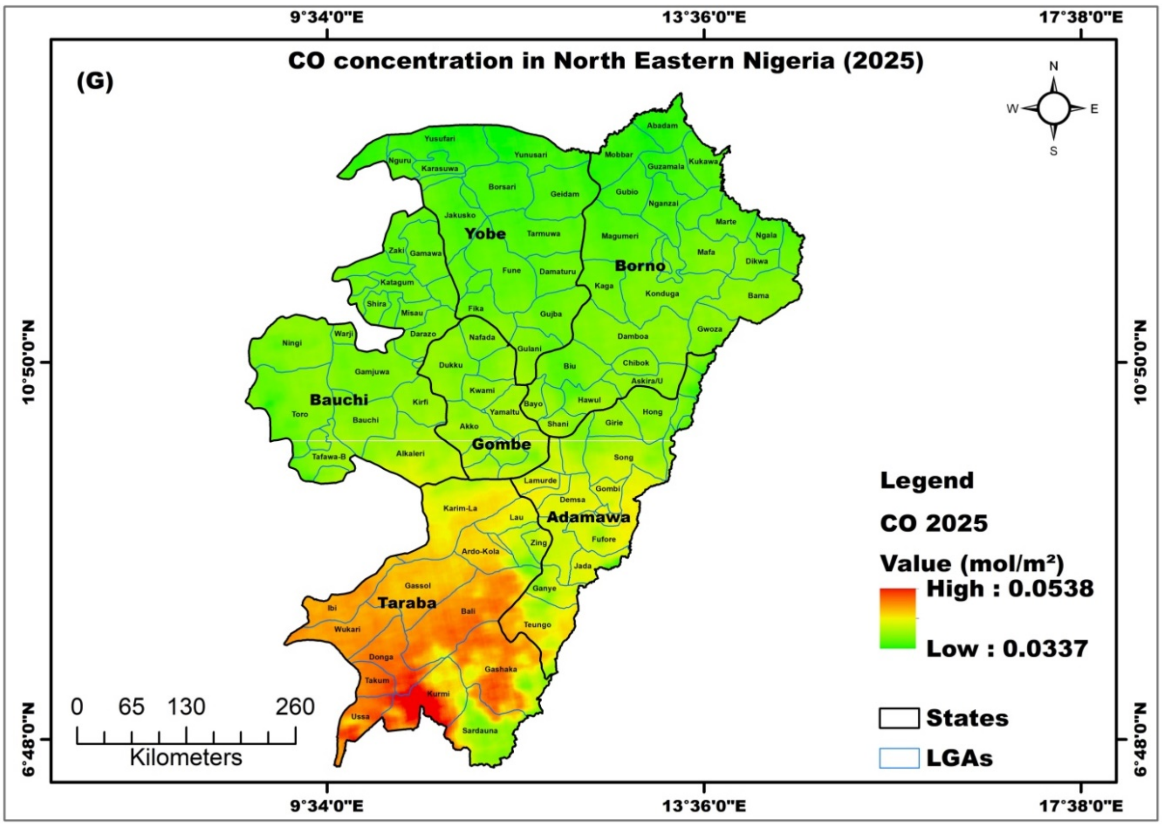

Figure 5f. Spatial distribution of CO in North Eastern Nigeria (2025)

In contrast, the repeated occurrence of elevated CO concentrations in Adamawa and, most notably, Taraba State may indicate sustained and spatially concentrated emission pressure in the southern part of North-Eastern Nigeria. These areas may include relatively more urbanised LGAs, denser transport corridors, and greater dependence on combustion-based energy sources such as vehicular traffic and small-scale power generation. Peer-reviewed studies consistently identify transport emissions and residential fuel combustion as dominant contributors to ambient CO in African and other developing regions, particularly where rapid urbanisation and energy insecurity increase reliance on inefficient combustion sources (Leguijt *et al*., 2023).

In addition to local emissions, atmospheric processes contribute to the persistence of the observed spatial structure. CO has a sufficiently long atmospheric lifetime to allow accumulation over regions with sustained emissions. Satellite and modelling studies show that such processes can reinforce spatial contrasts between emission-intensive and emission-limited areas, thereby maintaining stable concentration gradients over multiple years (Duncan *et al*., 2016).

3.6 Spatial distribution of aerosol in North Eastern Nigeria

The spatial distribution of aerosol concentration across North-Eastern Nigeria from 2019 to 2025 (Figures 6 (A-F)) displays a persistent and well-defined north–south gradient, with consistently higher aerosol level across the northern Sahelian states and progressively lower concentrations toward the southern part of the region. Throughout the study period, Borno and Yobe States repeatedly record moderate to high aerosol concentrations, Bauchi and Gombe States function as transitional zones with predominantly moderate levels, while Adamawa and Taraba States consistently exhibit the lowest aerosol concentrations. Although interannual fluctuations in magnitude are evident, the overall spatial distribution remains stable over time.

The consistently elevated aerosol concentrations observed across Borno and Yobe States reflect their location within the Sahelian belt, where atmospheric aerosol level is strongly influenced by dust emissions from the Sahara Desert (Yusuf and Sa'id, 2023). Northern Nigeria lies directly along major Saharan dust pathways associated with Harmattan circulation, which transport large quantities of mineral dust southward during much of the dry season (Ochei and Adenola, 2018). Satellite-based and ground-based studies over Nigeria demonstrate that aerosol peaks during the Harmattan period, with northern Nigeria experiencing persistently higher dust loading compared to southern regions (Prospero *et al*., 2002; Engelstaedter *et al*., 2006; Ochei and Adenola, 2018; Ayanlade *et al*., 2019). Historical and contemporary measurements further confirm that Harmattan dust dominates aerosol composition across northern Nigeria, reinforcing the observed spatial persistence of elevated aerosol concentrations in this zone (Pinker *et al*., 1994; Ginoux *et al*., 2012).

Bauchi and Gombe States consistently exhibit moderate aerosol concentrations and function as transitional zones between the high-aerosol Sahelian north and the lower-aerosol southern region. This pattern reflects their intermediate geographic position and environmental conditions, where Saharan dust influence weakens southward while surface moisture and vegetation cover increase. Studies focused on Nigeria and the broader West African region show that aerosol concentrations decline with increasing distance from primary dust source regions due to atmospheric dilution, gravitational settling, and changes in land surface properties (Engelstaedter *et al*., 2006; Ayanlade et al., 2019). Recent satellite analyses further demonstrate that central Nigerian states commonly exhibit moderate aerosol optical depths relative to both the northern Sahelian belt and the more humid southern zones (Ginoux *et al*., 2012; Sa'adu and Gana, 2025).

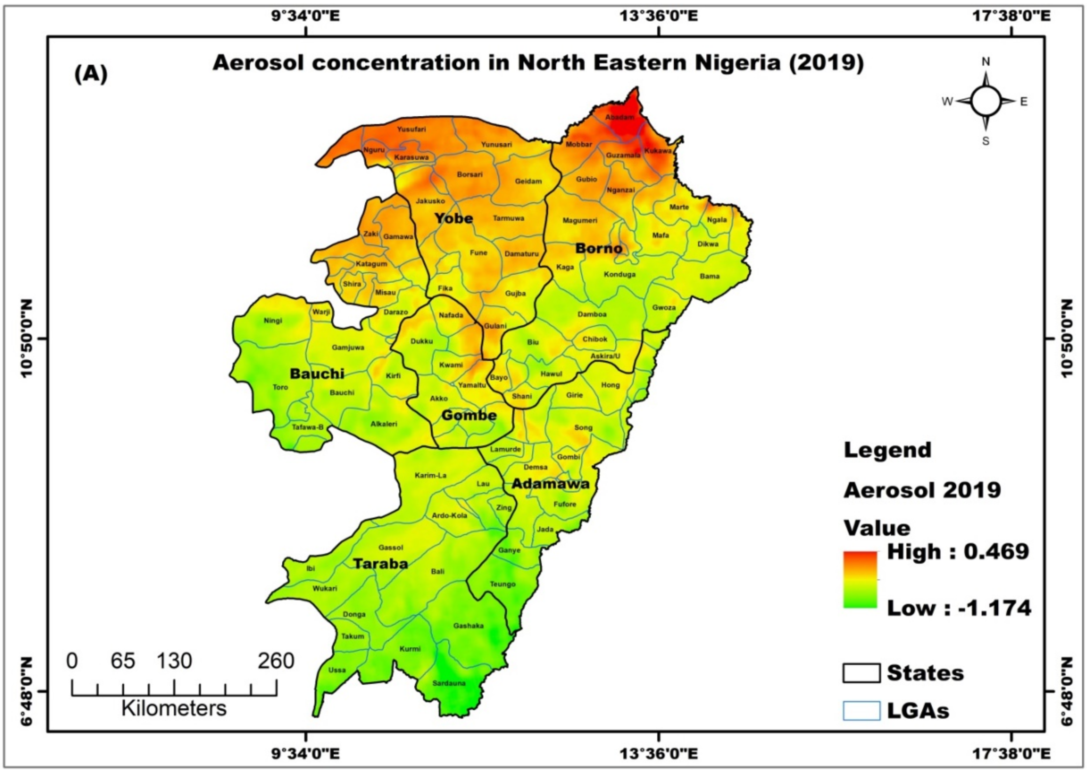

Figure 6g. Spatial distribution of aerosol in North Eastern Nigeria (2019)

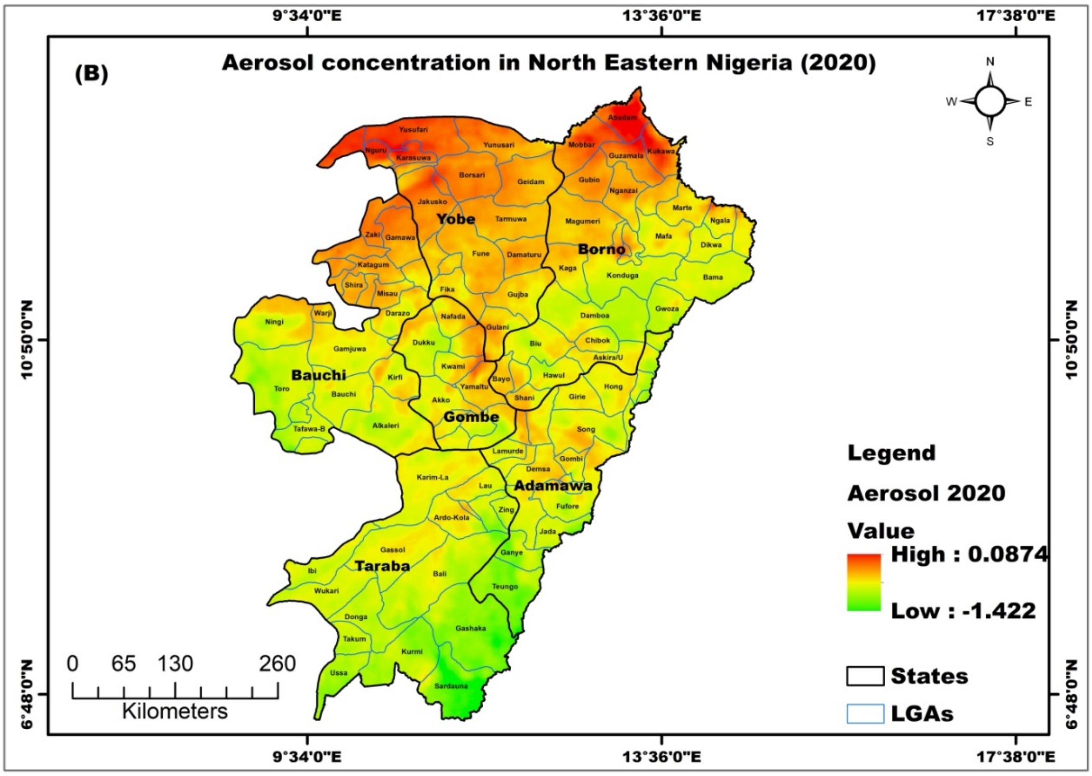

Figure 6b. Spatial distribution of aerosol in North Eastern Nigeria (2020)

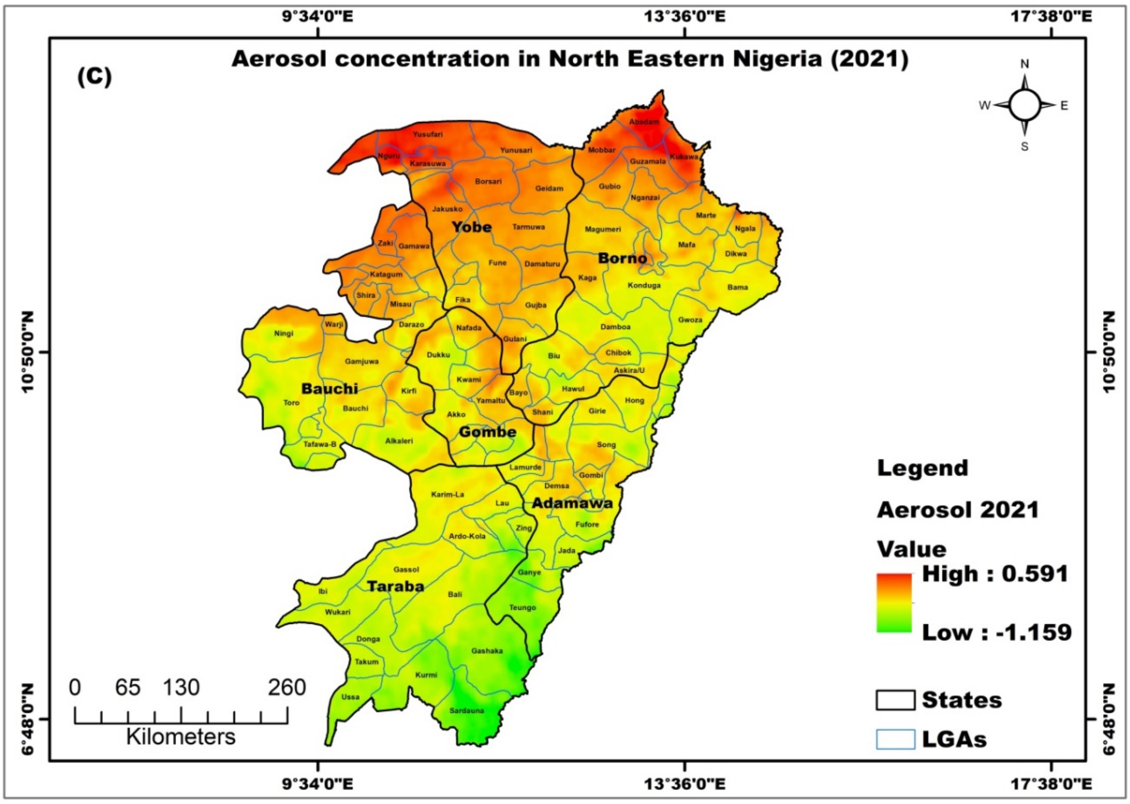

Figure 6c. Spatial distribution of aerosol in North Eastern Nigeria (2021)

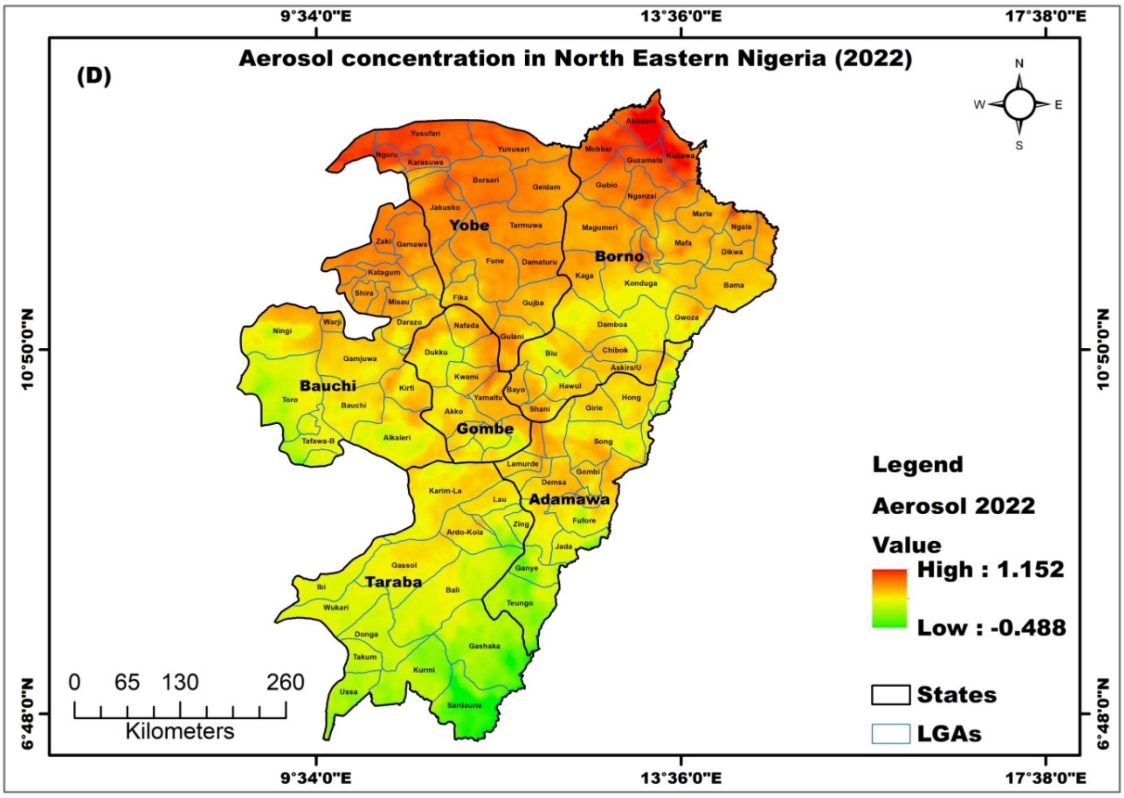

Figure 6d. Spatial distribution of aerosol in North Eastern Nigeria (2022)

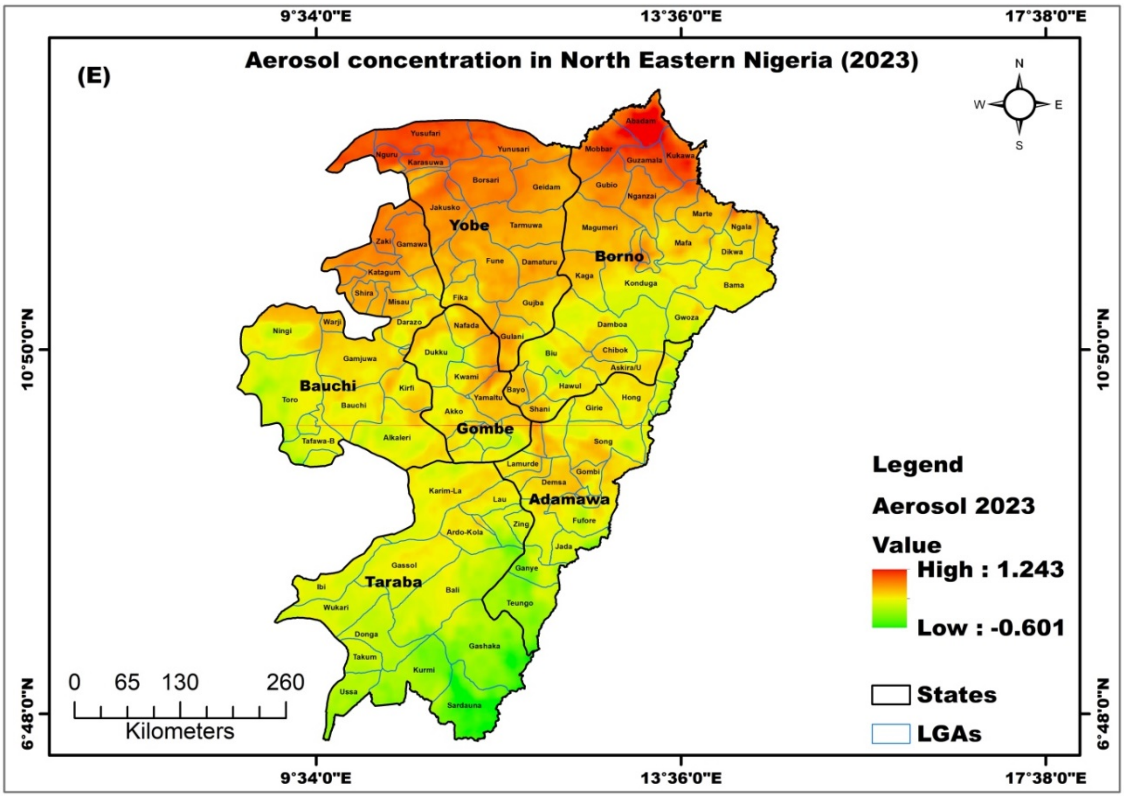

Figure 6e. Spatial distribution of aerosol in North Eastern Nigeria (2023)

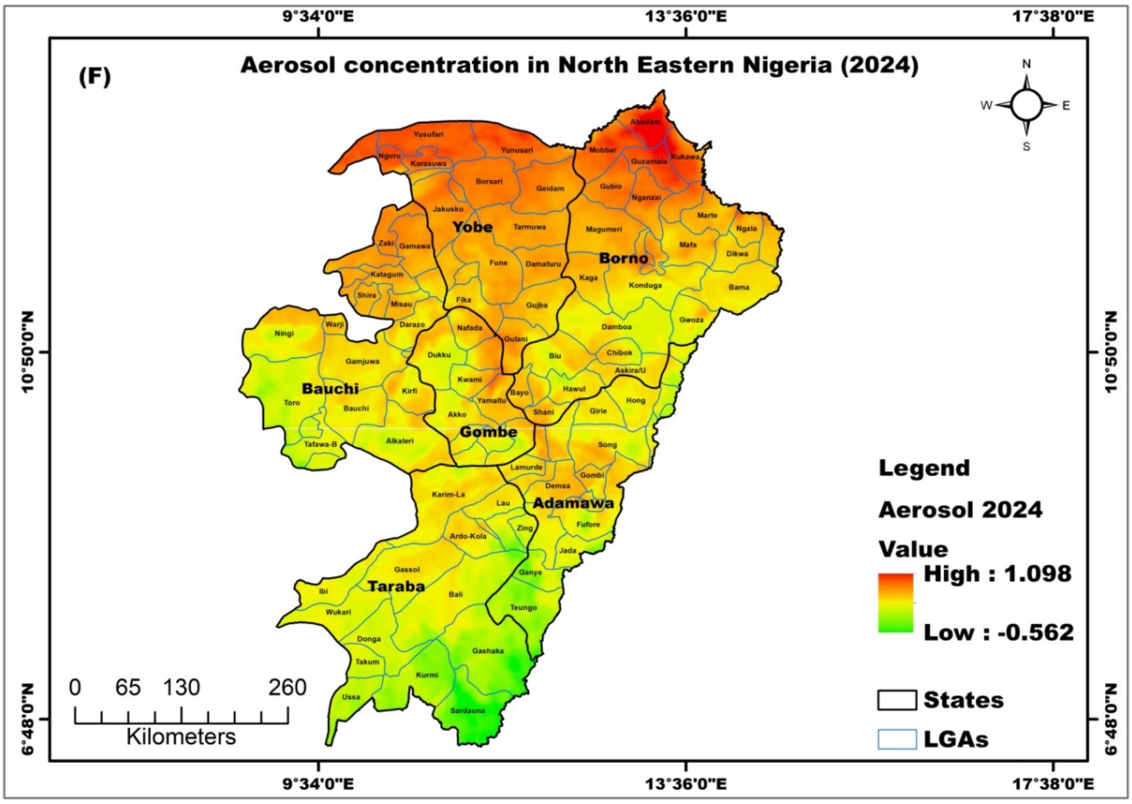

Figure 6f. Spatial distribution of aerosol in North Eastern Nigeria (2024)

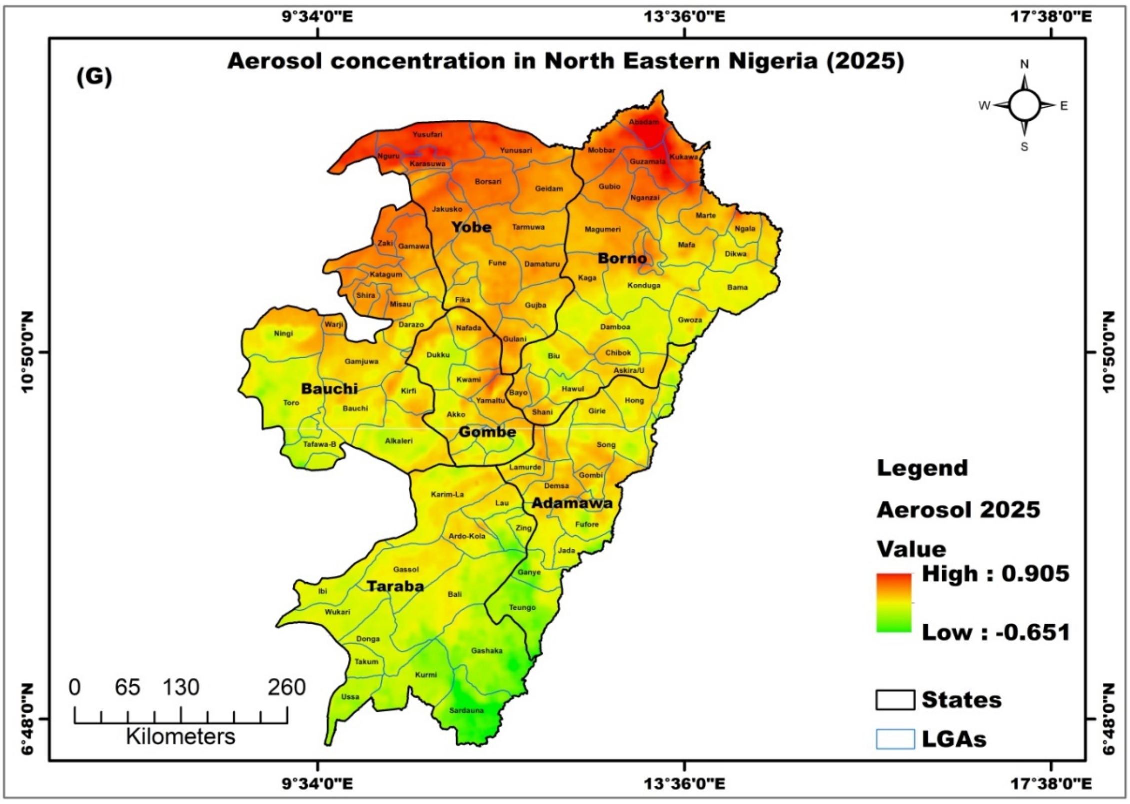

Figure 6g. Spatial distribution of aerosol in North Eastern Nigeria (2025)

In contrast, the persistently low aerosol concentrations recorded across Adamawa and Taraba States reflect environmental conditions that are less favourable for dust generation and accumulation. These southern states lie within the Guinea savanna and montane ecological zones, characterised by higher rainfall and denser vegetation cover (Happold and Lock, 2013; Chetouani *et al*., 2017). Studies conducted within Nigeria consistently show that increased precipitation and vegetation density reduce atmospheric aerosol by suppressing dust emission and accelerating particle removal from the atmosphere (Ayanlade *et al*., 2019; Obisesan, 2021).

The spatial and temporal patterns of CO and aerosol identified in this study represent not only environmental degradation but a measurable threat to population survival and wellbeing. The findings of this study demonstrate that the observed increases in CO and aerosol concentrations across North Eastern Nigeria can possibly have implications for human health and mortality. Air pollution is now recognised as one of the leading global environmental risk factors for premature death, particularly in low and middle-income countries where regulatory controls and healthcare capacity remain limited (WHO, 2021; HEI, 2020).

Extensive epidemiological evidence links exposure to particulate matter and gaseous pollutants to increased mortality (Orellano *et al*., 2020; Chen *et al*., 2021; Ma *et al*., 2024; Cao *et al*., 2025). Long-term exposure to aerosols, particularly $PM_{2.5}$, has been consistently associated with elevated risks of cardiovascular mortality, chronic respiratory disease, stroke, lung cancer, and premature death (Pope *et al*., 2002; Brook *et al*., 2010; Burnett *et al*., 2018). Global burden assessments indicate that ambient particulate matter alone accounts for several million premature deaths annually, with the highest mortality rates occurring in Africa and South Asia (Cohen *et al*., 2017; HEI, 2020). The elevated aerosol concentrations observed across North Eastern Nigeria, especially during the dry season imply a substantial hidden mortality burden in the region, particularly in Borno and Yobe States.

CO, while often associated with acute poisoning events, also contributes to increased mortality through chronic low-level exposure in polluted urban environments (Liu *et al*., 2024). Epidemiological studies have shown significant associations between ambient CO concentrations and cardiovascular mortality, hospital admissions, and respiratory complications (Bell *et al*., 2006; Atkinson *et al*., 2012). In regions where CO concentrations dominate, such as Taraba State of North Eastern Nigeria, chronic exposure to elevated CO levels may significantly increase mortality risk.

The temporal significance patterns identified through the paired sample t-test analysis further contextualise the health implications of air pollution in North Eastern Nigeria and are broadly consistent with findings from previous studies. The statistically significant difference in CO concentrations between 2019 and 2020 observed in this study aligns with results reported by Okoduwa and Amaechi (2023) and Amaechi *et al*. (2025a), suggesting that this period reflects a wider regional shift in emission dynamics or atmospheric conditions. Similarly, the absence of significant differences between 2020 and 2021 mirrors the relative temporal stability documented across Benin City, Anambra State, and Lokoja (Okoduwa and Amaechi, 2023; Amaechi *et al*., 2025a; Amaechi *et al*., 2025b), indicating that short-term equilibrium phases in CO concentrations are not uncommon across diverse Nigerian urban environments.

However, the re-emergence of statistically significant and highly significant CO differences in the later years of the present study, particularly between 2021 and 2022 and between 2023 and 2024, contrasts with the largely non-significant patterns reported for Lokoja (Amaechi *et al*., 2025b) but closely resembles the late-period variability observed in Anambra State (Amaechi *et al*., 2025a). This divergence highlights the role of regional meteorology in shaping pollutant dynamics. North Eastern Nigeria, characterised by widespread biomass burning, generator dependence, and seasonal dust transport, may therefore experience more pronounced interannual variability in combustion-related pollutants than less industrialised or transitional urban centres.

Aerosol variability in this study further reinforces these interpretations. The significant differences detected between 2019 and 2020 and between 2021 and 2022 are consistent with aerosol patterns reported for Lokoja and Anambra State (Amaechi *et al*., 2025a; Amaechi *et al*., 2025b), where statistically significant changes were confined to specific year pairs rather than exhibiting continuous trends. This episodic behaviour reflects the strong sensitivity of aerosols to interannual meteorology. Importantly, although earlier studies reported little variation between consecutive years, the highly significant long-term difference observed between 2019 and 2025 in the present study indicates that aerosol concentrations have changed substantially over time, even when individual year-to-year differences appear small.

The seasonal and spatial patterns in CO and aerosol concentrations identified for North Eastern Nigeria align closely with findings from other semi-arid and dust-influenced regions, reinforcing the broader climatic controls on pollutant variability. Several aerosol studies in the Sahel and wider West Africa demonstrate a strong seasonal cycle in dust and aerosol levels, with highest values during the dry Harmattan months and minima during the wet season, echoing the dry-season maxima and wet-season declines observed in this study (Ochei et al., 2023; Niamien *et al*., 2024). Long-term monitoring at different sites across West Africa reported pronounced seasonal peaks in aerosol associated with Sahara dust transport and biomass burning between December and March, followed by reduced aerosol levels during peak rainfall periods (Awoleye *et al*., 2025). Similarly, remote sensing analyses of mineral dust over West Africa found peak dust concentrations in the late dry season (February–April) with distinct seasonal minima in the rainy months, supporting the interpretation of Harmattan-driven aerosol enhancement in North Eastern Nigeria (Kaly *et al*., 2015).

Beyond Africa, studies in semi-arid South Asia reveal comparable seasonal dynamics; for example, long-term aerosol records over the Indo-Gangetic Plain show elevated aerosol levels in winter and pre-monsoon seasons linked to regional emissions and atmospheric stability, followed by lower concentrations during the monsoon season when wet scavenging is strongest (Shahid *et al*., 2022). Research in India's semi-arid regions also highlights higher scattering and absorbing aerosol coefficients during dry periods associated with combustion and dust sources, with meteorological influences controlling seasonal variability (Soyam *et al*., 2025). In East Africa, climatological analyses similarly document higher aerosol during dry months, with wet months showing significant decreases, further substantiating the influence of seasonal rainfall and atmospheric cleansing on aerosol distribution (Khamala *et al*., 2022).

The seasonal and spatial patterns of CO and aerosol variability documented for North Eastern Nigeria show strong parallels with findings from other semi-arid and dust-influenced regions. In West Africa, long-term observations at the Lamto atmospheric station in Côte d'Ivoire reveal a pronounced seasonal cycle for CO, with concentrations peaking during the dry season (January) and reaching minima in the wet season (June), patterns that reflect the influence of biomass burning and transport processes similar to those observed in this study (Tiemoko *et al*., 2021). Likewise, recent satellite and modelling analyses across West Africa demonstrate that CO seasonality is strongly tied to biomass burning and, in coastal zones, gas flaring activities, with higher CO during the December–March period and lower levels outside the dry season, reinforcing the influence of regional emission sources and meteorology on CO distributions (Onojeghuo *et al*., 2025). Collectively, these studies emphasise that the seasonal variation in CO and aerosol concentrations identified in North Eastern Nigeria reflects common drivers, which include long-range dust transport, biomass burning, combustion emissions, and rainfall-driven removal that characterise pollutant dynamics.

The co-occurrence of high CO and aerosol concentrations identified in this study further amplifies health risks through synergistic effects. Combustion sources such as vehicle exhaust, biomass burning, generator use, and waste combustion emit complex pollutant mixtures that jointly increase oxidative stress, systemic inflammation, endothelial dysfunction, and immune suppression (Kampa and Castanas, 2008; Schraufnagel *et al*., 2019). These mechanisms explain the observed associations between air pollution exposure and increased deaths from cardiovascular disease, chronic obstructive pulmonary disease, asthma exacerbations, and lower respiratory infections (Dockery *et al*., 1993; Pope and Dockery, 2006). Evidence from Africa supports these global findings. A study across multiple African countries has demonstrated statistically significant relationships between particulate matter exposure and mortality, particularly in young adults (Owili *et al*., 2017). In Nigeria specifically, air pollution has been identified as a leading environmental cause of premature death, with urban centres experiencing the greatest burden due to traffic emissions, poverty, and unregulated combustion activities (Amegah and Agyei-Mensah, 2017).

Seasonal dynamics further intensify mortality risk. The pronounced dry-season peaks in aerosol and CO concentrations observed in this study coincide with periods of increased respiratory morbidity and mortality in West Africa (Daffe *et al*., 2023). During the Harmattan season, increased dust transport and widespread biomass burning lead to sustained high pollutant exposure, particularly affecting vulnerable populations such as children, the elderly, and individuals with pre-existing health conditions. Studies have shown that mortality rates rise during periods of elevated particulate concentrations associated with dust and combustion activities, reinforcing the public health relevance of the seasonal patterns identified in this study (Perez *et al*., 2012; Giannadaki *et al*., 2014).

The policy implications of these findings are profound. The demonstrated links between elevated CO and aerosol concentrations and mortality highlight the urgent need for comprehensive air quality governance in Nigeria. Current regulatory frameworks remain weak, fragmented, and poorly enforced, with limited integration of air quality considerations into public health planning. Aligning national air quality standards with the World Health Organization guidelines would provide a scientifically grounded benchmark for protecting population health and reducing pollution-related mortality.

Targeted emission reduction strategies are essential. Policies promoting access to clean household energy, reducing dependence on diesel generators, regulating vehicular emissions, and controlling open burning would substantially reduce both CO and aerosol concentrations while delivering immediate public health benefits (Bonjour *et al*., 2013; Markandya *et al*., 2018). Urban planning interventions that reduce traffic congestion and encourage sustainable transport systems would further mitigate exposure in densely populated areas identified as pollution hotspots in this study.

In addition, integrating satellite-based air quality monitoring into national environmental management systems would enhance surveillance capacity in regions lacking ground-based stations. The spatial insights provided by geospatial analysis offer a powerful tool for identifying high-risk communities, estimating exposure-related mortality, and evaluating the effectiveness of policy interventions over time (Brauer *et al*., 2021; Clark *et al*., 2025). Such evidence-based approaches are critical for prioritising limited resources and addressing environmental health inequities across Nigeria.

Conclusion

This study provides clear evidence that CO and aerosol pollution represent a persistent and growing environmental and public health concern in North-Eastern Nigeria. The observed spatial patterns indicate that pollution burdens are unevenly distributed across the region, with higher concentrations recorded in areas influenced by urban activity and seasonal dust transport. These spatial disparities suggest that certain states and localities are disproportionately exposed to air pollution and its associated health risks. Temporally, the findings reveal that CO and aerosol concentrations do not follow a simple linear trend but instead exhibit episodic variability marked by statistically significant changes during specific periods. The presence of both short-term stability and long-term significant differences shows the importance of sustained monitoring rather than reliance on single-year assessments. Seasonal analysis further confirms that pollutant levels peak during the dry Harmattan season and decline during the wet season, highlighting the dominant role of meteorological conditions, particularly dust transport and rainfall, in influencing air quality across the region. Given the established links between air pollution and increased mortality from cardiovascular and respiratory diseases, the patterns identified in this study imply a substantial but largely unquantified health burden in North-Eastern Nigeria. In the absence of strong regulatory controls and comprehensive monitoring infrastructure, these risks are likely to persist or intensify. In conclusion, the study demonstrates that air pollution in North-Eastern Nigeria is not only an environmental issue but also a critical public health challenge. Addressing it requires coordinated scientific, policy, and institutional responses that recognise both the spatial complexity and temporal dynamics of atmospheric pollutants in the region.

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