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Comparative Assessment of Atmospheric Pollutants Across Geopolitical Zones in Southern Nigeria Using Sentinel-5p (2019 And 2024)

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Abstract
Air quality across Southern Nigeria declined between 2019 and 2024, with distinct spatial and temporal variations in carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), methane (CH_4), and aerosols. Using Sentinel-5P satellite data, pollution levels were mapped across the South-East, South-South, and South-West geopolitical zones. The South-West exhibited the highest overall pollutant concentrations, driven by vehicular emissions, industrial output, and extensive generator use, particularly in Lagos and Ogun states. The South-East recorded the steepest increases in CO, SO_2 and methane, linked to domestic energy reliance, population density, and widespread open waste burning. The South-South, despite intense oil and gas activity, showed comparatively lower mean pollutant values, likely mitigated by coastal ventilation, though localized hotspots in Benin city, Port Harcourt, Asaba and Warri remained severe. Between 2019 and 2024, methane and aerosol concentrations surged, with the SouthWest experiencing the sharpest rise in aerosol index. The data reveal a convergence in pollutant loads among zones by 2024, emphasizing the role of unregulated urban growth, fossil fuel dependence, and weak environmental governance. These findings emphasize rising regional air quality risks and the urgent need for differentiated policy strategies tailored to each zone's socioeconomic and environmental realities.

Keywords: Air pollution, Sentinel-5P, Southern Nigeria, Carbon monoxide (CO), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), Methane (CH_4), Aerosols, Geospatial analysis, Urban emissions, Gas flaring, Regional air quality, Environmental governance, Tropospheric Pollutants

Introduction
The atmosphere in Nigeria has undergone substantial transformation over the past two decades, shaped by shifting patterns of urbanization, increasing energy demands, and the expansion of industrial activities—all unfolding within a context where infrastructure development often lags behind rapid population growth and where environmental governance remains inconsistent [1-3]. Nowhere is this transformation more visible than in Southern Nigeria, where the air itself has become a canvas of human impact—marked by haze, soot, and chemical residues arising from a range of sources including vehicular emissions, oil exploration, industrial operations, and domestic combustion [4].

Despite the widespread presence of pollutants, the comparative severity of air quality challenges across regions remains poorly understood [5-7]. This is largely due to the limitations of existing environmental assessments, which often focus on specific cities or pollution sources, without accounting for broader regional dynamics [1,8-10]. The need for a regional lens is particularly urgent in Southern Nigeria, where environmental degradation intersects with high public health vulnerability, and where rapid economic activity is rarely matched by strong regulatory frameworks or scientific surveillance [2,3,11].

While countries like India, China, and Brazil have conducted extensive regional air quality assessments, Nigeria lacks any such comparative study across its geopolitical zones. This is despite clear differences in governance structures, energy consumption, and industrial activity among regions [12-14]. The absence of region-wide data obscures the true extent of pollution burdens and hampers institutional efforts to develop targeted and effective policy responses [15-17].

Among the major pollutants such as carbon monoxide, nitrogen dioxide, sulfur dioxide, methane and aerosols, carbon monoxide (CO) stands out as a colorless, odorless gas primarily released through the incomplete combustion of fossil fuels—commonly from generators, vehicles, and biomass burning. In Nigeria, CO exposure is prevalent in urban settings and in households relying on fuelwood or kerosene. Its physiological effects are serious, as it binds to hemoglobin and reduces the blood's capacity to carry oxygen, leading to headaches, dizziness, and, at high levels, fatal outcomes. Beyond its direct impact on human health, CO also indirectly contributes to ozone formation, further degrading air quality. Nitrogen dioxide (NO_2), primarily emitted from vehicle exhaust, power generation, and open burning, poses a different but equally serious threat [11,18-21]. Cities such as Lagos and Onitsha experience significant traffic congestion, a major source of NO_2. This pollutant aggravates respiratory conditions like asthma, increases vulnerability to infections, and contributes to acid rain and secondary particulate matter formation, which in turn damage crops and infrastructure [2,4,22,23]. Similarly, sulfur dioxide (SO_2), released from the burning of sulfur-rich fuels such as diesel, coal, and crude oil, is particularly concentrated in industrial zones and areas plagued by gas flaring, like the Niger Delta [24]. SO_2 exposure is known to irritate the throat and lungs, particularly in individuals with asthma, while its environmental impacts—acid rain, soil degradation, and aquatic ecosystem disruption—are equally severe [25]. Methane (CH_4), a potent greenhouse gas, originates from waste dumps, rice paddies, livestock, and oil and gas operations. In Nigeria, gas flaring and poorly managed landfills are significant contributors. Although methane does not pose direct health risks at ambient levels, its role in accelerating climate change indirectly amplifies heat-related illnesses and extreme weather events [26]. Aerosols, comprising fine particulate matter suspended in air, are another major pollutant. These particles stem from dust storms, biomass combustion, and industrial processes. In Northern Nigeria, desert dust and open burning are dominant sources, but Southern Nigeria also experiences aerosol build up from industrial activities. These particles penetrate deep into the lungs, triggering respiratory and cardiovascular diseases, while also affecting local climate by modifying solar radiation and cloud formation [27].

Southern Nigeria presents a striking environmental paradox. On one hand, states like Bayelsa and Port Harcourt are beset by persistent gas flaring and hydrocarbon leakage; on the other, densely populated urban centers like Aba and Onitsha grapple with heavy vehicular emissions, informal industrial activities, and the open burning of household waste [4,9,15,16,23]. While the health and environmental effects—such as spikes in hospital admissions and visible air discoloration—are evident, reliable longitudinal data linking pollution levels to these outcomes is sparse and fragmented [2,28,29]. Ground-based air quality monitoring, though valuable, remains limited due to its sparse distribution and the high costs associated with deploying and maintaining such systems in resource-constrained settings [3,30,31].

To overcome these limitations, remote sensing has emerged as a transformative tool for atmospheric research, particularly through the use of the Sentinel-5P satellite. Equipped with the Tropospheric Monitoring Instrument (TROPOMI), Sentinel-5P offers high-resolution data on key pollutants including nitrogen dioxide, carbon monoxide, sulfur dioxide, methane, and aerosols [32-34]. This satellite-based approach is ideal for countries like Nigeria, where ground-level monitoring is insufficient and where pollution sources vary significantly based on geography and economic activity [1,2,16]. Furthermore, remote sensing allows researchers to track pollution trends over time and evaluate the impacts of unique events—such as the COVID-19 lockdown—which inadvertently served as a natural experiment in emission reduction [1,35,36].

Nigeria's failure to develop a comprehensive national air quality framework that includes regional environmental health assessments has profound implications. These range from ineffective urban planning and insufficient healthcare preparedness to poor alignment with international sustainability targets [2,4,37]. The lack of comparative data weakens internal governance and impedes progress toward global benchmarks such as the Paris Agreement and the United Nations Sustainable Development Goals. In regions like Bayelsa, where gas flaring emits large volumes of methane and CO_2, or Onitsha, where particulate matter from traffic and dust clouds the air daily, these exposures remain largely unmeasured and unaddressed in policy discourse [4,15,23,38,39].

This study seeks to address these challenges by adopting a regional approach, focusing on Southern Nigeria and leveraging Sentinel-5P data from 2019 and 2024 to examine spatial and temporal variations in pollution. It represents the first comparative air quality assessment across multiple southern geopolitical zones, thereby filling a critical gap in the existing literature despite longstanding recognition of environmental inequality. The core objective is to identify which regions suffer from the worst air quality and which fare better, using pollutant data to highlight both anthropogenic and climatic influences Such distinctions are vital for crafting targeted policy interventions and for reframing air quality as a development issue rooted in regional disparities and historical legacies.

By analyzing concentrations of CO, NO_2, SO_2, methane, and aerosols, this research also aims to unpack how the sources and intensity of pollution differ across zones, and how these patterns correlate with factors such as energy poverty, population density, and unregulated industrial activity [1,15,38]. Ultimately, the study aims to provide a scientifically robust foundation for region-specific air quality strategies—moving Nigeria away from ineffective, one-size-fits-all approaches and toward policies that genuinely reflect the country's complex environmental realities.

Methodology

Description of Study Areas

The southern region of Nigeria comprises three distinct geopolitical zones—South-East, SouthSouth, and South-West—each defined not only by political boundaries but by varying environmental conditions, cultural practices, economic structures, and air pollution dynamics. These zones collectively host some of the country's most industrialized cities, densely populated communities, and ecologically vulnerable ecosystems. Understanding the regional characteristics of these areas is essential for interpreting patterns of air quality and contextualizing the observed variations in pollutant levels across different locations and periods.

The South-East zone, made up of Abia, Anambra, Ebonyi, Enugu, and Imo states, is a densely populated and highly urbanized region [40-42]. The zone lies within the humid tropical rainforest belt, featuring abundant rainfall, high humidity, and lush vegetation [4,39,43,45]. Its topography is defined by lowlands and undulating terrains, with pockets of higher elevation in areas such as Nsukka and parts of Ebonyi [4,39,40,43,46]. While rich in natural resources, the South-East is best known for its manufacturing sector, informal industries, and dynamic commercial activity [41,44,47].

Cities such as Aba and Onitsha have become economic hubs where large-scale industrial production operates alongside informal waste management and widespread generator usage due to inconsistent electricity supply [4,23,39,44,45,48,49]. These urban centers are characterized by poorly regulated emissions from small- and medium-scale industries, aging vehicles with no emission control mechanisms, and open waste burning—a practice driven by inadequate waste collection infrastructure [41,47,50]. In cities like Onitsha, air quality degradation is further compounded by high traffic volume and poor road networks, which increase vehicular idling and pollutant accumulation [42,46,50].

Population density is a critical factor shaping environmental stress in the South-East [4,23,39,43,44,48,49]. Onitsha, for instance, ranks among the most densely populated urban areas in Africa, with thousands of people per square kilometer and a spatial footprint that continues to expand rapidly [4,39,42,44,45,49]. The combination of dense habitation, commercial activity, and weak environmental regulation results in elevated concentrations of particulate matter, nitrogen dioxide, and carbon monoxide [46,47,50]. Seasonal variations also influence pollution dispersion, particularly during the harmattan season when Saharan dust intrudes into southern Nigeria, further increasing the ambient levels of fine particulate matter [40,43,50].

The South-East's air pollution profile is therefore the result of intersecting factors: industrial processes, vehicular emissions, energy-related pollution, and seasonal dust movement [4,39,45,49]. It remains one of the most environmentally stressed regions in Nigeria, yet the absence of consistent monitoring systems masks the full extent of its pollution burden [47,48,50].

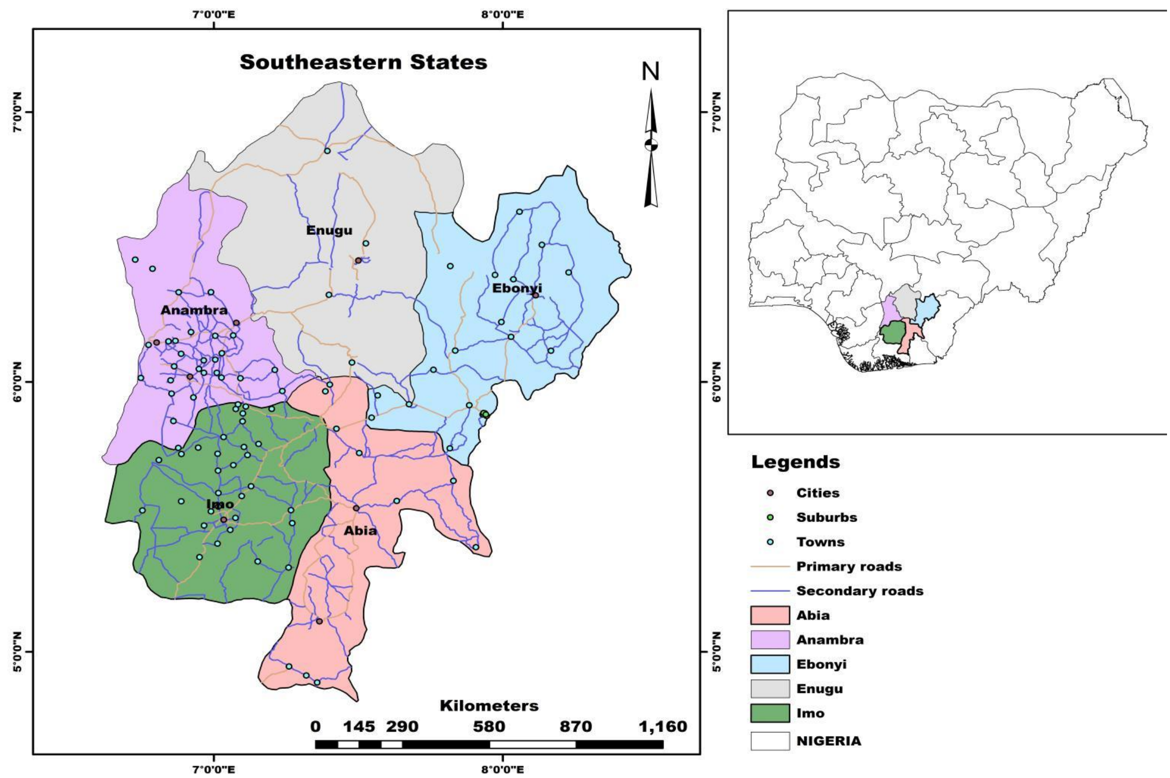

Figure 1: Map Showing South-Eastern States

Moving southward, the South-South geopolitical zone includes Akwa Ibom, Bayelsa, Cross River, Delta, Edo, and Rivers states [1,16,51,52,53]. This zone is ecologically distinct, encompassing the core of the Niger Delta—one of the world's largest wetlands and a globally recognized biodiversity hotspot [51,52,54]. The South-South zone is deeply intertwined with Nigeria's oil economy, as it hosts most of the country's petroleum reserves and infrastructure [53-55]. Rivers and Bayelsa states, in particular, are heavily industrialized and represent epicenters of oil exploration, refining, and gas flaring [16,51,53,54].

In communities such as Gbarain in Bayelsa or Ahoada in Rivers, flaring of natural gas occurs continuously, emitting large volumes of greenhouse gases, volatile organic compounds, and black carbon directly into the atmosphere [54,53,55]. These emissions contribute to localized heating, respiratory illnesses, acid rain, and the long-term degradation of air, soil, and water quality [52,53,54]. The geography of the South is dominated by low-lying floodplains, swamps, and estuaries, interspersed with patches of elevated dry land [1,16,51,52,55]. The climate is typically equatorial, characterized by two dominant seasons: a long-wet season with intense rainfall and a shorter dry season [51,53,54].

High humidity and frequent rain help to disperse certain gaseous pollutants but also lead to the formation of acid rain in areas with high concentrations of sulfur dioxide and nitrogen oxides [51,53,54]. Gas flaring, open refining (also known as artisanal refining), and illegal bunkering operations release a complex mix of pollutants, including sulfur compounds and heavy metals [53,54,55]. These practices are often carried out in remote areas with minimal regulation, further complicating efforts to track and manage emissions [51,52,53].

In addition to oil-related pollution, urban areas in the South—such as Port Harcourt, Uyo, and Warri—experience urban traffic emissions and domestic pollution from the use of biomass fuels and diesel generators [16,51,53,54]. Unlike the South-East, the South-South's environmental challenges are less driven by population density and more by industrialization, natural resource extraction, and governance failures [51,53]. Communities living close to oil infrastructure frequently report elevated health risks, including chronic respiratory issues and unexplained illnesses, which are often attributed to prolonged exposure to airborne pollutants [16,53,54,55].

In recent years, cities like Port Harcourt have been labeled as "soot cities" due to the persistent presence of black carbon in the atmosphere, stemming from both legal and illegal refining activities [16,51]. The environmental costs of oil wealth have become increasingly visible, yet systemic monitoring remains limited, and enforcement of air quality standards is either weak or absent [51,53,55].

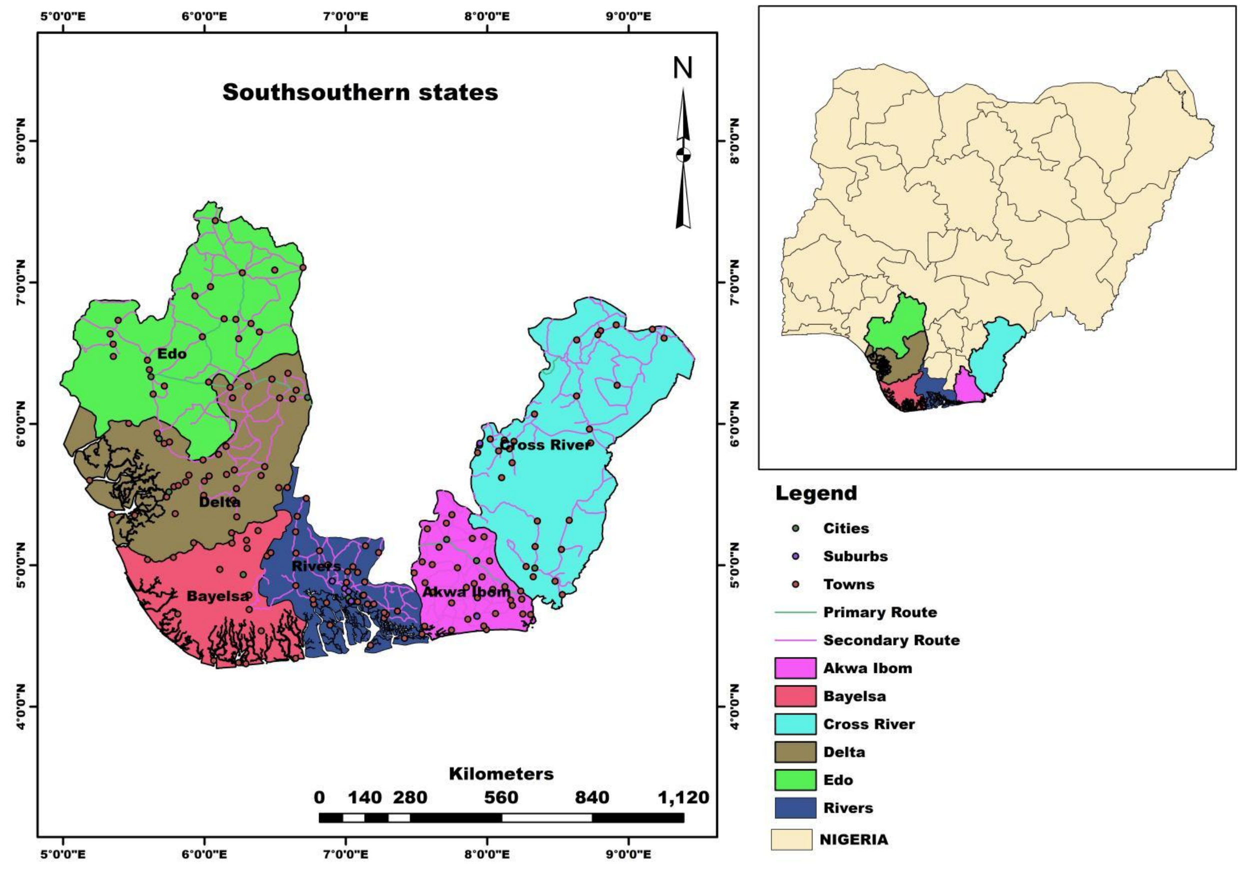

Figure 2: Map Showing South-Southern States

The South-West geopolitical zone, comprising Ekiti, Lagos, Ogun, Ondo, Osun, and Oyo states, offers a contrasting but equally complex air quality scenario [56,57]. As Nigeria's most economically advanced and urbanized region, the South-West is home to Lagos—the country's commercial capital and one of Africa's largest megacities [,1,2,57,59]. Lagos alone has a population exceeding 20 million, with corresponding levels of vehicular traffic, industrial activity, and domestic energy consumption [1,2,57,59]. The region features diverse landforms, ranging from the coastal plains of Lagos and Ondo to the forested hills of Ekiti and Osun [56,58].

It has a tropical wet-and-dry climate, with distinct rainy and dry seasons, and experiences periodic temperature inversions that can trap pollutants close to the ground, exacerbating pollution exposure in urban basins [1,2,58,59]. Air quality in the South-West is heavily influenced by traffic emissions, especially in Lagos where over 5 million cars operate daily, many of them old and poorly maintained [1,2,57,59]. The vehicle fleet in the region largely lacks emission control technologies, leading to high levels of nitrogen dioxide, carbon monoxide, and particulate matter [1,2].

Industrial zones in Ogun and Lagos—such as Agbara and Ikeja—contribute significantly to the regional pollution burden, releasing both regulated and unregulated emissions into the atmosphere [56,57]. Power generation is another major concern; due to irregular electricity supply from the national grid, millions of households and businesses operate diesel and petrol generators daily, releasing carbon monoxide and hydrocarbons at localized scales. In addition to outdoor pollution, indoor air quality is also compromised, especially in low-income settlements where biomass and kerosene are still used for cooking [1,2,56,57].

Urban planning challenges and waste management inefficiencies further worsen air quality in the South-West [56,58]. Open burning of refuse is still common in peri-urban communities, and unauthorized dumpsites emit methane, ammonia, and other pollutants [1,2,58,59]. Land use in this region reflects a mix of formal development and unregulated urban sprawl, making pollution management highly fragmented [56,58]. While Lagos has made strides in introducing air quality policies and investing in monitoring, most other states in the South-West lack the institutional capacity to implement systematic pollution control measures [1,2,57,59]. Even where monitoring stations exist, data is often unavailable to the public, limiting transparency and accountability [1,2,57,59].

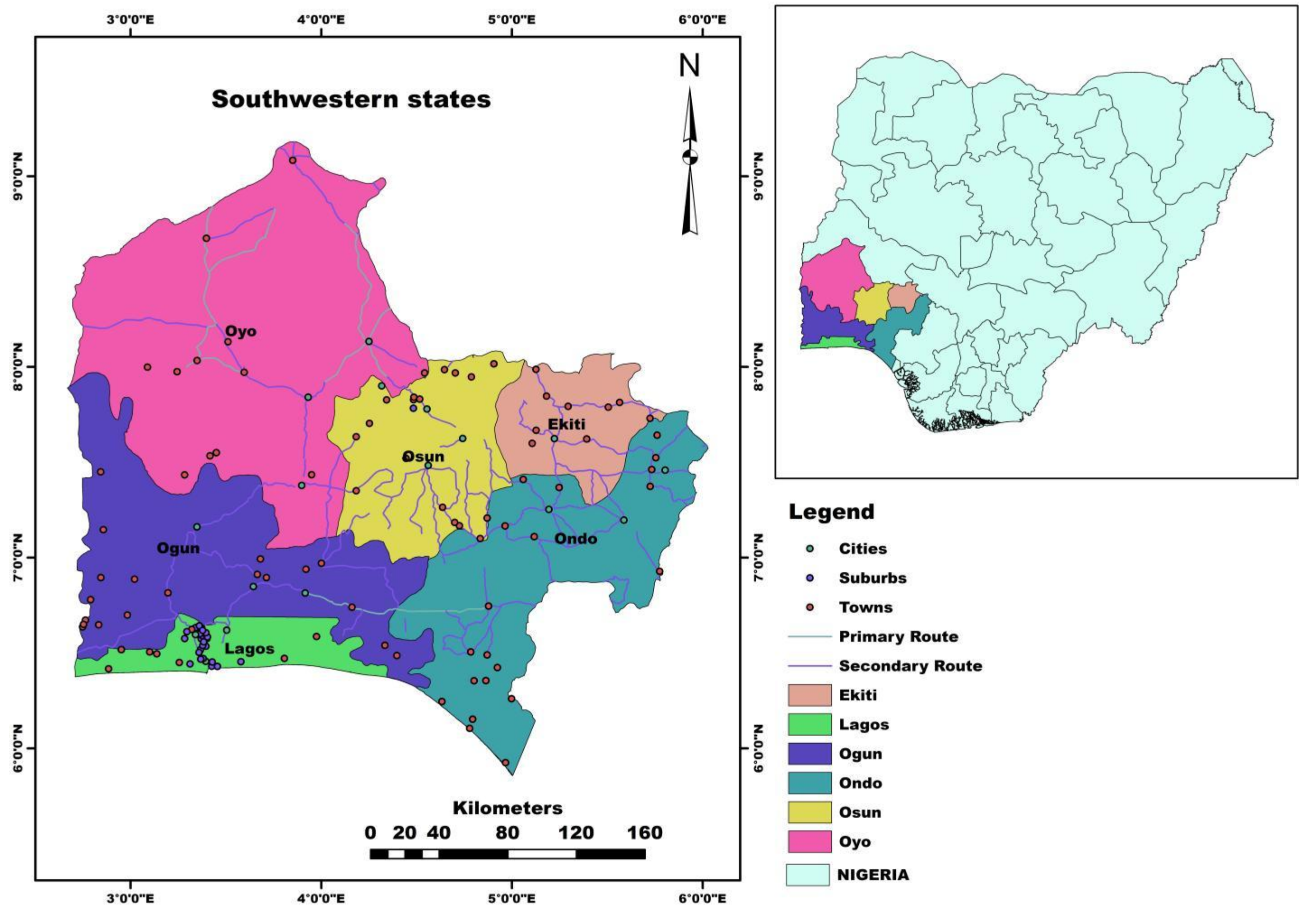

Figure 3: Map Showing South-Western States

Across these three zones, a common feature is the complex interaction between socioeconomic activity, environmental governance, and atmospheric health. While the South-East suffers from industrial congestion and traffic-related emissions, the South-South grapples with the consequences of extractive industries and systemic environmental neglect [4,16,23,39,49,52]. The South-West, on the other hand, presents a fast-urbanizing region where modern economic activity collides with weak infrastructure and informal energy practices [1,2]. Together, they reflect the multi-dimensional nature of air quality challenges in Southern Nigeria. Importantly, no comparative study has yet evaluated these regions side by side, which is precisely the gap this research seeks to address using geospatial datasets from Sentinel-5P.

By understanding the specific geographic, economic, and social characteristics of each zone, this study creates a framework for interpreting pollutant variations not just as abstract environmental phenomena, but as outcomes rooted in place-specific conditions. It also lays the foundation for targeted mitigation strategies that recognize the uniqueness of each region—whether it be the oilfields of the Delta, the markets of Onitsha, or the highways of Lagos.

Research Design

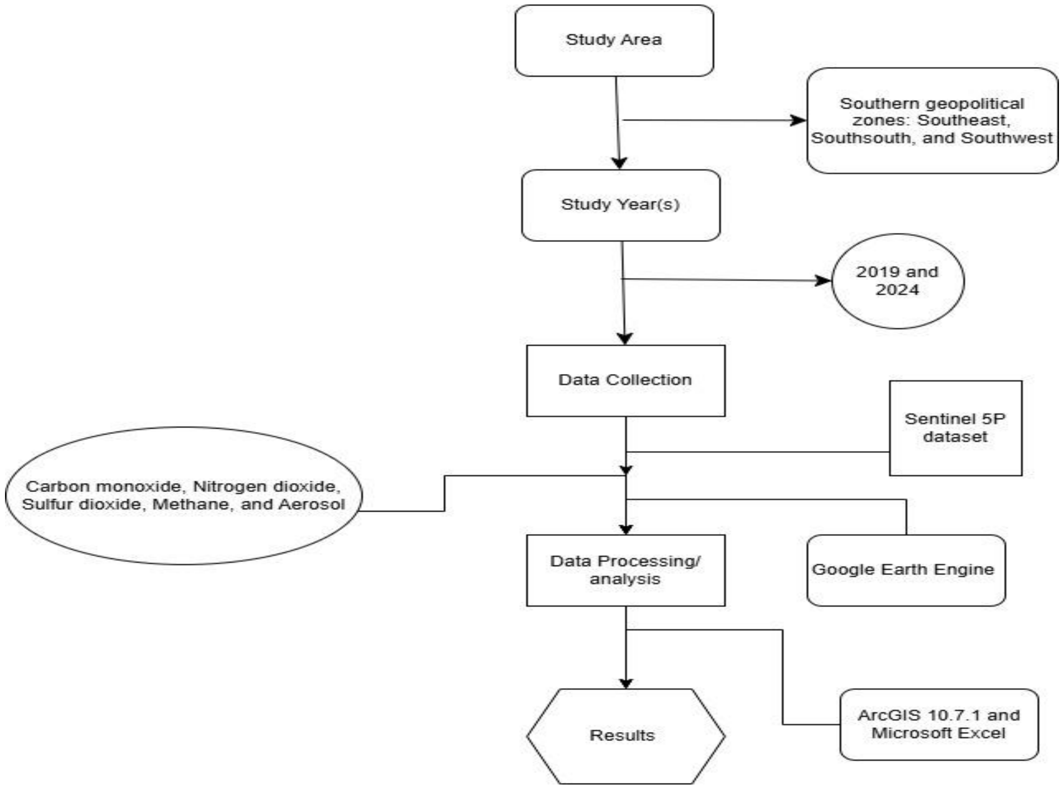

Figure 4: Research Design for the Study

Data Collection and Data Processing/Analysis

Data Collection

This study utilized satellite-based remote sensing data to examine atmospheric pollutants across the Southern geopolitical zones of Nigeria—South-East, South-South, and South-West— comparing data from the years 2019 and 2024. Data were acquired from the Sentinel-5 Precursor (Sentinel-5P) satellite via the Google Earth Engine (GEE) platform and subsequently processed using ArcGIS 10.7.1 (ArcMap). The atmospheric parameters analyzed included carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), methane (CH_4), and aerosols, as these pollutants represent key indicators of air quality degradation and anthropogenic environmental impact.

Sentinel-5P

Sentinel-5P, a mission under the Copernicus program of the European Space Agency (ESA), is equipped with the TROPOspheric Monitoring Instrument (TROPOMI). This sensor is capable of capturing high-resolution data on various atmospheric gases and aerosols, with a spatial resolution of approximately 7 km × 3.5 km. The instrument offers near real-time global measurements of pollutants, making it a valuable resource for environmental assessments [,1,2,60].

Sentinel-5P provides detailed data on the vertical column densities of gases like CO, NO_2, SO_2, and CH_4, as well as aerosol indices, all measured in mol/m² aside from methane (CH_4) which is measured in mole fraction and aerosol which has no unit of measurement. These datasets are openly accessible via platforms such as EO Browser and can be processed using GIS tools like ArcGIS. The satellite's wide coverage and high temporal resolution make it particularly suitable for monitoring air quality in developing regions with limited access to ground-based measurement stations [,1,2,61]. However, slight discrepancies may occur when comparing its outputs to ground observations, due to variations in spatial resolution and local meteorological conditions [,1,2,62]. Nevertheless, Sentinel-5P continues to serve as a robust and reliable source for large-scale air pollution monitoring.

Method of Data Collection

Shapefiles delineating the South-East, South-South, and South-West geopolitical zones were clipped from Nigeria's national shapefile using ArcMap. These files were then imported into Google Earth Engine. Custom scripts were written in GEE to extract pollutant data—specifically CO, NO_2, SO_2, CH_4, and aerosols—from the Sentinel-5P TROPOMI dataset for the years 2019 and 2024. These scripts defined both spatial and temporal parameters, enabling GEE to efficiently query, process, and export the relevant datasets for further analysis.

Google Earth Engine

Google Earth Engine (GEE) is a cloud-based geospatial analysis platform designed for the visualization and processing of large-scale satellite data [1,2,63]. Its capabilities include interactive scripting, filtering of satellite imagery, and computation over extensive spatial and temporal domains. These features make it highly effective for environmental monitoring, including assessments of air quality and pollutant dispersion patterns [1,2]. In the context of this study, GEE facilitated the retrieval of atmospheric pollutant data from Sentinel-5P for the Southern Nigerian geopolitical zones. By leveraging GEE's advanced tools, the study was able to perform comparative assessments of CO, NO_2, SO_2, CH_4, and aerosol concentrations across multiple regions and timeframes [64,65]. The integration of Sentinel-5P data and GEE's analytical power provided a comprehensive basis for evaluating air quality dynamics over time and space.

Name	Units	Min	Max	Description
CO_column_number_density	mol/m^2	-34.43*	5.71*	Vertically integrated CO column density.
NO_2_column_number_density	mol/m^2	-0.00051*	0.0192*	Total vertical column of NO_2 (ratio of the slant column density of NO_2 and the total air mass factor).
SO_2_column_number_density	mol/m^2	-0.4051*	0.2079*	SO_2 vertical column density at ground level, calculated using the DOAS technique.
CH_4_column_volume_mixing_ratio_dry_air	Mol fraction (mol/mol)	1285*	2405*	Column-averaged dry air mixing ratio of methane, as parts-per-billion
absorbing_aerosol_index		-21*	39*	A measure of the prevalence of aerosols in the atmosphere.

Table 1: CO, NO_2, SO_2, CH_4 and Aerosols Dataset Obtained from Sentinel-5P

Results and Discussion

CARBON MONOXIDE CONCENTRATION			
2019	**South-East**	**South-South**	**South-West**
MINIMUM	0.044	0.040	0.042
MAXIMUM	0.052	0.052	0.055
MEAN	0.048	0.046	0.049
STANDARD DEVIATION	0.006	0.009	0.009

Table 2: Minimum, Maximum, Mean and Standard deviation of Carbon monoxide

concentration across the study regions (2019)

Table 2 provides the minimum, maximum, mean, and standard deviation of carbon monoxide (CO) concentration across the South-East, South-South, and South-West in 2019. The results indicate that the mean CO concentration was highest in the South-West at 0.049 mol/m², followed by the South-East at 0.048 mol/m², and lowest in the South-South with 0.046 mol/m². The minimum concentration was lowest in the South-South (0.040 mol/m²), while the maximum CO value of 0.055 mol/m² was recorded in the South-West. Both South-South and South-West had a standard deviation of 0.009 mol/m², indicating a similar level of variability in CO concentration, while the South-East showed the lowest variability (SD = 0.006 mol/m²). These results reveal spatial differences in CO levels, with the South-South exhibiting the lowest mean concentration, and the South-West reflecting slightly higher overall CO levels. The values recorded indicate inter-regional differences in air quality levels attributed to CO in the base year 2019.

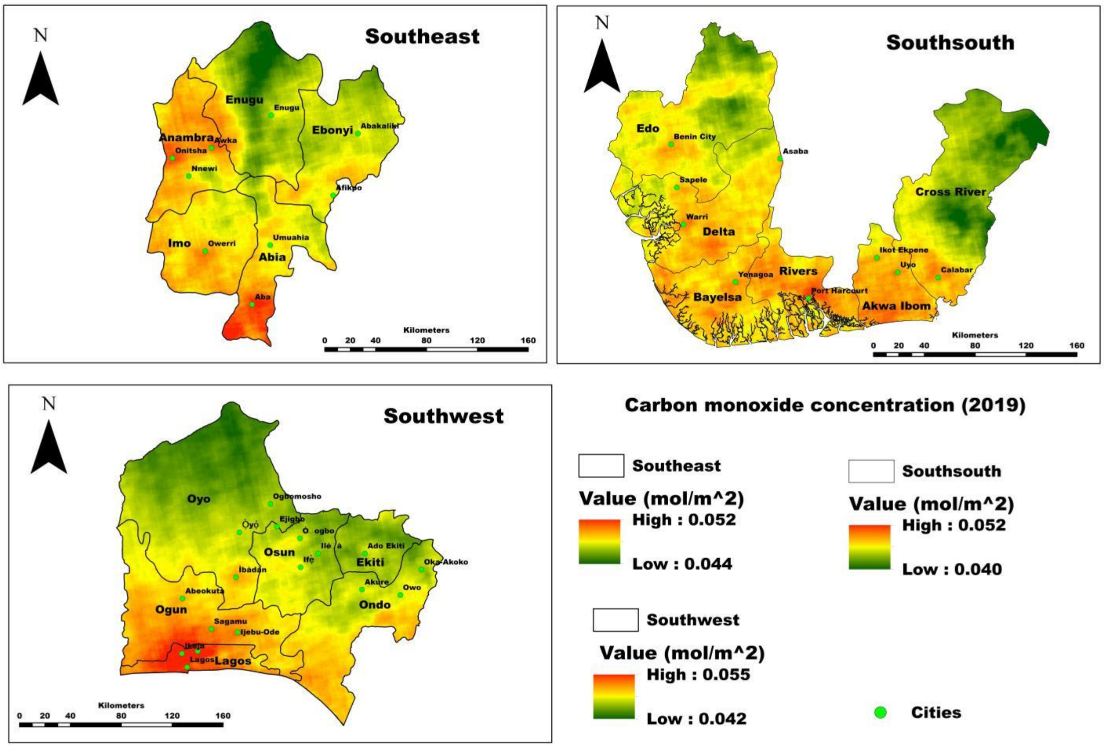

Figure 5: Carbon Monoxide concentrations in South-East, South-South and South-West for 2019

The spatial distribution Carbon monoxide concentration in 2019 (Figure 5) recorded high concentration levels across the three Southern geopolitical zones in Nigeria. In the South-East, major urban areas across states recorded high concentration levels (approximately 0.052 mol/m2). Places such as Aba in Abia state, Owerri in Imo state, Onitsha, Awka and Nnewi in Anambra state all recorded elevated Carbon Monoxide concentrations levels. In the South-south geopolitical zone, places such as Benin city in Edo state, Sapele, Asaba and Warri in Delta state, Yenogua in Bayelsa, Port Harcourt in Rivers state, Uyo and Ikot-Ekpene in Akwa ibom state and Calabar in Cross river state, all recorded high levels of carbon monoxide, approximately 0.052 mol/m2 for the year 2019. Similarly, urban areas in the South-West such as Lagos, Abeokuta, Ijebu-ode, Sagamu (Ogun state), Ibadan (Osun state) and Owo (Ondo state) indicated high concentrations levels of Carbon monoxide.

CARBON MONOXIDE CONCENTRATION			
2024	**South-East**	**South-South**	**South-West**
MINIMUM	0.047	0.044	0.045
MAXIMUM	0.056	0.058	0.057
MEAN	0.052	0.051	0.051
STANDARD DEVIATION	0.006	0.010	0.009

Table 3: Minimum, Maximum, Mean and Standard Deviation of Carbon Monoxide Concentration Across the Study Regions (2024)

Table 3 presents the 2024 statistics for carbon monoxide concentration across the same three regions. In this period, the South-East recorded the highest mean CO concentration at 0.052 mol/m², followed closely by South-South and South-West at 0.051 mol/m² each. The South-East also recorded the lowest standard deviation of 0.006 mol/m², indicating relatively low variability in CO concentration, while the South-South had the highest variation at 0.010 mol/m². Minimum CO levels ranged from 0.044 mol/m² in the South-South to 0.047 mol/m² in the South-East. Maximum concentrations were close in value: 0.058 mol/m² in South-South, 0.057 mol/m² in the South-West, and 0.056 mol/m² in the South-East. This table shows a rise in the mean CO concentration across all regions from the 2019 values, suggesting an upward shift in carbon monoxide levels over the five years. While values across regions were relatively close in 2024, the South-East displayed the highest central value, whereas the South-South showed the widest concentration range.

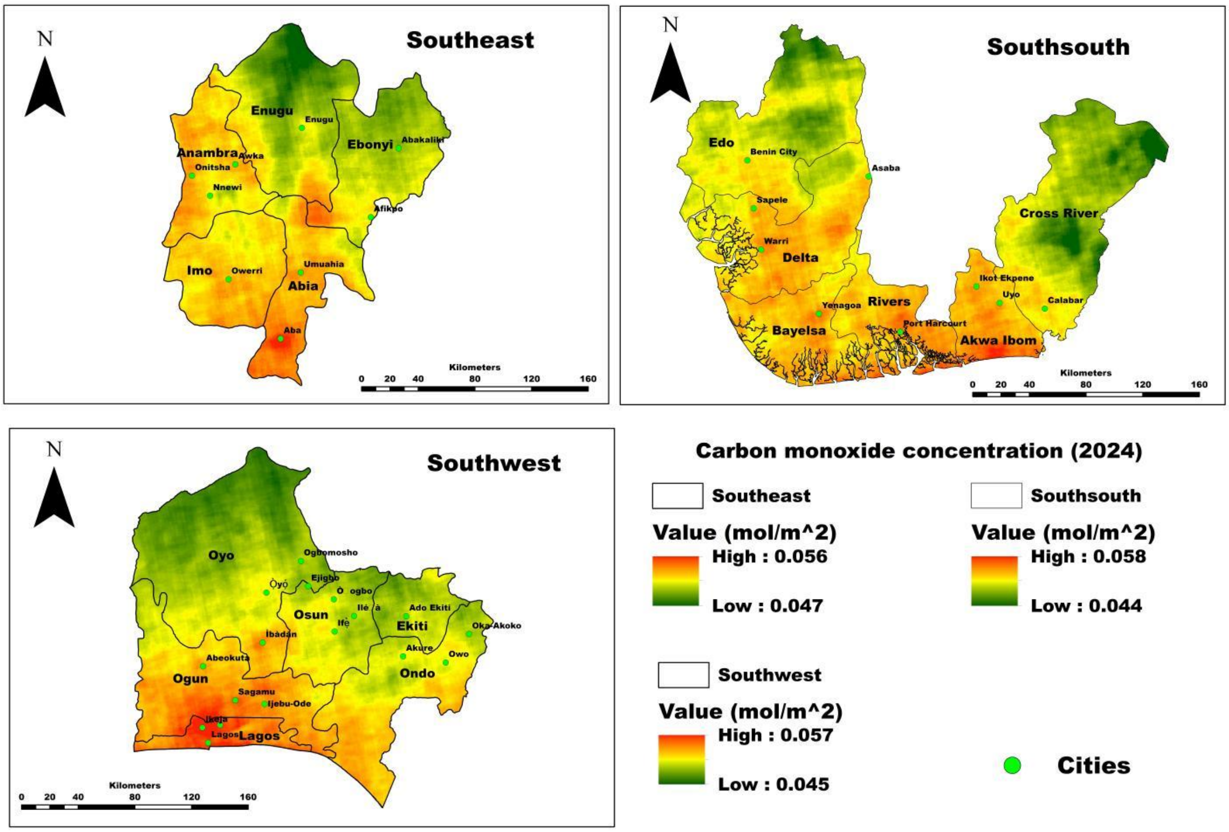

Figure 6: Carbon Monoxide Concentrations in South-East, South-South and South-West for 2024

For the year 2024 (Figure 6), the spatial distribution of Carbon monoxide concentrations levels revealed a slight increase and decrease in some areas as compared to year 2019. The South-Eastern zone recorded elevated concentration levels averaging around 0.056 mol/m2 in most major cities across the states Abia, Imo and Anambra, while low concentration levels of about 0.047 mol/m^2 were recorded in most parts of Enugu state and Ebonyi state. In the south south, high concentration levels of about 0.058 mol/m2 were experienced mostly in Akwa ibom state and cities across Rivers state, Delta state and Bayelsa state, while Edo state and Cross-river state experienced moderate and low-level concentrations of carbon monoxide of about 0.044 mol/m2.

In the South-Western geopolitical zone, very high levels of carbon monoxide concentrations of about 0.057 mol/m2 were recorded majorly in Lagos and Ogun state and sparsely in parts of Oyo and Ondo states which experienced lower carbon monoxide concentrations levels of about 0.045 mol/m2 for the year 2024.

CARBON MONOXIDE	South-East	South-South	South-West
2019	0.048	0.046	0.049
2024	0.052	0.051	0.051
MEAN	0.0498	0.0484	0.0499

Table 4: Carbon Monoxide Concentration Across the Study Regions (2019 and 2024)

Table 4 compares the mean CO concentrations across 2019 and 2024 in the three regions. In 2019, the CO concentration ranged from 0.046 mol/m² in the South-South to 0.049 mol/m² in the South-West. By 2024, all three regions experienced an increase in CO levels, with the SouthEast rising to 0.052 mol/m² and both South-South and South-West reaching 0.051 mol/m². The five-year average CO concentrations were: South-East (0.0498 mol/m²), South-South (0.0484 mol/m²), and South-West (0.0499 mol/m²). The table reflects a uniform increase in CO concentration over time, with a narrow gap between the zones. The difference in five-year mean values is marginal, but the South-South showed the highest increase between 2019 and 2024. The South-South maintained the lowest overall average over the five years, suggesting slightly lower levels of carbon monoxide compared to the other regions. This table encapsulates the trend and scale of change in CO concentration within the study timeframe.

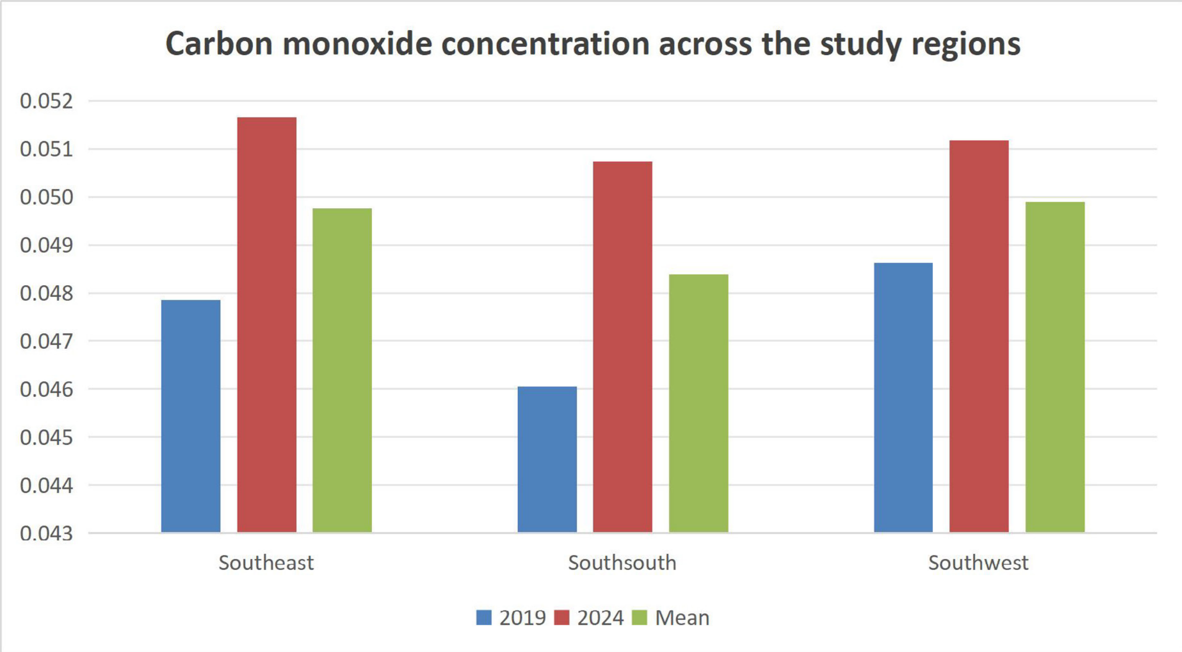

Figure 7: Bar Chart Showing the Trend of Annual CO Concentration (2019 and 2024)

Figure 7 shows the bar chart representation of the annual carbon monoxide concentrations for 2019 and 2024 across the South-East, South-South, and South-West regions. The figure visually confirms a rise in CO levels across all regions over the five years. In 2019, the CO concentration was lowest in the South-South and highest in the South-West. By 2024, the South-East surpassed the other regions with the highest CO level, while South-South and South-West registered identical values. The chart emphasizes that while the variation in CO levels among the regions in 2019 was slightly wider, by 2024, the gap between regions narrowed, converging around 0.051 to 0.052 mol/m². The increase from 2019 to 2024 is consistent and observable across all three bars for each region, suggesting that the change in CO concentration was not abrupt but gradual. The uniformity of the bars in 2024 highlights the emerging similarity in CO pollution levels among the geopolitical zones during that year.

NITROGEN DIOXIDE CONCENTRATION			
2019	**South-East**	**South-South**	**South-West**
MINIMUM	5.13e-05	4.26e-05	4.49e-05
MAXIMUM	7.08e-05	7.84e-05	0.000111987
MEAN	6.11e-05	6.05e-05	7.85e-05
STANDARD DEVIATION	1.38e-05	2.54e-05	4.74e-05

Table 5: Minimum, Maximum, Mean and Standard Deviation of Nitrogen Dioxide Concentration Across the Study Regions (2019)

Table 5 provides the 2019 nitrogen dioxide (NO_2) statistics. The South-West recorded the highest mean NO_2 concentration at 7.85e-05 mol/m², while the South-East and South-South reported 6.11e-05 mol/m² and 6.05e-05 mol/m² respectively. The South-West also exhibited the highest maximum value at approximately 1.12e-04 mol/m², and the highest standard deviation (4.74e-05 mol/m²), indicating both the highest concentration and greatest variability. The SouthSouth had the lowest minimum value (4.26e-05 mol/m²), while the South-East's range was more moderate. The differences in mean and maximum values across the zones indicate that the South-West had a relatively higher NO_2 burden in 2019. The broader variability in the SouthWest suggests inconsistent sources or fluctuating emission patterns. By contrast, the South-South and South-East, with lower means and less variability, reflect more consistent and lower NO_2 levels. Overall, this table highlights a clear spatial distinction in nitrogen dioxide concentrations across the regions in 2019.

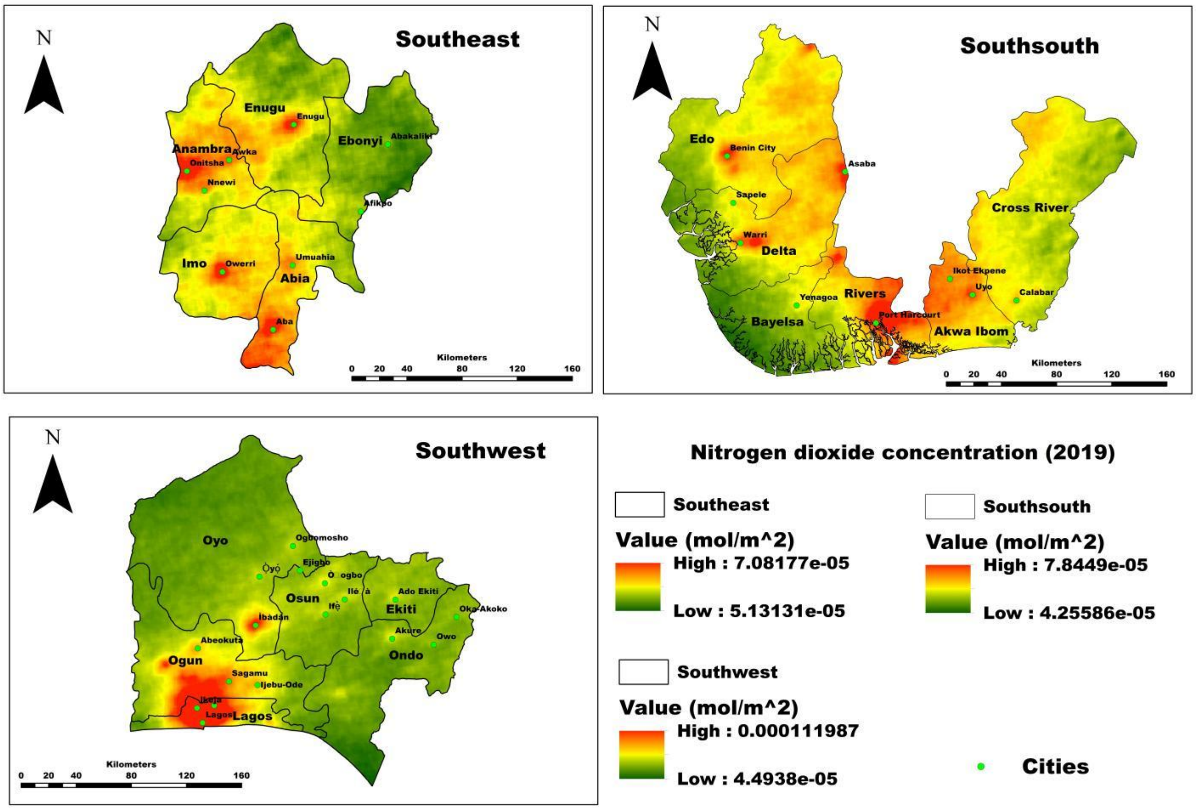

Figure 8: Nitrogen Dioxide Concentrations in South-East, South-South and South-West for 2019

In 2019 (Figure 8), nitrogen dioxide (NO_2) concentrations in the South-East were highest in the southern part of Abia State, particularly around Aba and Umuahia (7.08177e-05 mol/m²), the northwestern region of Anambra State encompassing Onitsha, Awka, and Nnewi, as well as the central part of Imo State (around Owerri), Enugu city, and the South-Western zone of Enugu State. Lower concentrations were recorded in the South-Eastern region of Ebonyi State (93% of the area) and the northeastern part of Abia State, with values near 5.13131e-05 mol/m², as well as in the northern part of Enugu State. In the South-South, elevated NO_2 levels were observed in the central part of Edo State, particularly around Benin City, and in the South-Western part of Delta State (around Warri), as well as the northeastern area near Asaba, with concentrations peaking at 7.8449e-05 mol/m². The South-Eastern part of Rivers State (Port Harcourt) and the northern region of Akwa Ibom State (including Uyo and Ikot Ekpene) also recorded high concentrations. The lowest levels, around 4.25586e-05 mol/m², occurred in the central and South-Eastern parts of Bayelsa State and the northeastern area of Cross River State, particularly along the outskirts of Delta and Edo States (western fringe). In the South-West, Lagos State, particularly the South-Western zone including Ikeja and Lagos city, recorded the highest NO_2 concentration (over 86%) at 0.000111987 mol/m². Elevated levels were also found in the southern part of Ogun State (Abeokuta and Sagamu) and the South-Eastern region of Oyo State (Ibadan). The lowest concentrations, approximately 4.4938e-05 mol/m², were recorded across the entirety of Ondo, Osun, and Ekiti States, as well as approximately 92% of Oyo State.

NITROGEN DIOXIDE CONCENTRATION			
2024	**South-East**	**South-South**	**South-West**
MINIMUM	5.64e-05	4.47e-05	4.92e-05
MAXIMUM	7.51e-05	8.33e-05	0.000114698
MEAN	6.58e-05	6.40e-05	8.20e-05
STANDARD DEVIATION	1.32e-05	2.73e-05	4.63e-05

Table 6: Minimum, Maximum, Mean and Standard Deviation of Nitrogen Dioxide Concentration Across the Study Regions (2024)

Table 6 shows NO_2 statistics for 2024. The results indicate an increase in mean NO_2 concentrations across all regions compared to 2019. The South-West continued to record the highest mean value at 8.20e-05 mol/m², followed by the South-East (6.58e-05 mol/m²) and the South-South (6.40e-05 mol/m²). The maximum concentration again appeared in the South-West (1.15e-04 mol/m²), consistent with 2019. Notably, the minimum concentrations remained lowest in the South-South (4.47e-05 mol/m²). The standard deviations were high in the South-West (4.63e-05 mol/m²) and South-South (2.73e-05 mol/m²), indicating persistent variability. The increase in mean and maximum values across the regions points to an upward trend in nitrogen dioxide levels over time. Although the order of NO_2 concentration by region remained unchanged, the absolute increase across all metrics emphasizes a steady accumulation of this pollutant between 2019 and 2024.

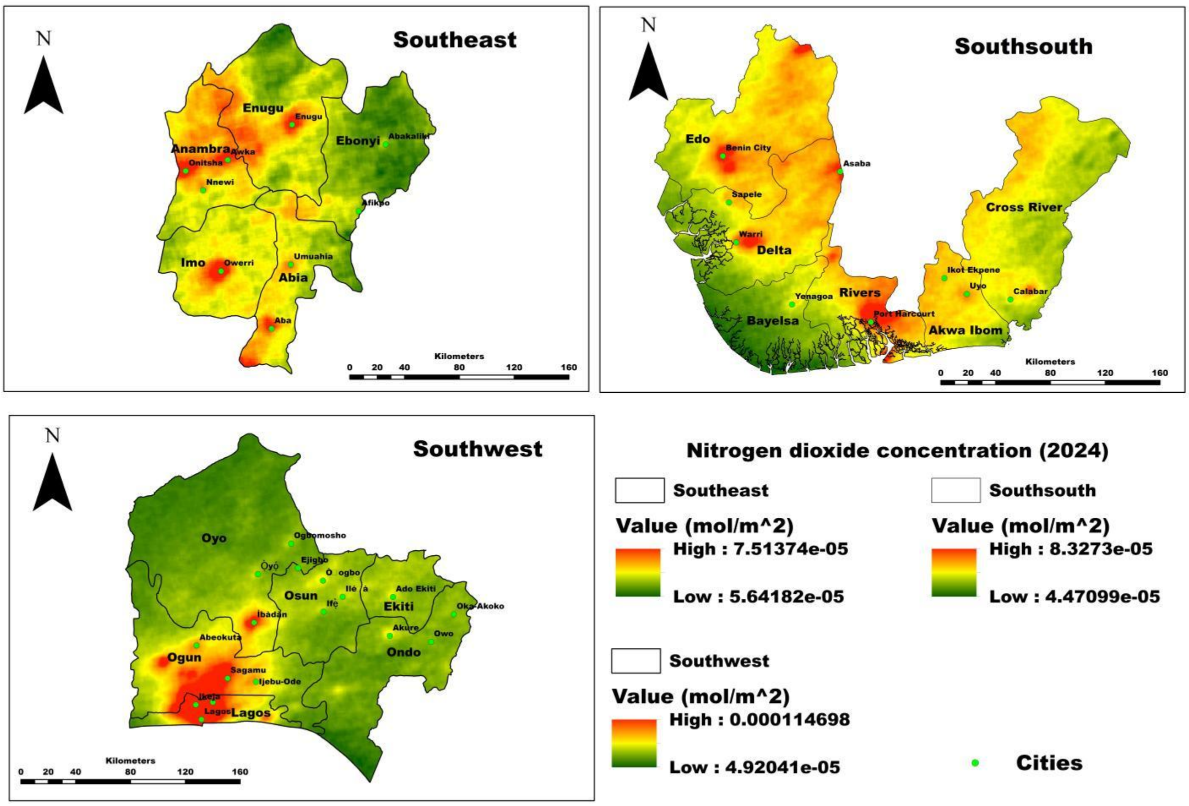

Figure 9: Nitrogen Dioxide Concentrations in South-East, South-South and South-West for 2024

In 2024 (Figure 9), NO_2 concentrations increased across all regions. In the South-East, high levels were observed in the northwestern zone of Anambra State (Onitsha, Awka, Nnewi), southern Imo (Owerri), most parts of Abia (especially Aba), and central Enugu State (Enugu), reaching up to 7.51374e-05 mol/m². The lowest concentrations, around 5.64182e-05 mol/m², persisted in the northeastern part of Abia and about 89% of Ebonyi State. In the South-South, NO_2 concentrations peaked at 8.3273e-05 mol/m² in the north-central region of Edo State (Benin City), the South-Western part of Delta State (Warri), the northeastern zone around Aniocha North (Asaba), the South-Eastern part of

Rivers State (Port Harcourt), and the central belt of Akwa Ibom (Uyo). Lower concentrations, approximately 4.47099e-05 mol/m², were found in the central region of Bayelsa and the northeastern part of Cross River State. In the South-West, the highest NO_2 concentrations were recorded in the South-Western part of Lagos State (Ikeja and Lagos city), southern Ogun State (Abeokuta, Ijebu Ode, and Sagamu), and north-central Oyo State (Ibadan), with a peak value of 0.000114698 mol/m². The lowest levels, near 4.92041e-05 mol/m², were observed across the entirety of Ekiti and Osun States, the northern part of Ondo State, and approximately 90% of Oyo State excluding Ibadan.

NITROGEN DIOXIDE	South-East	South-South	South-West
2019	6.10654e-05	6.05038e-05	7.84624e-05
2024	6.57778e-05	6.39914e-05	8.19509e-05
MEAN	6.34216e-05	6.22476e-05	8.02067e-05

Table 7: Nitrogen dioxide Concentration Across the Study Regions (2019 and 2024)

Table 7 summarizes the NO_2 values for 2019 and 2024 across the three regions. In 2019, the NO_2 values were 6.11e-05 mol/m² (South-East), 6.05e-05 mol/m² (South-South), and 7.85e-05 mol/m² (South-West). By 2024, these increased to 6.58e-05 mol/m², 6.40e-05 mol/m², and 8.20e05 mol/m² respectively. The average for both years placed the South-West highest at 8.02e-05 mol/m², while the South-South had the lowest mean concentration (6.22e-05 mol/m²). The data indicate that while all regions recorded an increase, the South-West consistently had the highest NO_2 values. The increase from 2019 to 2024 was modest but consistent, highlighting sustained accumulation. The five-year average further supports the trend of higher nitrogen dioxide levels in the South-West, with the South-East in the middle and South-South being the lowest throughout the period. This table offers a comparative look at long-term trends and the persistent gap between the zones.

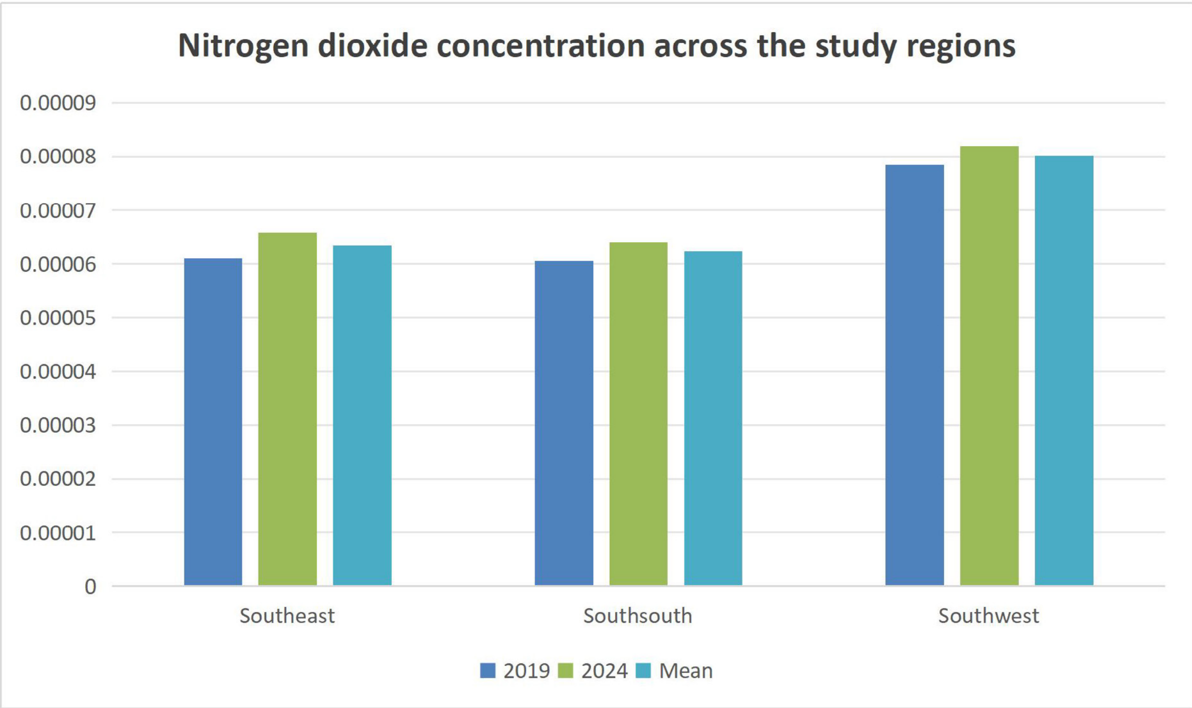

Figure 10: Bar Chart Showing the Trend of Annual NO_2 Concentration (2019 and 2024)

Figure 10 graphically illustrates the trend of nitrogen dioxide concentration from 2019 to 2024 across the three regions. The bar chart confirms a consistent increase in NO_2 levels over the five years for all zones. The South-East and South-South showed modest rises, while the South-West recorded a relatively larger difference between 2019 and 2024. This sustained upward trend across all regions underscores a general increase in nitrogen-based pollution over time. The chart visually distinguishes the South-West as the region with the highest NO_2 concentration in both years, clearly separating it from the other zones. This consistent pattern in the bars, both terms of height and progression, reinforces the spatial hierarchy observed in the data tables and supports a conclusion of persistent inter-regional differences in

NO_2 burden over the years under study.

SULFUR DIOXIDE CONCENTRATION			
2019	**South-East**	**South-South**	**South-West**
MINIMUM	-0.000111483	-9.74e-05	-0.000113075
MAXIMUM	5.79e-05	8.19e-05	7.95e-05
MEAN	-2.06e-05	-7.74054e-06	-1.67827e-05
STANDARD DEVIATION	0.000119747	0.000126808	0.000136178

Table 8: Minimum, Maximum, Mean and Standard deviation of Sulfur dioxide Concentration Across the Study Regions (2019)

Table 8 presents the 2019 data on sulfur dioxide (SO_2) concentrations across South-East, SouthSouth, and South-West. All the mean values are negative, with South-East at -2.06e-05 mol/m², South-South at -7.74e-06 mol/m², and South-West at -1.68e-05 mol/m². These negative values suggest the presence of very low SO_2 concentrations during this year. The minimum recorded concentrations are also negative across all regions, with South-West registering the lowest minimum (-0.000113075 mol/m²). Maximum values are positive, ranging from 5.79e-05 mol/m² in South-East to 8.19e-05 mol/m² in South-South. Standard deviations are relatively high, with the highest variability in the South-West (0.000136178 mol/m²). The spread between minimum and maximum values in each zone shows considerable variability despite the low average concentrations. The data highlight notable fluctuations in SO_2 levels during 2019, with SouthSouth having the least negative mean and South-East showing a broader concentration range, reflecting possible spatial inconsistencies in SO_2 emissions or measurement variability.

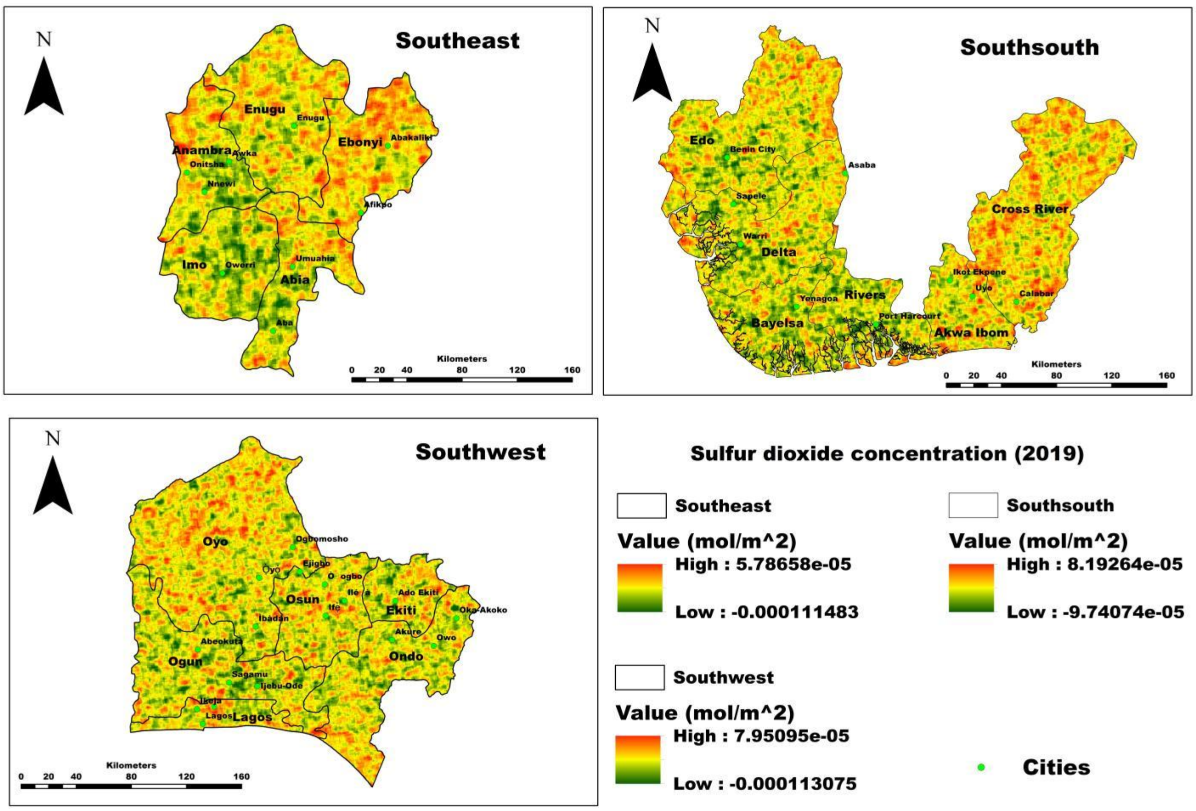

Figure 11: Sulfur dioxide Concentrations in South-East, South-South and South-West for 2019

The spatial distribution of Sulphur dioxide in 2019 (Figure 11) shows irregular concentration levels across the different southern geopolitical zones. In the South-East, States such as Ebonyi, Enugu and parts of Abia and Anambra experienced majorly high and moderate levels of Sulphur dioxide (approximately 5.78658e-05 mol/m2) while other parts of Abia and Anambra as well as Imo state, experienced much lower concentrations levels of Sulphur dioxide (approximately -0.000111483 mol/m2) for the year 2019. In the South-South zone, States such as Cross-river, Akwa Ibom and Edo, experienced elevated concentration levels of approximately 8.19264e-05 mol/m2, while other States such as Delta, Bayelsa and Rivers, experienced a lower concentratio (about -9.74074e-05 mol/m2) for the year 2019. The South-West zone comprising of States such as Oyo, Ogun, Osun, Ekiti and Ondo, experienced concentrations levels of Sulphur dioxide as high as 7.95095e-05 mol/m2 in some areas, and as low as -0.000113075e-05 mol/m^2 in others for the year 2019.

SULFUR DIOXIDE CONCENTRATION			
2024	**South-East**	**South-South**	**South-West**
MINIMUM	-7.73e-05	-8.69e-05	-9.75e-05
MAXIMUM	0.000111142	0.000115032	0.000130327
MEAN	1.69329e-05	1.40893e-05	1.64053e-05
STANDARD DEVIATION	0.000133231	0.000142755	0.000161109

Table 9: Minimum, Maximum, Mean and Standard deviation of Sulfur dioxide Concentration Across the Study Regions (2024)

Table 9 outlines sulfur dioxide concentration statistics for 2024. Unlike 2019, all three regions recorded positive mean values, indicating a shift in concentration levels. The South-East posted the highest mean at 1.69329e-05 mol/m², followed closely by the South-West (1.64053e-05 mol/m²), and the South-South recorded the lowest mean (1.40893e-05 mol/m²). The minimum concentrations remained negative across all regions, with the lowest minimum in the South-West at -9.75e-05 mol/m². The highest maximum concentration was found in the South-West (0.000130327 mol/m²), indicating that despite the overall increase, significant variability persists. The standard deviation values are also higher compared to 2019, ranging from 0.000133231 mol/m² in the South-East to 0.000161109 mol/m² in the South-West, further suggesting greater fluctuations in SO_2 concentrations. This table highlights an overall increase in SO_2 levels from 2019, with the highest increases seen in the South-East and South-West. Nonetheless, the SouthSouth continued to reflect the lowest average SO_2 levels, albeit with considerable variability.

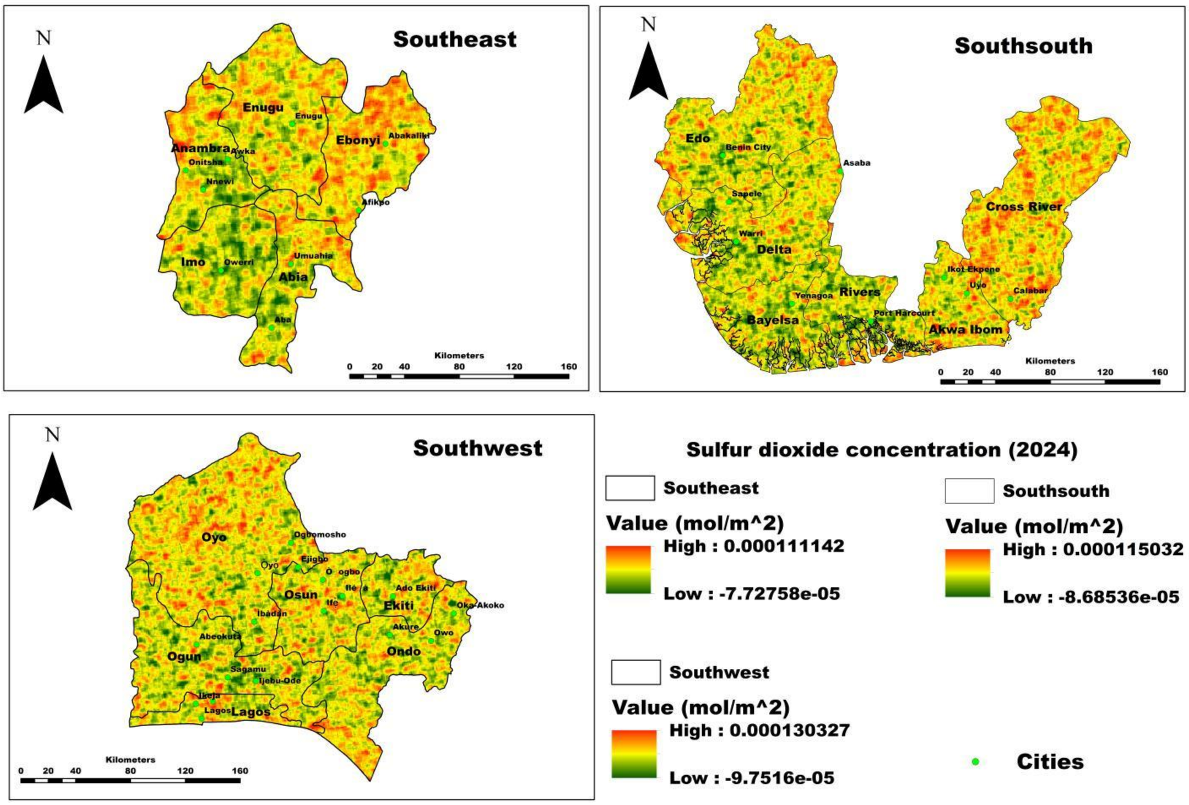

Figure 12: Sulfur dioxide Concentrations in South-East, South-South and South-West for 2024

The spatial distribution of Sulphur dioxide for the year 2024 (Figure 12) revealed the concentration levels across the three southern geopolitical regions. South-East experienced mostly high and moderate levels of sulphur dioxide concentrations in places such as Ebonyi state, Enugu state, Umuahia (Abia state), and the northern part of Anambra state. These areas had concentration levels as high as 0.00011142 mol/m2. In the South-South, Cross-river and Akwa Ibom state remained dominated by high and moderate levels of Sulphur dioxide (approximately 0.0001115032 mol/m^2) for the year 2024. While in the South-West, concentration levels experienced were as high as 0.000130327 mol/m^2 and as low as -9.7516-e05 mol/m^2 across the States Lagos, Ogun, Osun, Ondo and Ekiti for the year 2024.

SULFUR DIOXIDE	South-East	South-South	South-West
2019	-2.6808e-05	-7.7405e-06	-1.6783e-05
2024	1.69329e-05	1.40893e-05	1.64053e-05
MEAN	-4.938e-06	-3.1744e-06	-1.165e-07

Table 10: Sulfur dioxide Concentration Across the Study Regions (2019 and 2024)

Table 9 compares the SO_2 concentrations in 2019 and 2024 across the regions. In 2019, mean values were negative, with South-East at -2.68e-05 mol/m², South-South at -7.74e-06 mol/m², and South-West at -1.68e-05 mol/m². By 2024, these values became positive: 1.69329e-05 mol/m² (South-East), 1.40893e-05 mol/m² (South-South), and 1.64053e-05 mol/m² (South-West). The mean over the two years shows South-East with a slightly negative average (-4.938e-06 mol/m²), while South-South and South-West average -3.1744e-06 mol/m² and -1.165e-07 mol/m² respectively. These figures demonstrate a transition from generally low or negligible SO_2 concentrations in 2019 to consistently higher values in 2024. The South-West showed the smallest change in average concentration over the five years, while the South-East shifted from the most negative to the highest positive value. The consistent rise in all three zones is evident, but the South-South maintained the lowest mean value across both years, indicating a relatively lower SO_2 concentration profile over time.

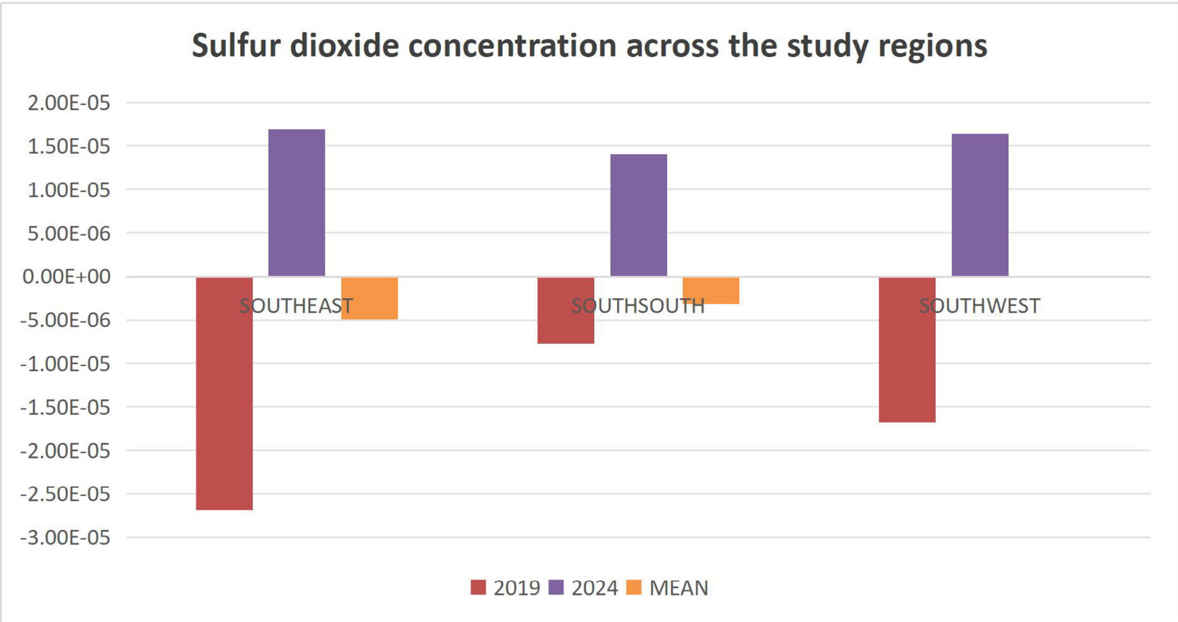

Figure 13: Bar Chart Showing the Trend of Annual SO_2 Concentration (2019 and 2024)

Figure 13 presents a bar chart showing SO_2 concentration trends in 2019 and 2024. In 2019, all three regions had negative SO_2 concentrations, suggesting either negligible amounts. By 2024, all bars had risen into the positive range, clearly indicating an increase in SO_2 levels over the five years. The South-East recorded the most significant change, transitioning from the lowest 2019 value to the highest 2024 level. The South-South region showed the smallest change in bar height between the two years, indicating a relatively stable SO_2 profile. The South-West also showed a considerable upward trend. The visual contrast between the years demonstrates that sulfur dioxide levels increased across all regions, with the South-East experiencing the sharpest rise. The figure thus affirms the transition observed in the tabulated data, where initially negative or near-zero values in 2019 were replaced by clearly positive values in 2024, reflecting an observable rise in SO_2 concentration across Southern Nigeria.

METHANE CONCENTRATION			
2019	**South-East**	**South-South**	**South-West**
MINIMUM	1841.8	1819.6	1837.0
MAXIMUM	1915.4	1924.1	1920.4
MEAN	1878.6	1871.8	1878.7
STANDARD DEVIATION	52.0	73.9	59.0

Table 11: Minimum, Maximum, Mean and Standard deviation of Methane concentration across the study regions (2019)

Table 11 provides methane (CH_4) concentration data for 2019. The average methane values were 1878.6 mol/mol in the South-East, 1871.8 mol/mol in South-South, and 1878.7 mol/mol in the South-West. The South-West recorded the highest maximum value (1920.4 mol/mol), and the South-South had the lowest minimum (1819.6 mol/mol). Standard deviation values were notably different across regions: South-South exhibited the highest variability (73.9 mol/mol), suggesting more fluctuation in methane levels. The South-East and South-West displayed more stable concentrations, with standard deviations of 52.0 and 59.0 mol/mol respectively. This table shows relatively consistent methane levels across regions in 2019, with very narrow differences in means. However, the standard deviation in South-South indicates that despite the similar mean, concentration levels may have been more erratic. These results illustrate that methane, this year, was broadly similar across Southern Nigeria, although the spread of values suggests varying degrees of emission control or methane source activity among the regions.

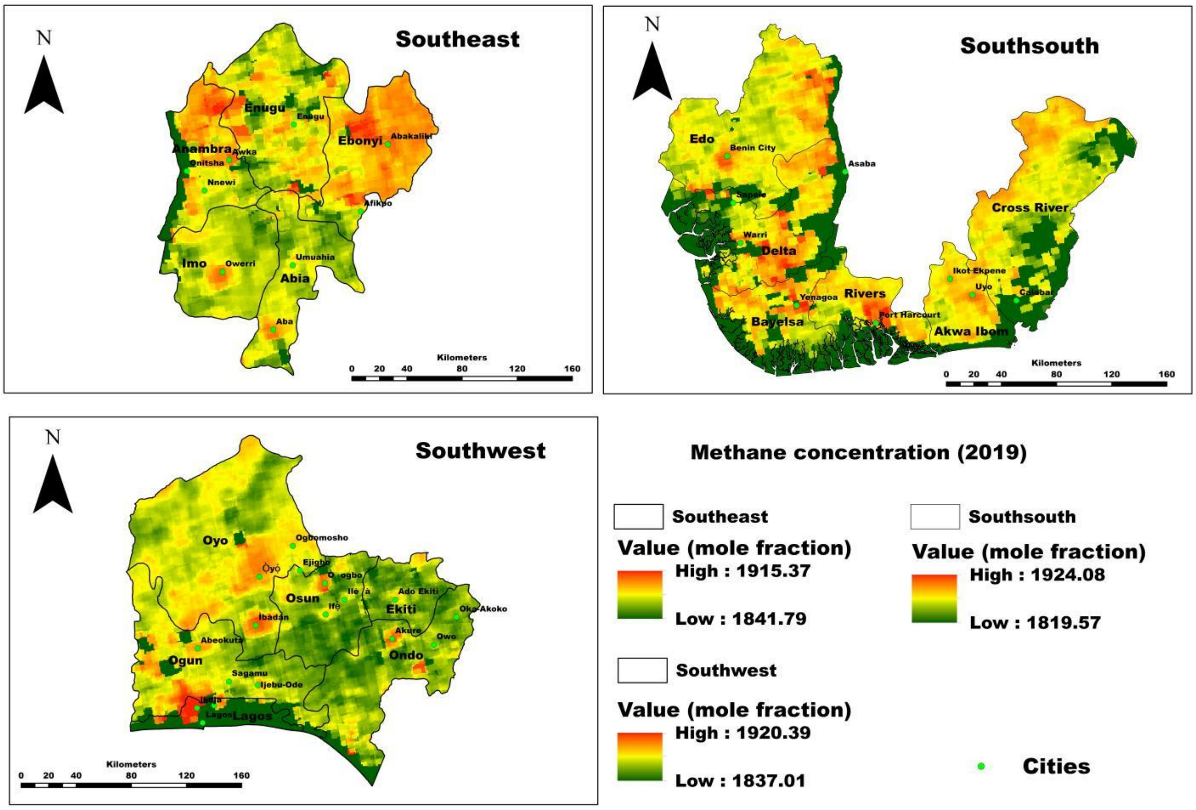

Figure 14: Methane Concentrations in South-East, South-South and South-West for 2019

The spatial distribution of methane concentration in 2019 (Figure 14) reveals a noticeable presence of moderate to high methane levels across key urban and semi-urban locations in Southern Nigeria, with each geopolitical zone showing a unique pattern of emission intensity. In the South-East, methane concentrations were moderately high, with peak values reaching 1915.37 mole fraction. Cities such as Awka and northern Anambra State recorded elevated concentrations, mirroring trends seen in neighboring Enugu State, particularly around the capital city, Enugu. Ebonyi State displayed extensive areas of high methane, especially around Abakaliki and Afikpo, suggesting increased anthropogenic activities in the region. Imo State also reflected notable methane emissions, with Owerri exhibiting relatively high values, while Aba in Abia State contributed significantly to the regional emissions, all within the mid-to-upper concentration range of the 2019 methane scale. Moving to the South-South region, methane distribution was even more intense, with a maximum concentration of 1924.08 mole fraction. This region recorded the highest methane levels in 2019 among the three zones. Delta State, particularly the southern region, experienced elevated values. Bayelsa State was heavily affected, with nearly three-quarters of its territory, especially the southern and western portions, displaying consistently high methane levels. The metropolitan area of Port Harcourt in Rivers State emerged as a prominent hotspot, reinforcing the link between fossil fuel activity and elevated methane presence. Edo State, particularly around Benin City, also exhibited considerable concentrations, which extended into southern parts of the state. Similarly, Uyo and its environs in Akwa Ibom, as well as Calabar and the northern stretches of Cross River State, showed moderate to high methane concentrations, indicating a broader distribution of emissions in the South-South region. In contrast, the South-West region showed slightly lower but still significant methane levels, with a maximum value of 1920.39 mole fraction. Lagos State, particularly in and around the Ikeja industrial zone, stood out with the highest concentrations in the region. Ogun State followed closely, with elevated values recorded in Abeokuta and IjebuOde, reflecting a combination of urban growth and industrial activity. Akure in Ondo State and locations in Oyo State also displayed notable concentrations, especially in Ibadan and Oyo town, while areas in Osun State such as Oshogbo showed mild to moderate methane levels. On the other hand, Ekiti and parts of northern Ondo recorded the lowest methane values across the South-West, suggesting fewer anthropogenic sources and limited industrial development in these locations during this period.

METHANE CONCENTRATION			
2024	**South-East**	**South-South**	**South-West**
MINIMUM	1886.8	1777.8	1882.9
MAXIMUM	1976.9	2017.4	1974.5
MEAN	1931.8	1897.6	1928.7
STANDARD DEVIATION	63.7	169.5	64.8

Table 12: Minimum, Maximum, Mean and Standard Deviation of Methane Concentration Across the Study Regions (2024)

Table 12 displays methane concentration data for 2024. Compared to 2019, all three regions recorded higher mean values. The South-East had the highest average at 1931.8 mol/mol, followed by the South-West at 1928.7 mol/mol, and South-South at 1897.6 mol/mol. Minimum and maximum values were also elevated, with the South-South region showing the lowest minimum (1777.8 mol/mol) and the highest maximum (2017.4 mol/mol), suggesting an expanded range and greater fluctuations. The standard deviation in South-South increased significantly to 169.5 mol/mol, nearly tripling from its 2019 value, indicating substantial variability in methane emissions or concentrations. The South-East and South-West maintained moderate variability with standard deviations of 63.7 and 64.8 mol/mol respectively. This data suggests not only a general increase in methane across all regions but also more erratic concentrations, particularly in South-South. The broader concentration range and increased averages across the board point to notable temporal changes in methane presence between 2019 and 2024.

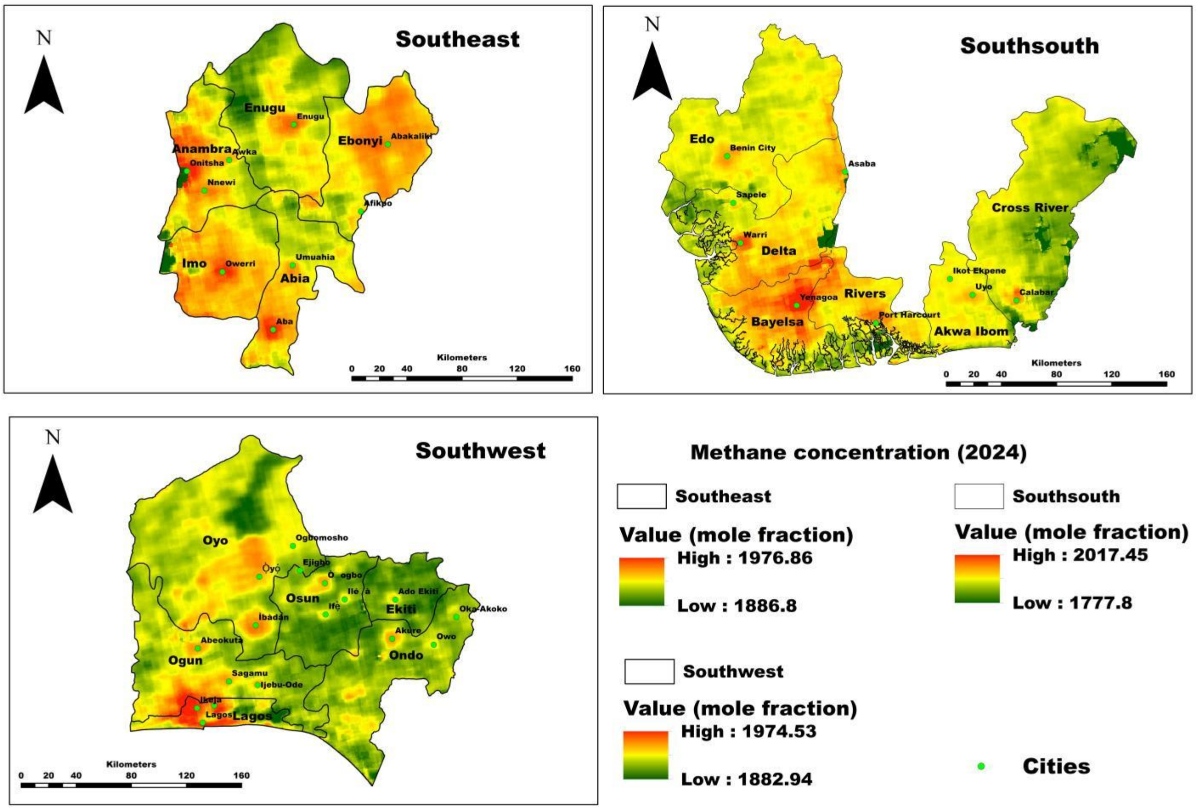

Figure 15: Methane Concentrations in South-East, South-South and South-West for 2024

In 2024 (Figure 15), methane concentrations had significantly increased across all three geopolitical zones, highlighting a continued upward trend in greenhouse gas emissions. The South-East experienced a marked rise, with concentrations peaking at 1976.86 mole fraction. The expansion of urbanization and increased waste decomposition likely contributed to the elevated levels observed in major cities. Enugu, Onitsha, Awka, and Nnewi recorded visibly higher concentrations compared to 2019. This upward trend extended across most parts of Anambra and Enugu States. In Ebonyi, the concentration was widespread and persistent, with nearly the entire state covered in high values, particularly around Abakaliki and Afikpo. Imo and Abia States also followed this trend, with cities such as Owerri, Aba, and Umuahia reflecting increased emissions across larger surface areas. The South-South region remained the most methane-concentrated zone in 2024, with values climbing to 2017.45 mole fraction.

This stark increase was particularly evident in oil-producing and industrial locations. Bayelsa State emerged as the epicenter of methane activity, where nearly the entire region registered elevated concentrations. Rivers State, especially Port Harcourt and its surroundings, exhibited intensified values, likely driven by continuous fossil fuel operations and flaring activities. Warri and Asaba in Delta State also saw further increases in methane levels, while Benin City in Edo State showed consistent emissions comparable to those observed in 2019. Akwa Ibom and Cross River also reflected higher concentrations, particularly around Uyo and Calabar, indicating a broader regional contribution to atmospheric methane. In the South-West, methane levels also rose significantly, with the highest values reaching 1974.53 mole fraction. Lagos State remained the primary source of emissions, with the city and surrounding industrial belts, such as Ikeja and the South-Western coastal area, showing intense methane concentrations. Ogun State again recorded high values, especially in Abeokuta and its southern corridors. Oyo State experienced a similar rise, with Ibadan continuing to serve as a regional hotspot. Interestingly, Osun State, particularly its northern parts, saw a notable increase compared to 2019, while Ekiti and Ondo States, though still among the least polluted within the zone, also exhibited modest rises in methane levels, hinting at a gradual spread of urban and industrial footprints. Overall, the 2024 distribution indicates that methane emissions have escalated throughout Southern Nigeria. The South-South region remains the most critically affected due to its concentration of oil exploration and flaring activities. The South-East is not far behind, particularly due to its dense urban settlements and growing population centers. The South-West, though slightly more moderate in concentration, has experienced a steady rise as well, especially in states like Lagos, Ogun, and Oyo. This trend underscores a deepening environmental concern tied to industrialization, urban waste management practices, and fossil fuel reliance across all three zones.

METHANE	South-East	South-South	South-West
2019	1878.6	1871.8	1878.7
2024	1931.8	1897.6	1928.7
MEAN	1905.2	1884.7	1903.7

Table 13: Methane Concentration Across the Study Regions (2019 and 2024)

Table 13 compares methane concentrations across 2019 and 2024. The South-East recorded values of 1878.6 mol/mol in 2019 and 1931.8 mol/mol in 2024, with a five-year mean of 1905.2 mol/mol. The South-South increased from 1871.8 to 1897.6 mol/mol, with a mean of 1884.7 mol/mol, while the South-West rose from 1878.7 to 1928.7 mol/mol, averaging 1903.7 mol/mol. These figures reflect a consistent upward trend in methane levels across all regions, with the largest increase occurring in the South-East. The South-South had the smallest overall rise and the lowest five-year average, indicating comparatively lower methane concentrations over the study period. Despite the general similarity of values, these differences in mean and annual progression suggest slight but noticeable variations in methane dynamics across regions. The table demonstrates not only the direction of change in methane levels but also reinforces the stability and relative concentration hierarchy among the zones.

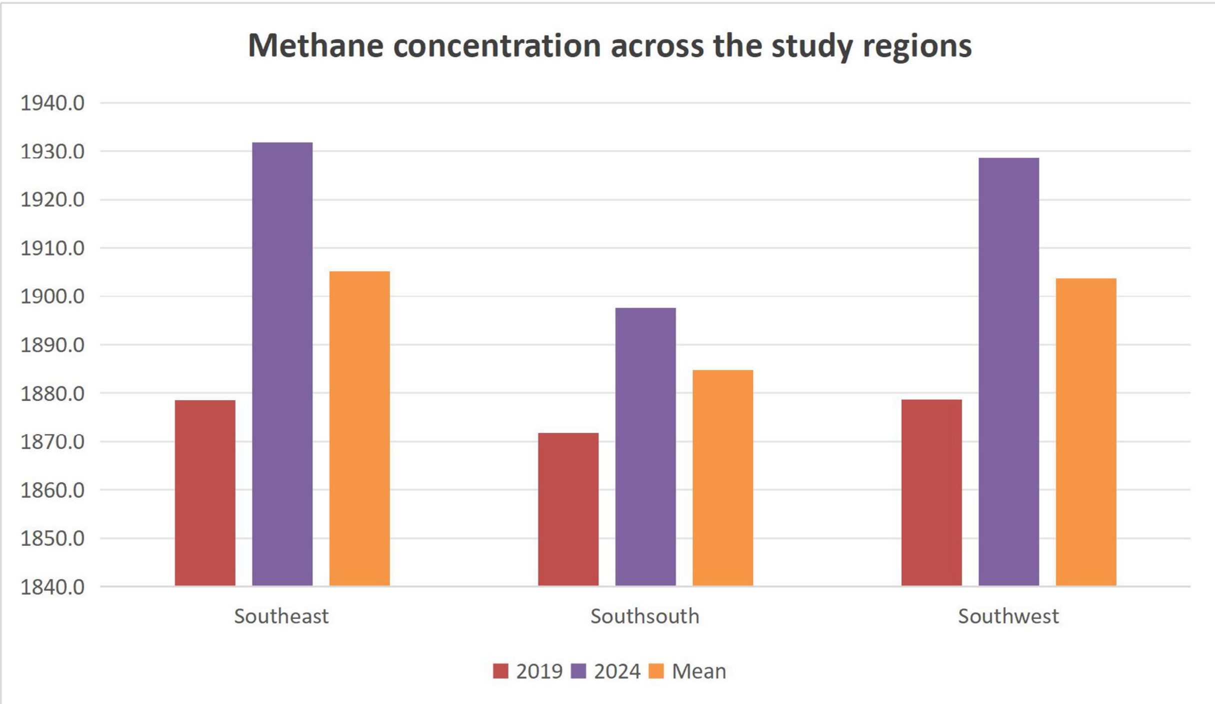

Figure 16: Bar Chart Showing the Trend of Annual Methane (CH4) Concentration (2019 and 2024)

Figure 16 illustrates the change in methane concentration from 2019 to 2024 across the study regions. The bar chart reflects an increase in all three regions over the five years, with South-East and South-West registering the most significant growth. South-South, while also increasing, recorded the smallest change in bar height, consistent with the numerical data. The visual symmetry between the South-East and South-West bars in 2024 reflects how closely their methane concentrations align, especially compared to their 2019 levels. The chart supports the conclusion that methane levels increased uniformly across the regions, with the South-East maintaining the lead in terms of concentration levels. The data visualized here confirms the steady rise in methane over time and further highlights the consistency in the ranking of the zones, with South-East and South-West at the higher end and South-South remaining slightly lower in both years.

AEROSOL CONCENTRATION			
2019	**South-East**	**South-South**	**South-West**
MINIMUM	-0.873	-1.087	-0.930
MAXIMUM	-0.583	-0.394	-0.334
MEAN	-0.728	-0.740	-0.632
STANDARD DEVIATION	0.205	0.490	0.422

Table 14: Minimum, Maximum, Mean and Standard Deviation of Aerosol Concentration Across the Study Regions (2019)

Table 14 presents aerosol concentration data for the year 2019 across the South-East, South-South, and South-West regions. The mean values are negative in all regions: -0.728 for the South-East, -0.740 for South-South, and -0.632 for the South-West. The negative values suggest either very low or baseline-adjusted aerosol concentrations, as sometimes reflected in remotely sensed aerosol optical depth indices. Among the regions, the South-West had the least negative mean, indicating relatively higher aerosol presence compared to the other two zones. Minimum concentrations were lowest in the South-South (-1.087) and highest in the South-East (-0.873), while the maximum concentrations ranged from -0.583 (South-East) to -0.334 (South-West). The highest standard deviation was recorded in the South-South (0.490), followed by the South-West (0.422), and the South-East had the lowest variability (0.205). These results suggest more stable aerosol conditions in the South-East and more fluctuations in the South-South, despite the latter having a lower mean. The South-West showed relatively elevated aerosol levels with moderate variability.

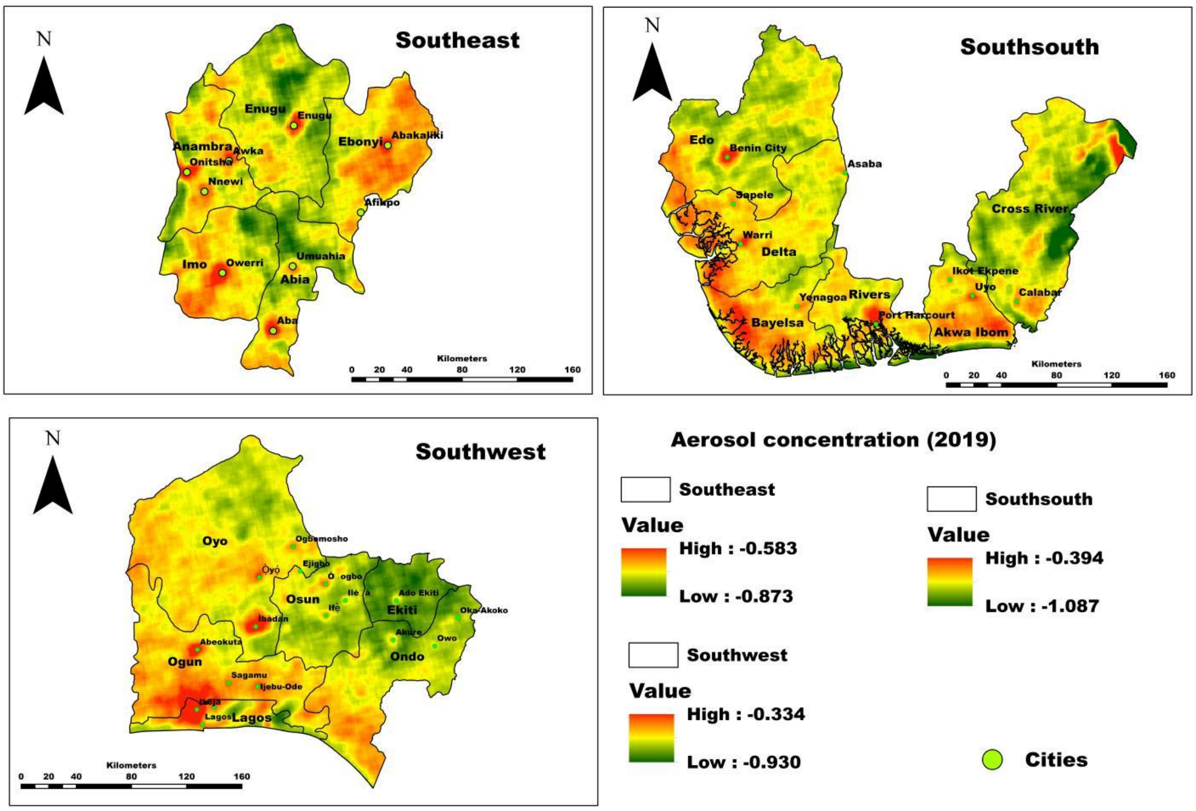

Figure 17: Aerosol Concentrations in South-East, South-South and South-West for 2019

Spatial distribution of aerosol concentration in 2019 (Figure 17) shows cities like Onitsha, Nnewi and Awka located in Anambra, Enugu city located at Enugu state, Abakaliki located at Ebonyi, Owerri located at Imo Aba and Umuahia located at Abia state all fall under the high category of -0.583 in the South-East, while in the South-South Benin city and the South-Western part of Edo state, warri and Asaba in Delta state, 78% of Bayelsa (Both the southern and western part), Port Harcourt located in Rivers state, Uyo and the southern part of Akwa ibom, Calabar and the Northern part of Cross river all fall under the high category of -0.394. in the South-Western Nigeria cities like Oyo and Ibadan located at Oyo state, Abeokuta and 93% of Ogun state, ikeja and 66% of Lagos state all fall under the high category of -0.334 while region like Ekiti and North part of Ondo state has relatively lower aerosol concentration of about -0.930

AEROSOL CONCENTRATION			
2024	**South-East**	**South-South**	**South-West**
MINIMUM	-0.101	-0.363	-0.093
MAXIMUM	0.236	0.238	0.383
MEAN	0.067	-0.062	0.145
STANDARD DEVIATION	0.238	0.425	0.336

Table 15: Minimum, Maximum, Mean and Standard Deviation of Aerosol Concentration Across the Study Regions (2024)

Table 15 presents the aerosol data for the year 2024. Unlike in 2019, the mean values are positive in two of the three regions, with the South-West registering the highest mean aerosol concentration at 0.145, followed by the South-East at 0.067. The South-South, however, still had a negative mean value (-0.062), indicating comparatively lower aerosol levels. The minimum values ranged from -0.363 in South-South to -0.093 in the South-West, while the maximum values ranged from 0.236 in the South-East to 0.383 in the South-West. Standard deviations were highest in South-South (0.425), indicating significant variability, followed by South-West (0.336), and South-East (0.238). The 2024 results show a considerable shift from the 2019 values, with an evident increase in aerosol levels in all regions, especially the South-West. This transition from predominantly negative to positive mean values reflects a measurable increase in atmospheric aerosol concentrations, most notably in the South-West and South-East, suggesting a change in aerosol dynamics within the five years.

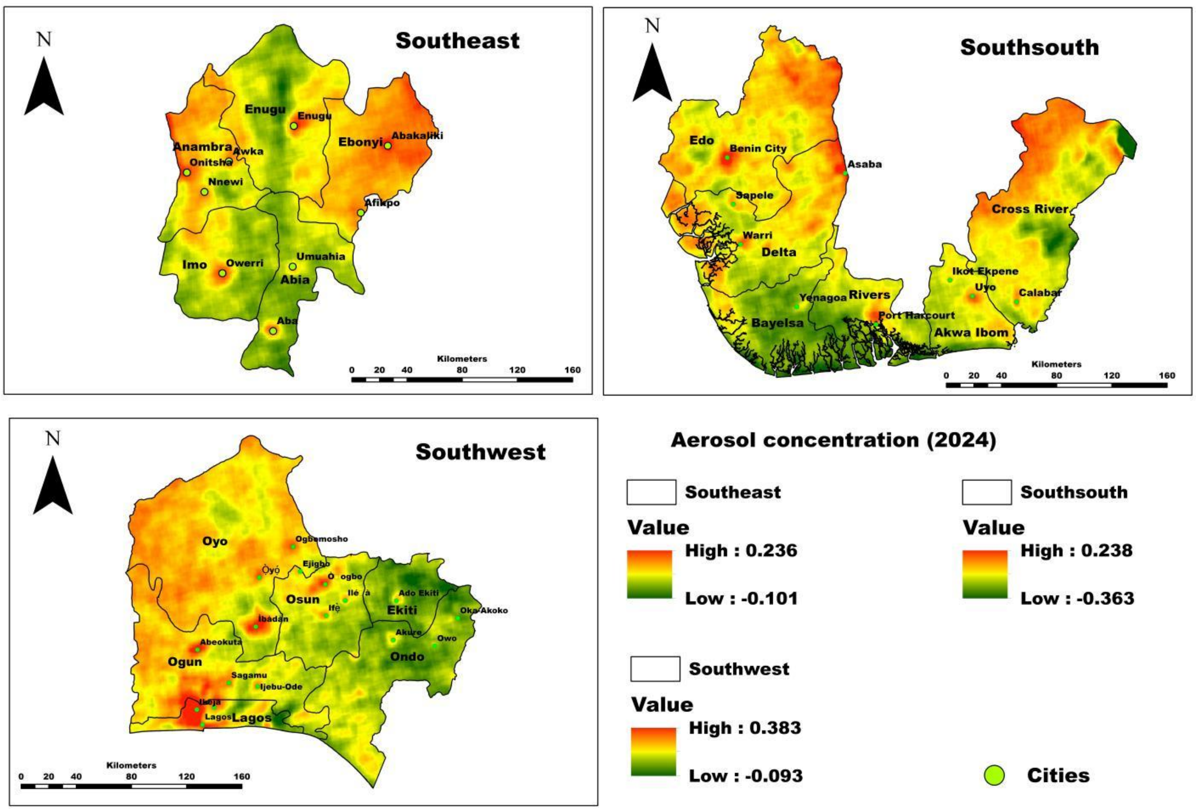

Figure 18: Aerosol Concentrations in South-East, South-South and South-West for 2024

In 2024 (Figure 18), aerosol concentration was high in Enugu city in Enugu state, Onitsha, Awka, Nnewi and the northwestern part of Anambra state, also in Owerri and southern part of Imo and Aba in Abia state and the entirety of Ebonyi state with the concentration of about 0.236. In the South-Southern region cities like Benin city and the western part of Edo state, warri and aniocha North including Asaba located in Delta state, Port Harcourt in Rivers, Uyo in Awka ibom and the northwestern part of Cross rivers all fall under the high category of about 0.238. In the South-Western part of Nigeria states like Oyo especially in Ibadan, Abeokuta and the southern part of Ogun state, ikeja and the western part of Lagos Northern part of Osun state all fall in the high category of about 0.383.

AEROSOL	South-East	South-South	South-West
2019	-0.728	-0.740	-0.632
2024	0.067	-0.062	0.145
MEAN	-0.330	-0.401	-0.244

Table 16: Aerosol Concentration Across the Study Regions (2019 and 2024)

Table 16 compares the mean aerosol concentrations across 2019 and 2024. In 2019, all three regions had negative mean values, with South-South at -0.740, South-East at -0.728, and SouthWest at -0.632. In 2024, the values shifted significantly: South-East increased to 0.067, South-South to -0.062, and South-West to 0.145. The five-year averages were: South-East (-0.330), South-South (-0.401), and South-West (-0.244). These data indicate an upward trend in aerosol concentrations in all zones, particularly in the South-West, which recorded the least negative five-year mean and the highest value in 2024. The South-South remained the only region with a negative average in both years, suggesting persistently lower aerosol concentrations over time. The South-East followed with a moderate increase, while the South-West consistently ranked highest across all parameters. This table demonstrates the relative shifts in aerosol pollution levels over the study period, with significant increases, particularly apparent in the South-West, where values transitioned from negative to strongly positive.

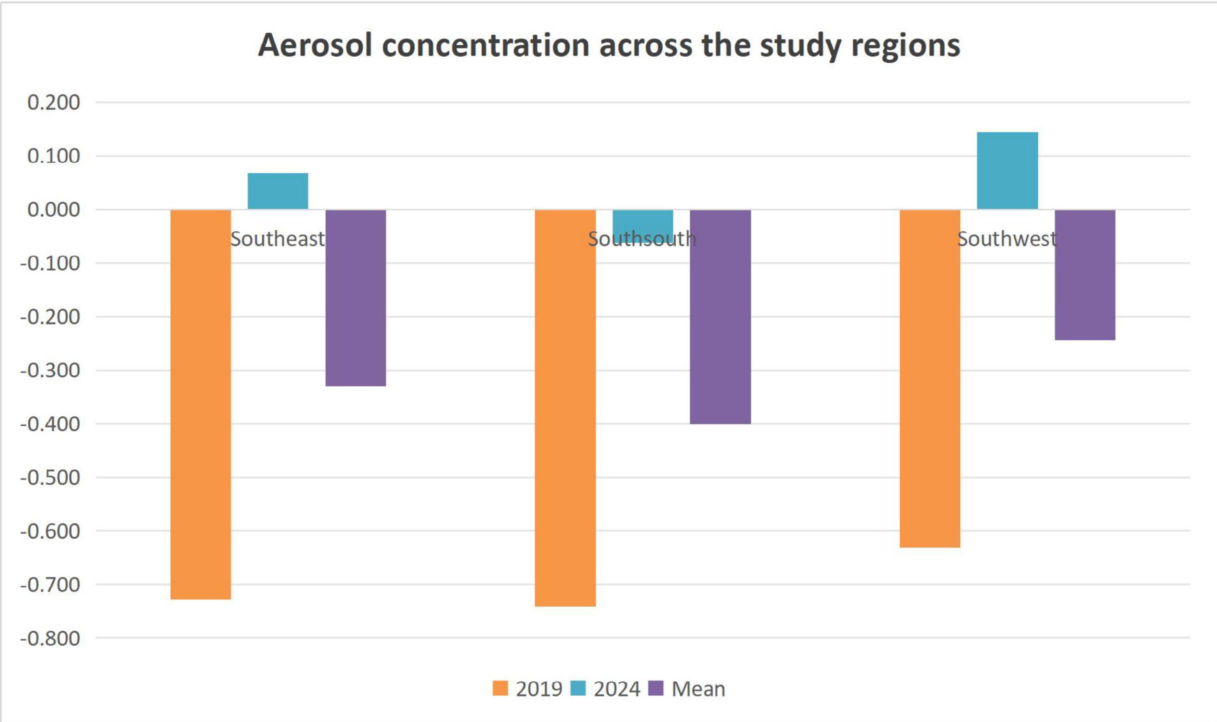

Figure 19: Bar Chart Showing the Trend of Annual Aerosol Concentration (2019 and 2024)

Figure 19 shows the bar chart of aerosol concentrations in 2019 and 2024 across the three study regions. In 2019, all regions recorded negative values, with the South-South having the most negative, followed by South-East and South-West. By 2024, the South-West exhibited a sharp rise into positive territory, registering the highest concentration, while the South-East showed a more moderate increase. The South-South, although improved from 2019, remained slightly negative. The bar chart effectively illustrates this shift, clearly demonstrating a rising trend in aerosol levels over time in all regions. The tallest bar in 2024 belongs to the South-West, visually reinforcing its position as the region with the most significant increase in aerosol presence. The contrast in bar heights between the two years captures the extent of change in aerosol dynamics across Southern Nigeria. This visual presentation aligns with the numerical data, highlighting a clear escalation in particulate presence between 2019 and 2024, most notably in the South-West region. Across both periods, the South-West consistently recorded the highest concentrations for several key air pollutants. Carbon monoxide (CO) had the highest mean in 2019 and remained among the top in 2024, with only a slight narrowing of the regional gap. Nitrogen dioxide (NO_2) was also highest in the South-West across both years, showing the widest range and greatest variability, indicating more frequent emission peaks. Sulfur dioxide (SO_2) levels transitioned from negative in 2019 to positive in 2024 in all regions, but the South-West recorded one of the most significant increases in both mean and variability, indicating growing sulfur-based emissions. Methane (CH_4) levels in the South-East and South-West were similar, but the SouthEast recorded a larger increase between 2019 and 2024. The South-South, in contrast, showed the lowest mean methane concentrations and the highest variability in 2024, suggesting sporadic but intense emission events. For aerosols, the South-West also recorded the greatest increase, shifting from the lowest negative mean in 2019 to the highest positive mean in 2024, indicating a clear rise in particulate pollution.

The South-South region generally showed the lowest pollutant concentrations. It had the lowest CO mean in 2019 and shared the lowest mean in 2024. NO_2 values were also lowest across both years, and SO_2 remained consistently below the other regions in both absolute values and rate of increase. Methane remained lowest in the South-South, and although variability increased in 2024, the overall mean stayed below that of the South-East and South-West. It was also the only region to maintain a negative aerosol mean in 2024, reinforcing its position as having the cleanest air overall. The South-East presented more moderate values, typically falling between the South-South and South-West. It recorded the highest CO value in 2024 and the steepest SO_2 increase but had lower NO_2 and methane concentrations compared to the South-West. This shows variable conditions, without consistent high or low values.

The South-East's pollutant load is largely due to high population density, rapid urban growth, and open burning of waste [4,39,49,66,67,68]. Cities like Onitsha, Aba, Owerri, and Enugu experience intense pressure from energy demand, mostly met through biomass fuels such as firewood and charcoal, which release CO and aerosols [4,39,49,66,67,68]. Limited access to formal waste disposal systems has led to frequent open waste burning, emitting CH_4, SO_2, and particulates [4,23,39,49,68]. Urban expansion into peri-urban areas like Awka and Nnewi, lacking infrastructure and regulation, contributes further [4]. Transport emissions are another factor—aging motorcycles and minibuses emit NO_2 and CO in large quantities, especially in traffic-prone areas [66,68]. Although industrial activity is lower than in the South-West, the accumulation of emissions from domestic, transport, and waste-related sources has raised pollutant levels over time. Between 2019 and 2024, CO, CH_4, and SO_2 all increased, driven by combustion and declining vegetation cover. The South-East shows mid-range pollution—higher than the South-South but below the South-West.

Despite being the base of Nigeria's oil industry, the South-South recorded the lowest overall pollutant levels. Key oil-producing states like Rivers, Bayelsa, and Delta face pollution from gas flaring, refining, and crude transport. Port Harcourt, Warri, and Yenagoa show localized spikes near oil facilities [69-72]. However, the coastal setting provides natural dispersion through sea breeze, reducing ground-level concentrations [69,72]. Lower population density in parts of Cross River and Bayelsa also contributes to reduced domestic and transport emissions [69-72]. Still, the region showed high variability in CH_4 and aerosols, likely from flaring and artisanal refining [69-72]. Although spikes occur, especially near industrial zones, average values remain low. This makes the South-South the least polluted region, with natural dispersion and lower urban intensity playing key roles.

The South-West had the highest and most consistent pollution across both years. States like Lagos, Ogun, and Oyo host large industrial zones, with Ogun ranking among the most industrialized in [73-77]. Emissions from factories, generators, and diesel machinery contribute heavily to NO_2, CO, and SO_2 levels. Lagos, Nigeria's economic hub, experiences chronic traffic, with old vehicles running on low-quality fuel emitting high levels of CO and NO_2 (Amaechi et al., 2023; Amaechi et al., 2024). Household fuel use— charcoal, kerosene, and biomass—is widespread in low-income areas [73-77]. Waste is often burned in the open, especially in peri-urban zones, adding aerosols and CH_4 to the atmosphere. Urban expansion and construction projects also stir up dust, contributing to aerosol load, especially in areas like Ibadan and Abeokuta [73-77]. Unlike the coastal South-South, the inland location and stagnant air in the South-West trap pollutants close to the ground. Widespread use of generators due to poor electricity access further adds to CO and NO_2 emissions. These combined factors— industrialization, traffic, biomass use, waste burning, and poor dispersion—explain the consistently high pollution in the South-West. Between 2019 and 2024, it ranked highest in NO_2, aerosols, CO, and CH_4.

Overall, the South-South had the cleanest air, the South-West the most polluted, and the South-East fell in between. These patterns reflect differences in industrial activity, population pressure, waste practices, and atmospheric conditions.

Recommendations

Air pollution patterns in Southern Nigeria vary by region, requiring distinct, zone-specific control strategies based on the dominant sources of emissions and socio-economic context. In the South-East, pollution is driven by high population density, informal transport systems, waste burning, and reliance on biomass for cooking. To reduce pollutant loads, state and local governments must ban open waste burning and provide structured waste collection services that reach peri-urban and densely populated settlements. Fuel-efficient stoves and cleaner cooking fuels such as LPG should be made affordable through subsidies. Motor vehicle emissions must be controlled through regular inspection and phase-out of outdated vehicles. Energy poverty must be addressed by expanding access to reliable grid electricity to limit household reliance on firewood, charcoal, and generators.

In the South-South, pollution stems mainly from gas flaring, artisanal refining, crude oil spills, and poorly regulated industrial emissions. Stronger enforcement of existing gas flaring policies is essential. Flare reduction technologies should be made compulsory for oil companies operating in Bayelsa, Rivers, and Delta States. Illegal refineries must be shut down using a multi-agency approach, while offering alternative livelihoods to communities involved in informal refining. Environmental monitoring units should be set up in proximity to major oil infrastructure to enable real-time tracking of pollutant levels. Additionally, environmental remediation programs must address the cumulative pollution load from decades of flaring and spills.

In the South-West, rapid urbanization, traffic congestion, industrial discharges, and widespread use of generators are the primary pollution sources. Lagos and Ogun should implement vehicle emission control zones and restrict the use of high-emission generators. Industrial estates must adopt stringent emission standards with regular environmental audits. Urban planning should incorporate green buffers to reduce particulate dispersion. To address traffic-related emissions, expanding public transport options such as rail and Bus Rapid Transit (BRT) systems is crucial. Additionally, promoting the adoption of Electric Vehicles (EVs) and increasing the number of trains will help reduce vehicular emissions and ease traffic congestion. Government incentives, infrastructure for EV charging, and improved rail connectivity should be prioritized. Furthermore, power infrastructure must be upgraded to reduce dependence on private energy sources, which are often heavy polluters.

Conclusion

Air quality across Southern Nigeria has significantly worsened from 2019 to 2024, with pollutant concentrations rising in all three geopolitical zones. The South-West remains the most polluted, driven by heavy industrialization, high vehicle density, and widespread generator use due to unreliable electricity. The South-East follows closely, where population growth, unregulated transport, biomass combustion, and open waste burning contribute heavily to emissions. In the South-South, although overall pollutant averages are lower, localized spikes from gas flaring, crude oil refining, and artisanal bunkering create serious environmental and health risks. The data confirm that air pollution is not evenly distributed but shaped by specific economic activities, land use patterns, and environmental enforcement gaps in each zone. The steady rise in CO, NO_2, SO_2, CH_4, and aerosol levels signals a growing threat to public health, agricultural productivity, and climate stability. Without effective policy enforcement, continued exposure to these pollutants will increase the burden of respiratory diseases, reduce labor productivity, and worsen regional environmental inequality. The absence of robust air quality monitoring systems across many states has further limited early detection and response capacity. Regional intervention is not optional—it is a necessity. Control measures must reflect the sources of pollution unique to each region. A one-size-fits-all approach will fail to address the scale and complexity of the problem. Urgent investments in regulatory enforcement, clean energy, sustainable transport, and waste management systems are essential to reverse current trends. Long-term planning must also integrate environmental data into urban development, public health policy, and infrastructure design. Addressing air pollution in Southern Nigeria requires both immediate action and sustained coordination between government, industry, and affected communities [78-95].

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