

Understanding the Chemical Evolution of the Atmosphere and Its Environmental Impact in Nigeria

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Abstract

Air pollution is a critical environmental challenge threatening ecological integrity, human health, and sustainable development in Nigeria. With over 208 million inhabitants, the country faces rising atmospheric burdens of carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄), nitrogen dioxide (NO₂), sulphur dioxide (SO₂), and sulphate aerosols (SO₄), largely driven by industrialization, fossil fuel combustion, deforestation, and open waste burning. These pollutants not only intensify climate change through greenhouse gas accumulation but also disrupt atmospheric chemistry, degrade ecosystems, and alter meteorological patterns. Despite the urgency, Nigeria's air quality monitoring infrastructure remains inadequate, leaving long-term atmospheric transformations poorly understood. This study investigates the chemical evolution of Nigeria's atmosphere from 2004 to 2024 using satellite remote sensing data from NASA's Atmospheric Infrared Sounder (AIRS) and Ozone Monitoring Instrument (OMI). Results reveal a significant decline in CO and SO₂ concentrations, suggesting progress in emission control, while CO₂ and CH₄ levels exhibited a steady increase, reflecting fossil fuel dependence, urbanization, geopolitics, and agricultural pressures. Conversely, NO₂ and SO₄ displayed fluctuating but inconclusive trends, pointing to complex emission dynamics and atmospheric processes. These findings underscore the intricate interplay between pollutants, climate systems, and environmental impacts.

Keywords

Atmospheric Chemistry, Carbon Monoxide (CO), Carbon Dioxide (CO₂), Nitrogen Dioxide (NO₂), Methane (CH₄), Sulfur Dioxide (SO₂), Sulfate Aerosols (SO₂)

1. Introduction

The World Health Organization (WHO) defines a healthy environment as a cornerstone of sustainable human development, emphasizing the intrinsic link between environmental quality and societal well-being [1]. In Nigeria, a country with an estimated population of 208.3 million [1], environmental degradation, particularly from air pollution, presents a significant barrier to achieving both ecological sustainability and economic resilience. The widespread presence of atmospheric pollutants such as carbon monoxide (CO), carbon dioxide (CO₂), nitrogen dioxide (NO₂), methane (CH₄), sulfur dioxide (SO₂), and sulfate aerosols (SO₄) contributes to complex environmental transformations with far-reaching consequences. These pollutants, originating from both natural and human-induced sources, disrupt atmospheric chemistry, accelerate climate change, degrade ecosystems, and influence meteorological patterns. This creates an urgent need to understand their long-term trends and impacts within the Nigerian context [2]. Despite the critical role of air quality in environmental sustainability, Nigeria currently lacks comprehensive and consistent air quality monitoring—particularly for assessing long-term changes. This gap highlights the importance of adopting advanced approaches such as satellite remote sensing to enhance monitoring and inform policy interventions.

Air pollution arises from the introduction of harmful substances into the environment at concentrations exceeding natural or manageable levels, affecting air, water, and land [3]. In Nigeria, a diverse array of anthropogenic activities drives the release of CO, CO₂, NO₂, CH₄, SO₂, and SO₄ into the atmosphere. Industrial processes, including oil and gas exploration, gas flaring, chemical manufacturing, and mining, are major contributors, alongside agricultural practices such as deforestation, fertilizer application, and biomass burning [2]. Open waste burning, vehicular and aviation emissions, and marine activities like shipping and salt sprays further amplify pollutant loads [4]. Natural sources, including dust storms from the Sahel and wildfires, also play a significant role in altering atmospheric composition [5]. These emissions participate in intricate atmospheric chemical reactions such as oxidation, photolysis, and hydrolysis—occurring across different atmospheric layers (troposphere, stratosphere, mesosphere, thermosphere, and exosphere) [6]. These reactions produce secondary pollutants like ground-level ozone, photochemical smog, and inorganic aerosols, including SO₄, which contribute to environmental degradation [7].

The environmental impacts of these pollutants are profound and multifaceted. CO₂ and CH₄, as potent greenhouse gases, trap heat in the atmosphere, driving global warming and altering Nigeria's climate [8]. These changes manifest as rising surface temperatures, intensified heatwaves, and shifting precipitation patterns, which have increased the frequency and severity of extreme weather events like floods and droughts [7].

For instance, flooding events in Nigeria, affecting 34 out of 36 states, have caused significant damage to infrastructure, agriculture, and livelihoods [9]. NO₂ and SO₂, primarily emitted from fossil fuel combustion and industrial activities, contribute to the formation of acid rain, which degrades soil fertility, reduces agricultural productivity, and contaminates freshwater systems [10]. Sulfate aerosols (SO₄), formed through the oxidation of SO₂, scatter sunlight and influence cloud formation, altering regional weather patterns and contributing to desertification in Nigeria's northern regions [6]. CO, a product of incomplete combustion, and CH₄, released from agricultural and waste management practices, further exacerbate the greenhouse effect, amplifying climate variability [11]. Also, Greenstone in his book highlights that particulate pollution, including SO₄ aerosols, contributes to ecosystem stress, reducing biodiversity and affecting flora and fauna [12].

The interplay of these pollutants with atmospheric processes has broader implications for Nigeria's environment [13]. Atmospheric chemical reactions, driven by interactions between gases, particulates, and meteorological factors, lead to phenomena like photochemical smog, which reduces visibility and disrupts photosynthesis, and acidic precipitation, which erodes soil nutrients essential for agriculture [14]. Climate change, fueled by greenhouse gas accumulation, intensifies environmental challenges, including coastal erosion, land degradation, and loss of arable land, all of which threaten Nigeria's economic stability and food security [15]. The complex feedback loops between pollutants and climate systems can also exacerbate extreme weather events, such as heavy rainfall and flooding, which damage infrastructure and displace communities. For example, Nigeria's reliance on fossil fuels and biomass burning contributes to elevated CO₂ and CH₄ levels, which in turn amplify global warming, leading to more frequent and severe environmental disruptions [16]. These impacts underscore the urgency of understanding the chemical evolution of Nigeria's atmosphere to inform mitigation strategies and policy development.

Despite the severity of these environmental challenges, Nigeria's air quality monitoring infrastructure remains limited, with sparse ground-based stations unable to capture the spatial and temporal variability of pollutants across the country's diverse regions [17]. Satellite remote sensing, utilizing instruments such as the Atmospheric Infrared Sounder (AIRS) and the Ozone Monitoring Instrument (OMI), offers a powerful solution by providing consistent, high-resolution spatiotemporal data over large areas [18]. Unlike short-term studies, which focus on event-specific impacts, long-term analyses spanning 2004 to 2024 enable

the identification of trends in pollutant concentrations, offering insights into historical changes and future projections. Such data are critical for modeling the sources, transport, and transformation of CO, CO₂, NO₂, CH₄, SO₂, and SO₄, as well as their contributions to climate change, ecosystem degradation, and meteorological shifts. This study aims to investigate the long-term chemical evolution of Nigeria's atmosphere by analyzing trends in these pollutants using AIRS and OMI data, focusing on their environmental impacts. By providing a comprehensive baseline for atmospheric changes, this research seeks to inform evidence-based environmental policies to foster sustainable development in Nigeria.

The atmosphere is a dynamic system influenced by various natural and anthropogenic factors, leading to chemical changes that can affect human health and the environment. In Nigeria, industrialization, urbanization, and agricultural activities have contributed to significant alterations in atmospheric composition. Understanding the chemical evolution of the atmosphere and its environmental impact is crucial for developing effective air quality management strategies and mitigating adverse effects on public health and ecosystems.

Despite the increasing awareness of air pollution issues in Nigeria, there is a lack of comprehensive studies focusing on the chemical evolution of the atmosphere and its specific environmental implications. Limited data on atmospheric pollutants, their sources, and spatial-temporal variations hinder the formulation of evidence-based policies and interventions to address air quality challenges in the country. Additionally, the lack of understanding regarding the interactions between atmospheric pollutants and environmental factors limits our ability to assess their cumulative effects on human health and ecosystems.

Conducting a study on the chemical evolution of the atmosphere and its environmental impact in Nigeria is justified for several reasons. Firstly, it addresses a critical gap in current knowledge regarding air quality dynamics and pollution sources in the country. Furthermore, by elucidating the environmental impact of atmospheric pollutants, the study can inform policy decisions aimed at promoting sustainable development and safeguarding the environment.

This work aims to investigate the chemical evolution of the atmosphere and its environmental impact in Nigeria while looking at data from 2004 to 2024 (**Table 1**).

The specific objectives are as follows:

- 1) To evaluate the changes that have occurred in selected chemicals in the atmosphere over a twenty-year period in Nigeria.
- 2) To assess the environmental impacts of selected atmospheric pollutants (CO, CO₂, NO₂, CH₄, SO₂, and SO₄) by analyzing their concentrations in relation to established air quality standards and guidelines.
- 3) To evaluate the effectiveness of existing air quality management strategies and recommend evidence-based interventions for improving air quality in Nigeria.

Table 1. Atmospheric compounds, description, and the environmental threats they pose.

Atmospheric Compound	Brief Description	Threats They Pose
Carbon Monoxide (CO)	This is a colorless, odorless gas produced by the incomplete combustion of carbon-containing fuels. Major sources include vehicle emissions, industrial processes, and biomass burning.	While CO itself is not a greenhouse gas, it indirectly affects the climate by influencing the concentrations of methane and tropospheric ozone, both of which are potent greenhouse gases.
Carbon Dioxide (CO ₂)	CO ₂ is produced through natural processes like respiration and volcanic eruptions, as well as human activities such as fossil fuel combustion and deforestation.	Elevated CO ₂ levels can lead to ocean acidification, affecting marine life, and can alter plant growth patterns.
Nitrogen Dioxide (NO ₂)	NO ₂ forms during high-temperature combustion processes, such as those in vehicles and power plants, through the oxidation of nitrogen in the air.	It plays a role in the formation of acid rain, which can harm ecosystems and structures.
Methane (CH ₄)	Methane is emitted during the production and transport of coal, oil, and natural gas, as well as from livestock and other agricultural practices.	It contributes to global warming, some of which are rising temperatures, increased storms, droughts, etc.
Sulfur Dioxide (SO ₂)	Sulfur dioxide is a colorless gas with a sharp, irritating smell. It is predominantly produced by volcanic eruptions and anthropogenic sources such as burning coal, oil, and natural gas. Industrial operations, particularly those involving fossil fuels and metal smelting processes, are significant contributors to SO ₂ emissions.	It impacts the environment by lowering the pH of water bodies, leaching Aluminum from the soil, and destroying algae growth.
Sulfate (SO ₄ ²⁻)	Atmospheric sulfate (SO ₄ ²⁻) is primarily formed through oxidation of sulfur dioxide (SO ₂) in the atmosphere. The process occurs via both gas-phase and aqueous-phase reactions, and it plays a key role in air pollution, acid rain, and climate change.	Deposition of sulfates contributes to the acidification of soils and water bodies, impacting plant and aquatic life.

Table 2 lists measures put in place by the federal government of Nigeria to combat certain atmospheric gases known as SLCPs (Short-Lived Climate Pollutants), as released by the Ministry of Environment in 2018 [19].

Table 2. SLCP abatement measures adopted in the National SLCP Plan.

Source Sector	SLCP Abatement Measures	Target
Transport	<ol style="list-style-type: none"> 1. Renewal of urban bus fleet in Lagos 2. Adoption of CNG Buses in Nigeria 3. Introduction of low Sulphur Diesel and Petrol 4. Elimination of high-emitting vehicles that do not meet vehicle emission standards 5. Reduction of vehicle journeys 	5,000 new buses in Lagos are complete and Danfo buses fully replaced by 2021; 25% all Buses converted to CNG by 2030; 50 ppm diesel fuel introduced in 2019; 150 ppm petrol introduced in 2021; Euro IV limits met by all vehicles by 2030; 500,000 daily journeys shifted from road to rail and waterways.
Residential	<ol style="list-style-type: none"> 6. Increase in population using modern fuels for cooking (LPG, electricity, kerosene, biogas, solar cookers) 7. Replacement of traditional biomass cookstoves with more efficient, improved biomass stoves 8. Elimination of kerosene lamps 	80% of H/H using modern fuels for cooking in 2030; 20% H/H using improved biomass stoves for cooking in 2030; All kerosene lighting replaced by solar lamps by 2022.

Continued

Oil & Gas	9. Elimination of gas flaring	100% of gas flaring eliminated by 2020; 50% methane reduction by 2030.
	10. Fugitive emissions/leakages control	
	11. Methane leakage reduction	
Industry	12. Improved energy efficiency in the industrial sector	50% improvement in energy efficiency by 2050.
	13. Reduction of methane emissions and open burning of waste at open dumpsites through the adoption of digesters at dump sites	50% methane recovered from landfills by 2030; 50% reduction in open burning of waste by 2030; Promote Septic sludge collection, treatment, and recycling in 37 municipalities; Establish, expand sewerage systems and municipal wastewater treatment plants in Lagos, Kano, and Port Harcourt.
	14. Septic sludge collection	
	15. Sewerage systems and municipal wastewater treatment plants	
	16. Increased adoption of intermittent aeration of rice paddy fields (AWD)	
17. Reduce open-field burning of crop residues		
Waste Management	18. Anaerobic digestion (AD)	50% cultivated land adopts AWD management system by 2030; 50% reduction in the fraction of crop residue burned in fields by 2030; 50% reduction by 2030 30% reduction in emission intensity by 2030.
	19. Reduce methane emissions from enteric fermentation	
	20. Expansion of national electricity coverage	
Power (Energy)	21. Increase the share of electricity generated in Nigeria from renewables	90% of the population will have access to the electricity grid by 2030; 30% electricity will be generated using renewable energy in 2030.

2. Materials and Methods

Data for this work were obtained from NASA Giovanni from 2004 to 2024 for the selected atmospheric gases. Python (Matplotlib, Numpy, and Pandas) was used for the analysis of the acquired data. The instrument characteristics of the satellite components are shown in **Table 3**.

Table 3. Instrumental characteristics of the satellite components [20].

Atmospheric Variable	Detection Range ± Sensitivity Limit	Satellite/Reprocessed Data	Source Data
CO (ppb)	50 - 500 ± ~10	AIRS	OFFL/AIRS3STD
CO ₂ (ppm)	360 - 420 ppm ± 1	AIRS	OFFL/AIRS3 C2D_005_mole_fraction_of_carbon_dioxide_in_free_troposphere
NO ₂ (mol/m ²)	0 - 0.1	OMI	OFFL/OMI-Aura_L3-OMNO2D
CH ₄ (ppb)	1600 - 2000 ± ~10	AIRS	OFFL/AIRS3STM_7_0_CH4_VMR_A/D
SO ₂ (DU)	0.1 - 10	OMI	OFFL/OMI-Aura_L3-OMSO2e
SO ₄ (µg/m ³)	0.1 - 10	OMI	OFFL/OMI-Aura_L3-OMSO2e

2.1. Study Area

Nigeria, situated in West Africa, stands as one of the continent's most populous countries with various ethnic groups such as the Yoruba, Igbo, and Hausa, each contributing to the country's unique identity with 36 states and a federal capital territory. The nation's climatic variations, rain patterns, and temperature ranges contribute to

its multifaceted profile. Nigeria's climatic conditions vary widely due to its geographical spread, with tropical climates in the south and arid conditions in the north.

2.2. Data Collection

The NASA (National Aeronautics and Space Administration) Giovanni (Goddard Earth Sciences Data and Information Services Center (GES DISC) Interactive Online Visualization and Analysis Infrastructure) platform is a web-based tool that provides users.

The key features of the NASA Giovanni platform (<https://giovanni.gsfc.nasa.gov/giovanni>) are data accessibility, user-friendly interface, data visualization, multiple datasets (AIRS, OMI), temporal and spatial analysis, intercomparison of datasets, and educational resources [21]. The NASA Giovanni platform conducts aerosol and gas concentration, wildfire and biomass burning events, satellite observations, and model comparison. The platform plays a crucial role in advancing scientific research, supporting environmental monitoring efforts, and promoting public awareness of air quality and atmospheric dynamics.

2.3. Data Used

In this study, we carried out data retrievals (**Table 1**) from the NASA Giovanni Platform for the spatiotemporal analysis of nitrogen dioxide (NO₂), sulphur dioxide (SO₂), carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄) through the Ozone Monitoring Instrument (OMI) and Atmospheric Infrared Sounder (AIRS). Ozone Monitoring Instrument (OMI), a part of NASA Aura mission is a nadir viewing wide-field spectrometer satellite that was launched in July 2004, measurement started in October 2004; and was used to get coverage for 24 h coverage at a resolution of 1° × 1°, which measures criteria pollutants such as NO₂, SO₂, at Visible range of 350 - 500 nm and Ultraviolet range of UV-1 (270 - 314 nm) and UV-2 (306 - 380 nm).

Atmospheric Infrared Sounder (AIRS) is a hyperspectral infrared instrument developed by NASA and launched in May 2002 with 2378 infrared spectral coverage from 3.74 to 4.61 μm (2674 - 2170 cm⁻¹); 6.20 - 8.22 μm (1613 - 1217 cm⁻¹) and 8.80 - 15 μm (1136 - 649 cm⁻¹) at ± 49.5° and 13.5 km diameter around the nadir wide view. The altitude of the scan is 7 - 5 km, the scan period is 2.667 s, and ground footprints at 90 per scan, which scans the ascending daytime and descending nighttime for complete better coverage for full 24 h at a resolution of 1° × 1° [22] that analyses physical parameters (surface temperature, pressure, water vapour, relative humidity, cloud height and cover, precipitation), and trace gas amount.

2.4. Limitation

1) The sensor for CO₂ was calibrated to pick values from 360 - 420 ppm, which is to say values below and above this range were not be captured. Therefore, this data may not be the real representative data that captures the real CO₂ situation in Nigeria.

2) The data available for CO₂ on the NASA Giovanni website ended in 2022.

3. Result

There is a clear decreasing trend in CO concentrations over the years. Seasonal fluctuations are strong, with recurring peaks and troughs roughly every year (Figure 1).

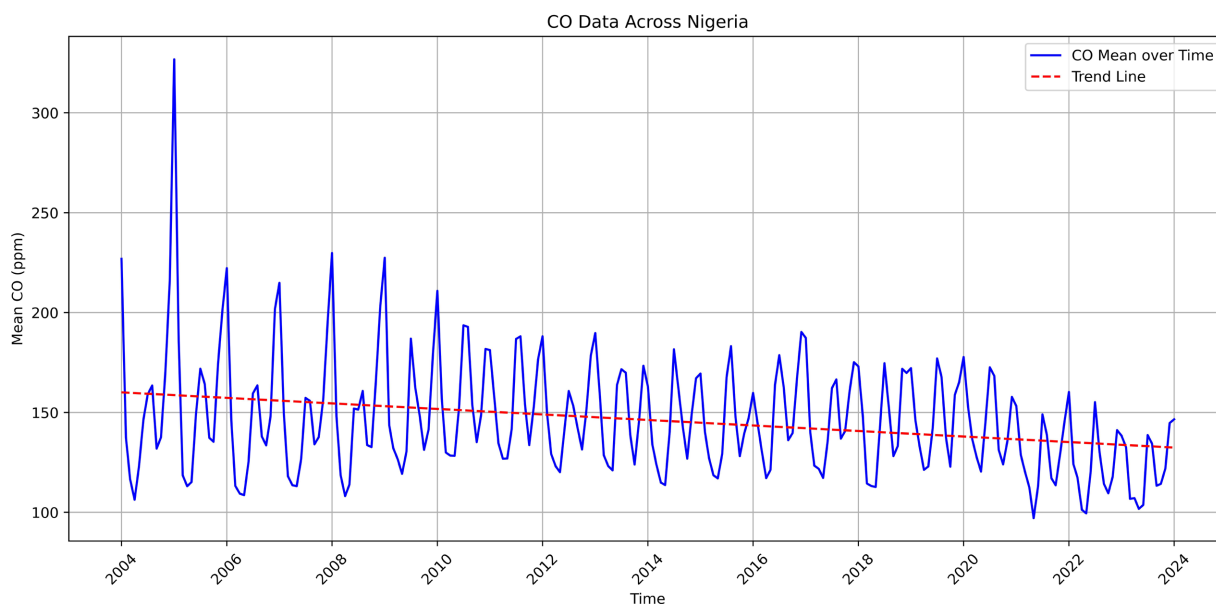


Figure 1. Carbon monoxide (CO).

The values appear to stabilize and drop steadily after around 2008. With the highest point occurring in 2005 at approximately 325 ppb. While the lowest point according to the chart occurred in 2021, when the CO levels dropped below 100 ppb.

The steady decline suggests progress in emission control, possibly cleaner energy sources, or even better enforcement of air quality regulations.

There is a consistent upward trend in CO₂ concentrations over the period captured, with the highest peak found in 2021 and around early 2022 at approximately 416 ppm. While the lowest point on the chart can be seen in 2004, with a value slightly above 370 ppm.

This reflects steady growth in emissions, likely due to increased fossil fuel consumption, population growth, urbanization, industrial expansion, and energy use (Figure 2).

From the chart above, there is a clear upward trend in CH₄ levels over the two decades. This suggests increasing methane emissions over time, potentially from agriculture (livestock, rice paddies), waste, energy production (oil/gas industry), or biomass burning. The peak methane concentration is observed around late 2023 to early 2024, reaching approximately 1890 ppm. This is the highest value on the graph and indicates a significant spike, which could reflect a major emission event or trend acceleration. The lowest CH₄ concentration is observed around 2004, where the value dips to approximately 1790 ppm. This dip represents the min-

imum recorded level across the two decades (Figure 3).

The Nitrogen Dioxide (NO_2) concentration fluctuates over time with no strong long-term upward or downward trend. The highest peak can be seen in 2018 with a value slightly above 4.2 ppm, and the lowest peak seen around 2023 and 2022 with values of approximately 1.7 ppm and 2.3 ppm, respectively.

Figure 4 displays a clear seasonal pattern (regular peaks and valleys), likely reflecting periodic emissions or atmospheric behavior affecting Nitrogen Dioxide levels.

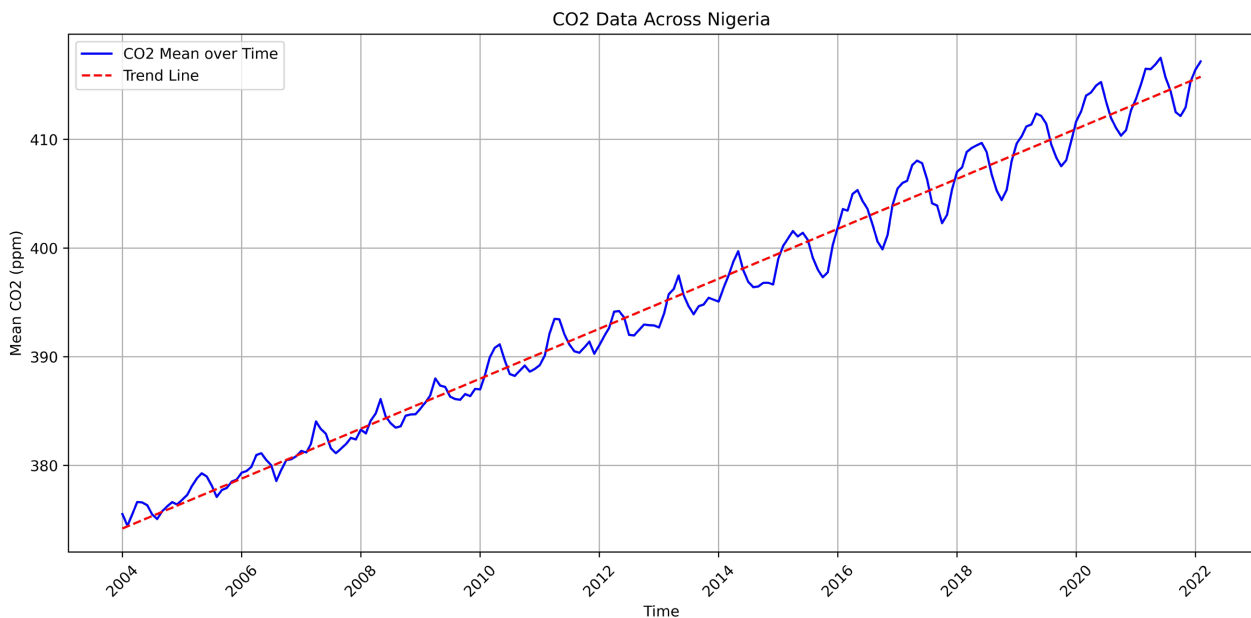


Figure 2. Carbon dioxide (CO_2).

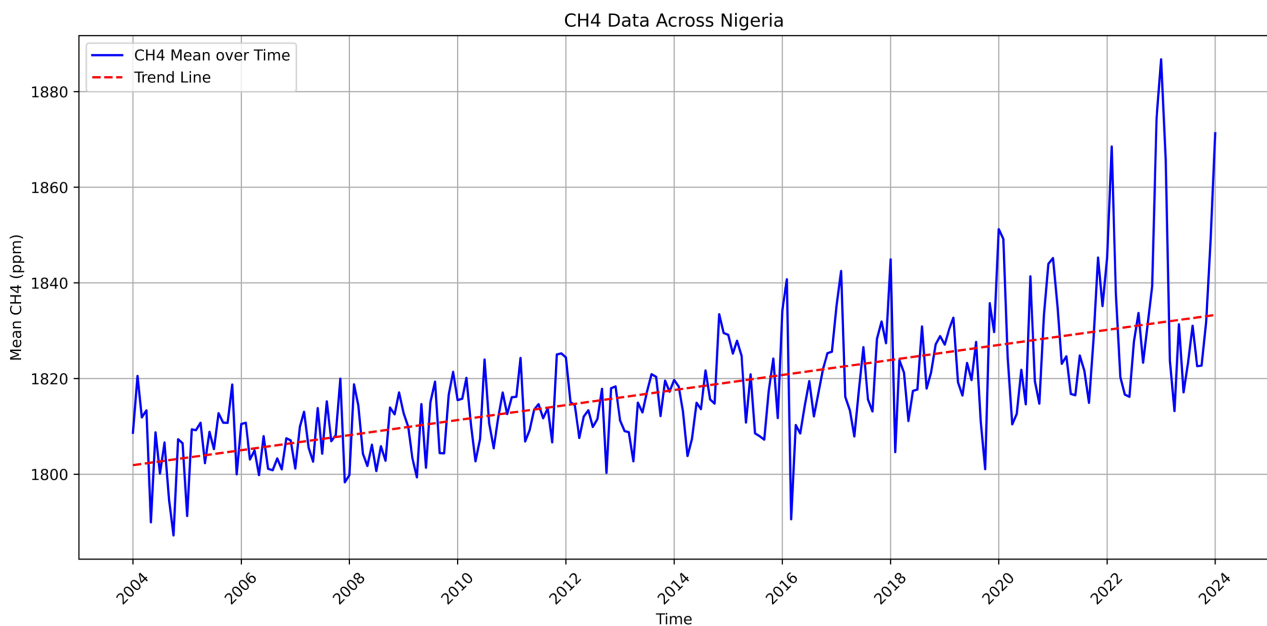


Figure 3. Methane (CH_4).

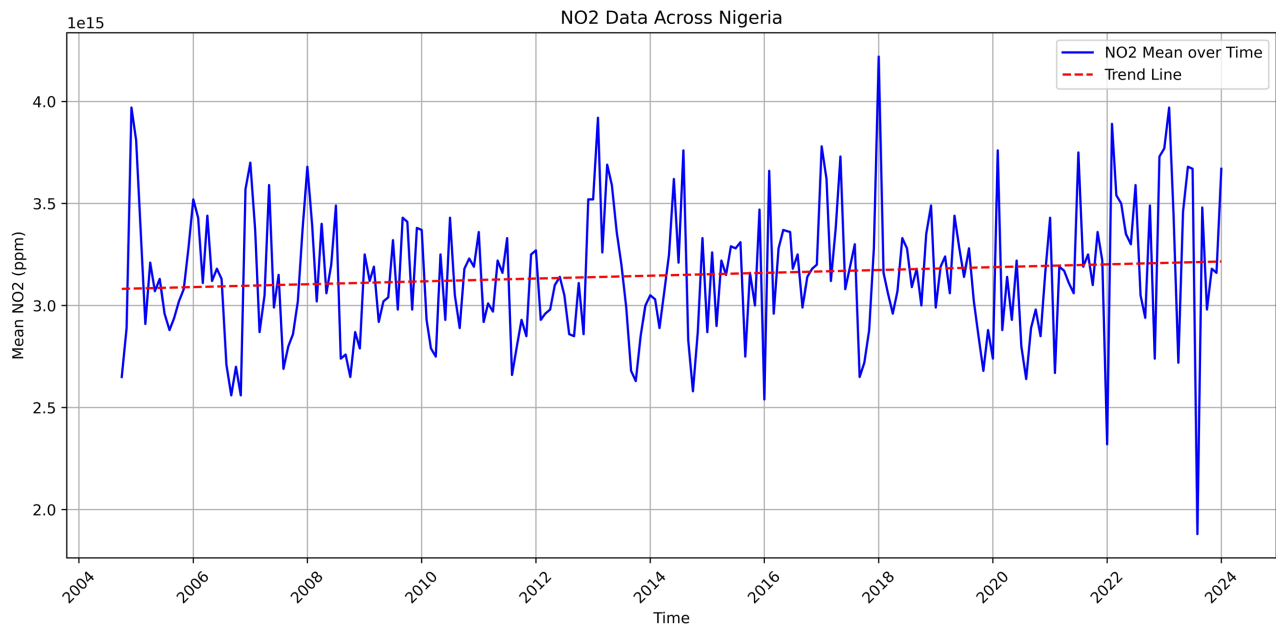


Figure 4. Nitrogen dioxide (NO₂).

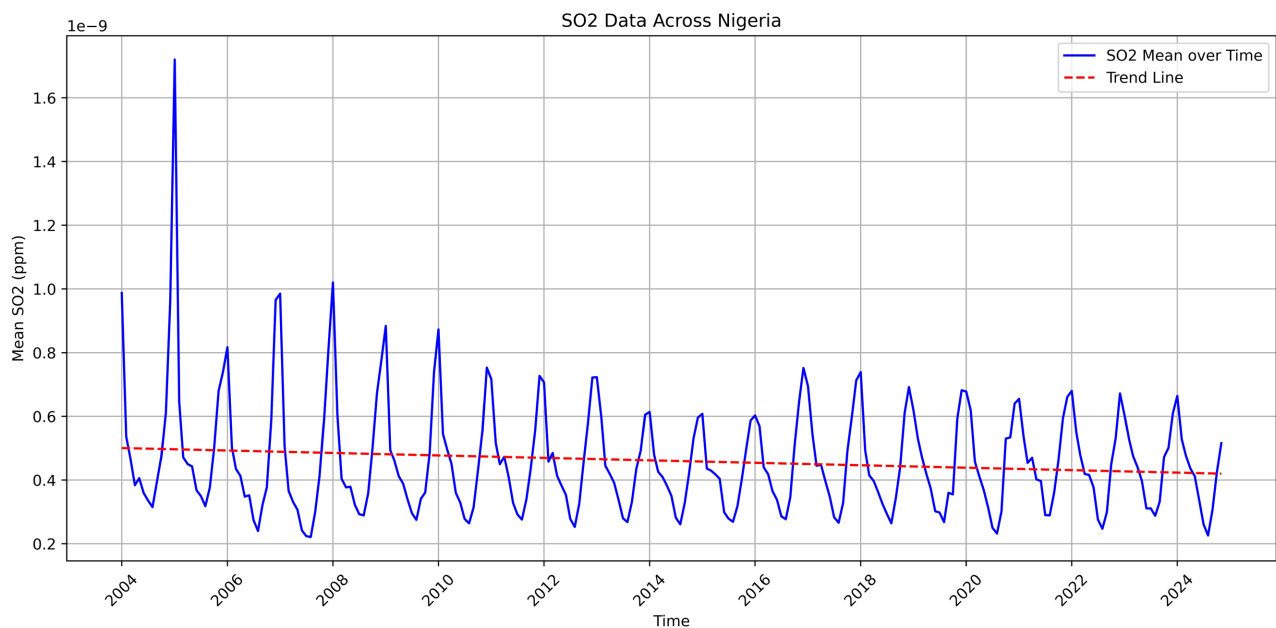


Figure 5. Sulfur dioxide (SO₂).

Figure 5 displays a clear seasonal pattern (regular peaks and valleys), likely reflecting periodic emissions or atmospheric behavior affecting SO₂ (sulfur dioxide) levels.

Over time, the overall trend appears to be a gradual decline in the average SO₂ levels. The highest SO₂ concentration occurred around late 2004 to early 2005. The value is approximately $1.7 \times 10^{-9} \mu\text{g}/\text{m}^3$, as seen in the tall spike on the graph. The lowest SO₂ concentration appears in the middle of 2007 and the middle of

2024, where the line dips closest to the $0.2 \times 10^{-9} \mu\text{g}/\text{m}^3$ mark.

Peaks may correspond to dry seasons when dust and emissions from fires, vehicles, or industrial sources are higher.

Dips may occur during the rainy season, when precipitation helps clear pollutants from the atmosphere.

The sharp peak in 2004-2005 could have resulted from a major industrial activity or an environmental event.

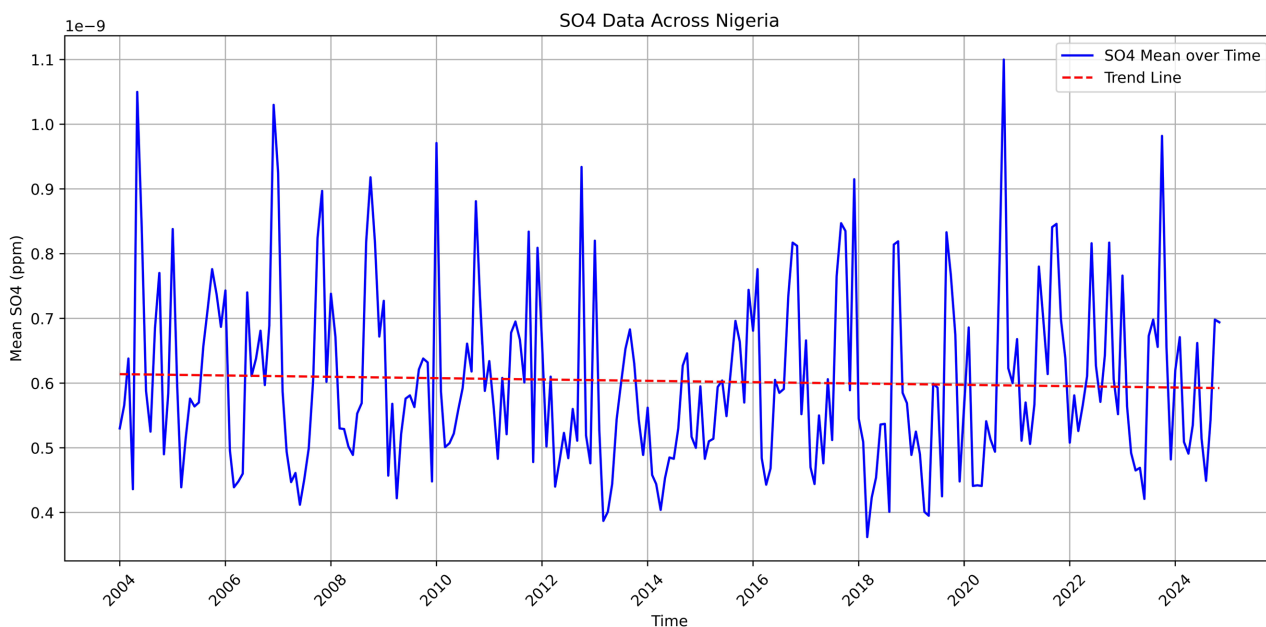


Figure 6. Sulfate (SO₄).

Table 4. Environmentally accepted levels versus the average of the selected atmospheric variables in Nigeria.

Atmospheric Variable	Environmentally Safe Levels/Units [7]	Average of the Highest and Lowest Points	Result
CO	<0.2 ppm	0.213 ppm	High
CO ₂	<350 ppm	370 ppm	High
NO ₂	<10 $\mu\text{g}/\text{m}^3$	2.95 $\mu\text{g}/\text{m}^3$	Low
CH ₄	<1.8 ppm	1.840 ppm	High
SO ₂	<10 - 20 $\mu\text{g}/\text{m}^3$	0.95 $\mu\text{g}/\text{m}^3$	Low
SO ₄	<5 $\mu\text{g}/\text{m}^3$	0.75 $\mu\text{g}/\text{m}^3$	Low

The data shows high-frequency fluctuations with less obvious seasonality compared to the SO₂ graph. Unlike SO₂, SO₄ levels fluctuate more irregularly, indicating more complex emission or atmospheric processes influencing sulfate concentrations (Figure 6). No clear long-term upward or downward trend is visible. The concentration oscillates with high variability throughout the entire period. The

highest sulfate concentration occurs between 2020 and 2022, where the graph spikes above $1.1 \times 10^{-9} \mu\text{g}/\text{m}^3$. Another near-peak is visible around 2004, reaching slightly below $1.1 \times 10^{-9} \mu\text{g}/\text{m}^3$. The lowest point occurs around 2018, with a sharp dip slightly below $0.4 \times 10^{-9} \mu\text{g}/\text{m}^3$. **Table 4** shows a comparison of the average values of selected atmospheric variables in Nigeria with environmentally acceptable levels.

4. Conclusions and Recommendation

The changes that have been observed in the following atmospheric gases (CO, CO₂, NO₂, CH₄, SO₂, and SO₄) over the period of 20 years from 2004 to 2024 have been profound, and interestingly, the following were in decline: CO, SO₂, SO₄, and NO₂, while CH₄ and CO₂ increased over time.

The reason for the decline of CO and SO₂ could be as a result of better policies in managing these atmospheric gases since the government introduced and incentivized CNG (compressed natural gas) powered buses, which produce cleaner and environmentally friendly wastes at the end of their cycle when compared to fuel and gasoline, although more can still be done. While methane increased by about 100ppm over a twenty-year period, although the accepted norm globally is <1800 ppm, which means Nigeria can do more in bringing the CH₄ level down. CO₂, on the other hand, increased by about 36 ppm, although the increase was not astronomical.

In terms of policy, Nigeria has a good policy document that has been designed to eradicate or drastically reduce these atmospheric pollutants; however, the will-power to implement the policy document completely is what we need to work on for better output. Also, incentivization of electric Vehicles (EVs), especially in urban areas, can lead to a reduction of particulate matter (PM) to at least 20% within 5 years of implementation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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