

**SENTINEL-5P REMOTE SENSING ANALYSIS OF SO<sub>2</sub> AND CO EMISSIONS IN  
DELTA AND EDO STATE FROM 2020-2024**

**BY**

**AKODE OSAYUWAMEN OJONE**

**LCS2103835**

**DEPARTMENT OF ENVIRONMENTAL MANAGEMENT AND TOXICOLOGY,  
FACULTY OF LIFE SCIENCES, UNIVERSITY OF BENIN, BENIN CITY, EDO  
STATE, NIGERIA.**

**NOVEMBER, 2025.**

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**AN UNDERGRADUATE PROJECT SUBMITTED TO THE DEPARTMENT OF  
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BACHELOR OF SCIENCE (B.Sc) DEGREE IN ENVIRONMENTAL  
MANAGEMENT AND TOXICOLOGY.**

**NOVEMBER, 2025.**

## CERTIFICATION

This is to certify that this research titled "Sentinel-5p remote sensing analysis of SO<sub>2</sub> and CO emissions in Delta and Edo state from 2020-2024" was carried out by "AKODE OSAYUWAMEN OJONE" and presented to the Department of Environmental Management and Toxicology, Faculty of Life Sciences, University of Benin, Benin City; in partial fulfillment of the requirements for the award of Bachelor of Science (B.Sc) in Environmental Management and Toxicology. It was conducted under suitable conditions, was carefully supervised and subsequently approved as having met the requirements for the award of Bachelor of Science degree in Environmental Management and Toxicology.

.....

**PROF. A. A. ENUNEKU**

**Project Supervisor**

.....

**Date**

.....

**Dr A. F. EGHOMWANRE**

**Project Coordinator**

.....

**Date**

.....

**PROF. (MRS) E. T. AISIEN**

**Head of Department**

.....

**Date**

## DECLARATION

I “**AKODE OSAYUWAMEN OJONE**” declare that “**Sentinel-5p remote sensing analysis of SO<sub>2</sub> and CO emissions in Delta and Edo state from 2020-2024**” is my own work and that all sources that I have used or quoted have been acknowledged by means of complete references and that this work has not been submitted before for any other degree at any other University.

**AKODE OSAYUWAMEN OJONE**

.....

**Date**

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## ABSTRACT

This study examines the levels and patterns of two important air pollutants, sulfur dioxide (SO<sub>2</sub>) and carbon monoxide (CO), over Delta and Edo States in Nigeria's oil-producing Niger Delta region during the years 2020 to 2024. Using data from the Sentinel-5P satellite, processed through the Google Earth Engine platform, the research maps where these pollutants are most concentrated and looks at how their presence changes over time and across different locations. Sulfur dioxide pollution is mainly found near gas flaring sites in Delta State, which is a common practice in oil extraction that releases large amounts of pollutants. Carbon monoxide pollution is spread over both states and comes from several sources including heavy traffic, burning of plant material, and industrial activities.

The study identifies that the highest levels of these pollutants occurred in 2022, which may be linked to increased industrial and economic activities following the easing of COVID-19 lockdowns. Despite existing environmental regulations aimed at controlling pollution from these sources, the study finds that high emissions persist, indicating challenges in enforcement and monitoring. These pollutants are known to cause serious health problems, including respiratory and heart diseases, posing significant risks to the local population.

This research highlights the value of using satellite remote sensing for air quality monitoring, especially in areas like the Niger Delta where there is a lack of ground-based air pollution measurement stations. While this method provides broad coverage and useful long-term data, the study notes some limitations such as interference from clouds and difficulty in measuring pollution close to the ground. The findings provide evidence to support stronger environmental policies and targeted actions to reduce pollution, protect public health, and promote sustainable development in oil-producing areas of Nigeria. This work contributes important scientific information to guide policymakers, environmental agencies, and communities in managing air quality risks effectively.

# CHAPTER ONE

## INTRODUCTION

### 1.1 Background to the Study

#### 1.1.1 The Global Air Quality Crisis

Air pollution represents one of the most formidable environmental and public health challenges confronting contemporary society (Saxena and Sonwani *et al.*, 2019). The World Health Organization has consistently documented that atmospheric contamination contributes to approximately seven million premature deaths globally each year, with the burden disproportionately affecting populations in developing regions. Among the multitude of atmospheric contaminants, sulphur dioxide (SO<sub>2</sub>) and carbon monoxide (CO) emerge as particularly significant due to their widespread occurrence and severe health implications. ). Air pollution can have serious expenses, drawbacks and concerns for the health and well-being of humans and equally callously distresses the natural biocomplex network and ecosystems as a whole; it has several impacts including the formation of acid rain, smog, ozone depletion and global warming (Ashfaq and Sharma *et al.*, 2012).

Sulphur dioxide, a colourless gas with a pungent odour, originates primarily from the combustion of sulphur-containing fossil fuels and industrial metallurgical processes. Its presence in the atmosphere initiates a cascade of environmental degradation, including the formation of acid precipitation, deterioration of vegetation, corrosion of infrastructure, and exacerbation of respiratory ailments such as asthma and chronic bronchitis. Furthermore, SO<sub>2</sub> serves as a precursor to secondary sulphate aerosols, which contribute significantly to particulate matter formation and regional haze development.

Carbon monoxide, conversely, is an insidious pollutant odourless, colourless, and tasteless yet profoundly toxic. It results predominantly from the incomplete combustion of carbonaceous materials, including vehicular emissions, biomass burning, and industrial

furnaces (Penney *et al.*, 2010, Zajemska *et al.*, 2014). Upon inhalation, CO binds preferentially to haemoglobin, forming carboxyhaemoglobin, thereby diminishing the blood's oxygen-carrying capacity and potentially causing cardiovascular complications, neurological impairment, and in extreme cases, mortality (Sircar *et al.*, 2015). . It is important to know that CO serves as a precursor for tropospheric ozone, contributing to a net warming effect. With residence time ranging from 30 to 90 days, the lifetime of CO can vary based on its altitude in the atmosphere (Myhre *et al.*, 2013 , Seinfeld and Pandis *et al.*, 2016).

The intricate relationship between industrialisation, urbanisation, and atmospheric degradation has become increasingly evident across developing nations (Raub *et al.*, 2000). Nigeria, as Africa's largest economy and a major petroleum producer, exemplifies this challenge, particularly within its Niger Delta region where decades of hydrocarbon exploitation have generated substantial environmental consequences. The pollutant and particles generated by this industry are often carried by the wind and deposited in both nearby and distant areas from the factory (Oyedele *et al.*, 1990).

### **1.1.2 The Niger Delta Context: Delta and Edo States**

The Niger Delta region occupies a unique position in Nigeria's economic landscape, serving as the nation's primary petroleum production zone. This coastal area, characterised by extensive wetlands, mangrove forests, and riverine systems, has experienced intensive industrial activity for over six decades. Within this broader region, Delta and Edo States represent distinct yet complementary case studies for examining atmospheric pollution dynamics.

Delta State constitutes the epicentre of Nigeria's gas flaring activities, with the continuous combustion of associated gas from oil extraction operations releasing substantial quantities of SO<sub>2</sub>, CO, and other pollutants into the atmosphere. The state hosts numerous flow stations, oil wells, and processing facilities, particularly concentrated around communities such as

Warri, Ughelli, and Sapele. These flaring operations have persisted for over fifty years, creating persistent atmospheric contamination that affects local communities through direct exposure to toxic emissions.

Edo State presents a different emission profile whilst remaining within the broader Niger Delta environmental zone. Although less dominated by petroleum extraction activities compared to Delta State, Edo features significant industrial infrastructure including cement manufacturing plants, notably in Okpene, alongside power generation facilities and the densely populated capital city of Benin City (Akinnibosun *et al.*, 2023). The state's pollution sources reflect a mixture of industrial emissions, vehicular exhaust from urban traffic congestion, and biomass combustion for domestic energy needs.

The exploration and production of petroleum in this region has generated a complex array of gaseous pollutants including methane, ammonia, nitrogen oxides, particulate matter, sulphur oxides, and volatile organic compounds, all of which pose significant hazards to human populations, wildlife, and the broader environment (Okpoko and Ilaboya *et al.*, 2021). Despite these documented impacts, comprehensive atmospheric monitoring remains severely limited.

### **1.1.3 The Monitoring Challenge and Remote Sensing Solutions**

Traditional air quality assessment relies upon ground-based monitoring stations equipped with reference-grade instrumentation capable of continuous measurement. However, the establishment and maintenance of such networks requires substantial financial investment, technical expertise, and institutional capacity resources that remain scarce across much of sub-Saharan Africa (Kumar and Mutanga *et al.*, 2018). Nigeria's existing monitoring infrastructure concentrates predominantly in major metropolitan centres such as Lagos and Abuja, leaving vast geographical areas, including most of the Niger Delta, without adequate surveillance.

This monitoring deficit creates several critical challenges: it obscures the true magnitude and spatial distribution of pollution; it hinders the development of evidence-based environmental policies; it prevents the identification of pollution hotspots requiring urgent intervention; and it limits the capacity to assess trends over time or evaluate the effectiveness of mitigation measures (Mutanga and Kumar *et al.*, 2019).

Satellite remote sensing technology has emerged as a transformative tool for addressing these limitations. The European Space Agency's Sentinel-5 Precursor (Sentinel-5P) satellite, launched in October 2017, carries the TROPospheric Monitoring Instrument (TROPOMI) a state of the art spectrometer providing unprecedented spatial resolution (3.5 km × 5.5 km at nadir) for atmospheric composition monitoring. TROPOMI delivers daily global coverage with valuable spatial and temporal resolutions, enabling comprehensive monitoring of air pollutants such as CO and formaldehyde across extensive geographical areas (Enuneku *et al.*, 2025).

The open-access nature of Sentinel-5P data, combined with cloud-based processing platforms such as Google Earth Engine, enables researchers to conduct sophisticated spatio-temporal analyses without requiring extensive local computational infrastructure (Zhao *et al.*, 2021). This democratisation of environmental monitoring capability holds particular promise for data-scarce regions such as the Niger Delta.

#### **1.1.4 Temporal Context: 2020-2024**

The study period from 2020 to 2024 encompasses a particularly dynamic phase in Nigeria's environmental and economic history. The year 2020 marked the onset of the COVID-19 pandemic, which precipitated unprecedented restrictions on mobility, industrial activity, and economic operations (Halder *et al.*, 2023). This provided a unique natural experiment for observing how reduced anthropogenic activity influences atmospheric composition. The

subsequent years witnessed varying degrees of economic recovery, fluctuations in petroleum production levels, and evolving environmental regulatory approaches.

Furthermore, this timeframe corresponds with increased national and international attention to gas flaring reduction. The Nigerian government has periodically announced deadlines for ending routine flaring, whilst international pressure has mounted regarding climate change mitigation and the wastage of valuable energy resources (Mgbamena and Uzoma *et al.*, 2015). Examining pollutant trends across this period offers insights into whether such policy initiatives have achieved measurable atmospheric improvements.

## **1.2 Statement of the Problem**

Despite the well-documented health and environmental consequences of atmospheric pollution, systematic monitoring of air quality across Nigeria's Niger Delta remains critically deficient. The region has been subjected to gas flaring on an unprecedented scale, with estimates suggesting that flaring activities cost over US\$2.5 billion annually whilst the toxic emissions affect the health and livelihoods of Delta inhabitants. Moreover, investigations have revealed that carbon monoxide levels in ambient air reach concerning concentrations in many communities within the region.

Existing research examining air quality in Delta and Edo States suffers from several critical limitations. First, studies have typically been geographically constrained, focusing on isolated communities or individual pollution sources rather than providing comprehensive state-wide assessments (Ukpebor *et al.*, 2010). Second, temporal coverage has been limited, with most investigations representing snapshot assessments rather than continuous multi-year monitoring. Third, methodological approaches have often relied upon sporadic field sampling or low-resolution global models that fail to capture local-scale variations crucial for policy formulation.

The absence of continuous, high-resolution atmospheric data for these states impedes several critical functions: the precise identification of pollution hotspots requiring urgent intervention; the assessment of temporal trends to determine whether pollution is intensifying or abating; the evaluation of policy effectiveness, including gas flaring reduction initiatives; the establishment of baseline conditions against which future changes can be measured; and the provision of evidence for environmental health studies linking exposure to health outcomes (Okedere *et al.*, 2021).

According to Okechukwu, 2021, Understanding why unsustainable practices such as continuous gas flaring have persisted requires unravelling the dynamics of political influence that multinational corporations exert over natural resources management in developing countries. However, before political and regulatory solutions can be effectively designed and implemented, the fundamental empirical question must be addressed: what is the actual spatial distribution and temporal evolution of SO<sub>2</sub> and CO concentrations across Delta and Edo States?

The advent of Sentinel-5P satellite data since 2018, with particular reliability from 2020 onwards following instrument calibration refinements, presents an unprecedented opportunity to address these knowledge gaps through systematic remote sensing analysis.

### **1.3 Aim and Objectives**

#### **1.3.1 Aim**

This research aims to conduct a comprehensive spatio-temporal analysis of sulphur dioxide (SO<sub>2</sub>) and carbon monoxide (CO) concentrations over Delta and Edo States, Nigeria, utilising Sentinel-5P satellite remote sensing data for the period from January 2020 to December 2024.

#### **1.3.2 Specific Objectives**

To achieve this aim, the study pursues the following specific objectives:

1. To retrieve and pre-process Sentinel-5P Level-2 data products for SO<sub>2</sub> total column density and CO total column density over the study area, applying rigorous quality assurance protocols.
2. To generate annual, seasonal, and monthly spatial distribution maps of SO<sub>2</sub> and CO concentrations across Delta and Edo States, identifying pollution hotspots and their geographical characteristics.
3. To quantitatively analyse temporal trends in pollutant concentrations over the five-year study period, assessing whether concentrations are increasing, decreasing, or remaining stable.
4. To conduct comparative statistical analysis between Delta and Edo States to identify significant differences in emission profiles, pollutant concentrations, and temporal patterns.
5. To examine seasonal variations in SO<sub>2</sub> and CO concentrations, distinguishing between dry season (November-March) and wet season (April-October) patterns.
6. To correlate identified pollution hotspots with known emission sources, including gas flaring sites, industrial facilities, urban centres, and major transportation corridors.
7. To benchmark observed pollutant concentrations against World Health Organization air quality guidelines and Nigerian National Ambient Air Quality Standards to assess public health implications.
8. To provide evidence-based recommendations for environmental management, policy intervention, and future monitoring strategies.

#### **1.4 Research Questions**

This investigation addresses the following principal research questions:

1. What is the spatial distribution of SO<sub>2</sub> and CO concentrations across Delta and Edo States, and where are the primary pollution hotspots located?
2. How have SO<sub>2</sub> and CO concentrations changed temporally across the study period (2020-2024), and are there statistically significant trends?
3. Do significant differences exist between Delta and Edo States in terms of pollutant concentrations, spatial patterns, and temporal trends?
4. What seasonal variations characterise SO<sub>2</sub> and CO concentrations, and how do dry and wet seasons influence pollutant levels?
5. Can identified pollution hotspots be attributed to specific emission sources such as gas flaring operations, industrial facilities, or urban activities?
6. To what extent do observed pollutant concentrations exceed international and national air quality standards, and what are the implications for public health?

## **1.5 Justification and Significance of the Study**

This research addresses several critical knowledge gaps whilst offering practical applications for environmental management and public health protection in Nigeria's Niger Delta region.

### **1.5.1 Scientific Contributions**

From a scientific perspective, this study advances understanding in several domains. It provides the first comprehensive, multi-year satellite-based assessment of SO<sub>2</sub> and CO specifically for Delta and Edo States, filling a significant geographical gap in atmospheric composition research for West Africa (Yang *et al.*, 2022). The application of Sentinel-5P data for monitoring air quality enables spatial data collection, air quality modelling, hotspot identification, and source distribution analysis, which are crucial for understanding pollution dynamics (Enuneku *et al.*, 2025).

According to Ermida, 2020, the research contributes methodologically by demonstrating the application of advanced remote sensing analysis in a developing country context where ground-based monitoring infrastructure is limited. This serves as a model for similar assessments in other data-scarce regions globally.

Furthermore, the study develops and validates mathematical models for predicting gaseous pollutant concentrations, which can be employed for forecasting and scenario analysis in petroleum drilling and processing operations. Such predictive capabilities enable proactive rather than reactive environmental management.

### **1.5.2 Public Health Relevance**

The public health significance of this research cannot be overstated. Gas flaring contributes to respiratory illnesses, asthma, impaired lung function, and cancer, whilst also causing painful breathing, chronic bronchitis, decreased lung function, body itching, blindness, impotency, and premature death. Carbon monoxide exposure at high concentrations can lead to lung cancer, heart problems, respiratory conditions, and damage to other organs by reducing oxygen levels available to vital organs and tissues.

By providing detailed spatial mapping of pollutant concentrations, this study enables identification of communities facing the highest exposure risks, thereby informing targeted public health interventions. The temporal analysis reveals whether health risks are escalating or diminishing, guiding resource allocation for healthcare infrastructure and disease surveillance systems.

### **1.5.3 Environmental Management and Policy Applications**

For environmental regulators and policymakers, this research delivers actionable intelligence. The identification of pollution hotspots enables prioritisation of enforcement activities and focused deployment of ground-based monitoring equipment where it will yield maximum value (Okoduwa and Amaechi *et al.*, 2023). Constant monitoring of air quality and

atmospheric pollutants ensures early detection of decreases or increases in pollutant concentrations, whilst implementation of air pollution control policies can be guided by empirical evidence.

The investigation into gas flaring politics reveals that governmental weakness in asserting strength to control and reduce flaring, combined with political intrigues, has relegated the health and environmental wellbeing of Niger Delta inhabitants to the background. This study provides the empirical foundation necessary to challenge such political inertia with irrefutable evidence of environmental degradation.

The comparative analysis between Delta and Edo States offers insights into how different emission source profiles petroleum extraction versus mixed industrial and urban sources generate distinct pollution signatures. This understanding enables development of differentiated policy approaches appropriate to each state's specific circumstances.

#### **1.5.4 Alignment with Sustainable Development Goals**

This research directly supports achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being) and SDG 13 (Climate Action). By documenting atmospheric pollution that undermines public health, the study contributes evidence necessary for health-protective policies. By quantifying emissions of climate-relevant pollutants such as CO, which contributes to tropospheric ozone formation and indirectly influences climate, the research informs climate mitigation strategies.

The economic implications are also substantial, as Nigeria loses considerable funds by failing to capture and monetise flared gas whilst simultaneously bearing the costs of pollution-related health impacts. Evidence from this study can support arguments for alternative gas utilisation strategies that deliver both economic and environmental benefits.

#### **1.6 Scope and Limitations**

### **1.6.1 Geographical Scope**

The study is geographically confined to the administrative boundaries of Delta and Edo States within Nigeria's South-South geopolitical zone. Delta State encompasses approximately 17,698 square kilometers, whilst Edo State covers approximately 17,802 square kilometers (Ogunleye *et al.*, 2010). Together, these states represent a substantial portion of the Niger Delta region and provide contrasting emission source profiles suitable for comparative analysis.

### **1.6.2 Temporal Scope**

The temporal domain extends from 1 January 2020 to 31 December 2024, providing a five-year continuous monitoring period. This timeframe captures significant socio-economic variations, including pandemic-related disruptions, economic recovery phases, and evolving industrial activities, thereby enabling robust trend analysis.

### **1.6.3 Pollutant Scope**

The analysis focuses exclusively on two atmospheric pollutants:

1. **Sulphur Dioxide (SO<sub>2</sub>) Total Column Density** – measured in mol/m<sup>2</sup> and retrieved from Sentinel-5P TROPOMI Level-2 SO<sub>2</sub> products.
2. **Carbon Monoxide (CO) Total Column Density** – measured in mol/m<sup>2</sup> and retrieved from Sentinel-5P TROPOMI Level-2 CO products.

Whilst numerous other pollutants warrant attention, including nitrogen dioxide, particulate matter, ozone, and volatile organic compounds, resource constraints necessitate focusing on these two priority pollutants for which Sentinel-5P provides high-quality retrievals.

### **1.6.4 Methodological Scope and Limitations**

The research employs exclusively satellite remote sensing data from Sentinel-5P, processed using Google Earth Engine and Geographic Information System software. This approach offers several advantages, including comprehensive spatial coverage, consistent temporal

resolution, and freedom from the logistical constraints of ground-based sampling. However, several limitations must be acknowledged.

**Cloud Interference:** Tropical regions such as the Niger Delta experience frequent cloud cover, particularly during the wet season (Zhan and Kim *et al.*, 2020). Although quality assurance filters exclude cloud-contaminated pixels, this may result in reduced data availability for certain time periods or locations, potentially introducing bias toward clear-sky conditions.

**Vertical Sensitivity:** Satellite retrievals represent total column measurements, integrating pollutant concentrations throughout the atmospheric column. Near-surface concentrations, which are most relevant for human health exposure, cannot be directly isolated from these total column values. The relationship between column density and surface concentration depends on vertical mixing, boundary layer dynamics, and atmospheric stability factors that vary seasonally and spatially (Theys *et al.*, 2019).

**Validation Limitations:** The paucity of ground-based reference measurements within the study area precludes comprehensive validation of satellite retrievals against in-situ observations. Whilst Sentinel-5P products have been extensively validated globally, local validation specific to Delta and Edo States cannot be performed within this study's scope (Veefkind *et al.*, 2012).

**Spatial Resolution:** Although TROPOMI provides unprecedented spatial resolution for a satellite atmospheric sensor ( $3.5 \text{ km} \times 5.5 \text{ km}$ ), this remains coarse compared to ground-based point measurements. Consequently, highly localised pollution plumes or street-level concentration gradients within urban areas cannot be fully resolved.

**Temporal Aggregation:** To reduce noise and data gaps, daily observations are typically aggregated to monthly or seasonal means. This averaging process may obscure short-term

pollution episodes or diurnal variations, although it enhances the robustness of long-term trend analysis.

Despite these limitations, satellite remote sensing remains the most viable approach for achieving comprehensive spatio-temporal pollution assessment in the Niger Delta context, and careful data processing protocols mitigate many of these concerns.

## **CHAPTER TWO**

### **LITERATURE REVIEW**

#### **2.1 Introduction**

This chapter critically examines existing scholarly literature relevant to atmospheric pollution monitoring in Nigeria's Niger Delta, with particular emphasis on sulphur dioxide and carbon monoxide. The review is organised thematically, beginning with fundamental concepts of air pollution and its health impacts, progressing through specific characteristics of the pollutants under investigation, examining the Niger Delta's unique environmental context including gas flaring practices, evaluating remote sensing methodologies for atmospheric monitoring, reviewing previous studies utilising Sentinel-5P data, and concluding by identifying critical knowledge gaps that justify this research.

#### **2.2 Air Pollution: Definitions, Sources, and Impacts**

##### **2.2.1 Conceptual Framework**

Air pollution encompasses the introduction into the atmosphere of substances or energy forms that cause discomfort, disease, or environmental damage to humans and other living organisms (Saxena and Sonwani *et al.*, 2019). These contaminants, termed pollutants, may exist as gases, particulate matter, or biological molecules, and originate from diverse natural and anthropogenic sources.

The atmosphere serves as both a repository for emissions and a medium through which pollutants disperse, transform chemically, and ultimately deposit onto terrestrial and aquatic surfaces. Understanding pollution dynamics requires consideration of emission sources, atmospheric transport mechanisms, chemical transformation processes, deposition pathways, and exposure scenarios.

### 2.2.2 Classification of Air Pollutants

Air pollutants are conventionally classified as either primary or secondary. Primary pollutants are emitted directly from identifiable sources for example, sulphur dioxide from coal combustion or carbon monoxide from vehicular exhaust. Secondary pollutants form through atmospheric chemical reactions involving primary pollutants and naturally occurring atmospheric constituents for instance, ozone generated through photochemical reactions involving nitrogen oxides and volatile organic compounds, or sulphuric acid aerosols formed through oxidation of sulphur dioxide.

Pollutants may be further categorised by their physical state (gaseous versus particulate), chemical composition (inorganic versus organic), or environmental persistence (short-lived versus long-lived). Each classification system offers distinct analytical advantages for understanding pollution behaviour and impacts.

### 2.2.3 Major Sources of Atmospheric Pollution

Anthropogenic emission sources dominate contemporary atmospheric pollution, particularly in industrialised and urbanising regions. Key source categories include:

**Industrial Processes:** Manufacturing facilities, petroleum refineries, chemical plants, metallurgical operations, and mineral processing generate substantial emissions of SO<sub>2</sub>, nitrogen oxides, particulate matter, heavy metals, and volatile organic compounds. Gas processing plants emit common harmful gaseous pollutants into the atmosphere through continuous flaring, with pollutants including methane, ammonia, nitrogen dioxide, particulate matter, sulphur oxides, and volatile organic compounds.

**Energy Generation:** Coal-fired and oil-fired power stations represent major point sources of SO<sub>2</sub> and nitrogen oxides. Even natural gas combustion, whilst cleaner than coal, produces nitrogen oxides and releases uncombusted methane.

**Transportation:** The internal combustion engine constitutes a ubiquitous and diffuse pollution source. Vehicular emissions contribute substantially to urban CO, nitrogen oxide, particulate matter, and volatile organic compound burdens. Increasing vehicular usage over recent years has contributed to rising atmospheric pollutant concentrations, making vehicle emissions one of the biggest environmental and public health issues, particularly in developing nations.

**Residential and Commercial Combustion:** Domestic cooking and heating, particularly using solid fuels such as wood, charcoal, and coal, generates significant quantities of CO, particulate matter, and polycyclic aromatic hydrocarbons. This source category disproportionately affects indoor air quality in developing regions.

**Petroleum Extraction and Processing:** The Niger Delta's petroleum operations, involving large-scale combustion of gas through horizontal and vertical flares, generate consequential gaseous pollutants including methane, ammonia, nitrogen dioxide, particulate matter, sulphur oxides, and volatile organic compounds, all hazardous to humans, animals, and the total environment.

#### **2.2.4 Health Impacts of Air Pollution**

The health consequences of atmospheric pollution manifest across multiple physiological systems and temporal scales. Acute exposures to elevated pollutant concentrations trigger immediate health responses including respiratory irritation, exacerbation of pre-existing conditions such as asthma, cardiovascular stress, and in extreme cases, premature mortality. Chronic exposure to moderate pollution levels over years or decades contributes to development of cardiopulmonary diseases, cancer, cognitive decline, and reduced life expectancy.

The World Health Organization attributes millions of premature deaths annually to ambient air pollution exposure, with the burden concentrated in low- and middle-income countries

where pollution levels tend to be highest and healthcare systems least equipped to address pollution-related morbidity. Vulnerable populations including children, elderly individuals, pregnant women, and those with pre-existing health conditions face disproportionate risks.

Research has documented that thousands of people worldwide die each year due to heart and lung diseases resulting from air pollution, establishing atmospheric contamination as an extremely serious problem for the modern industrialised world. The economic costs encompass not only direct healthcare expenditures but also productivity losses from illness and premature mortality.

### **2.2.5 Environmental and Climate Impacts**

Beyond human health, air pollution inflicts substantial damage upon ecosystems and environmental systems. Acid deposition, resulting from atmospheric sulphur and nitrogen oxides, acidifies soils and freshwater systems, compromising terrestrial and aquatic biodiversity. Tropospheric ozone impairs photosynthesis and crop productivity. Particulate deposition alters albedo of snow and ice surfaces, accelerating melting. Atmospheric nitrogen deposition leads to eutrophication of sensitive ecosystems.

Several air pollutants also function as climate forcers. Carbon monoxide, whilst not itself a greenhouse gas, influences atmospheric hydroxyl radical concentrations, thereby affecting the lifetimes of methane and other climate-relevant species. Black carbon aerosols absorb solar radiation, contributing to regional warming. Conversely, sulphate aerosols exert a cooling effect through reflection of incoming solar radiation, partially offsetting greenhouse warming a complexity that complicates climate policy formulation.

## **2.3 Sulphur Dioxide: Properties, Sources, and Impacts**

### **2.3.1 Chemical and Physical Properties**

Sulphur dioxide (SO<sub>2</sub>) is a colourless gas characterised by a sharp, acrid odour detectable at concentrations as low as 0.5 parts per million. Its molecular structure (O=S=O) renders it highly reactive, readily participating in atmospheric oxidation reactions. SO<sub>2</sub> is moderately soluble in water, forming sulphurous acid (H<sub>2</sub>SO<sub>3</sub>), and undergoes photochemical oxidation to sulphur trioxide (SO<sub>3</sub>), which subsequently hydrates to sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) a key constituent of acid precipitation and secondary sulphate aerosols.

The atmospheric lifetime of SO<sub>2</sub> ranges from hours to several days, depending on meteorological conditions, oxidant availability, and surface characteristics. This intermediate lifetime enables SO<sub>2</sub> to be transported regionally whilst still maintaining elevated concentrations near emission sources, creating localised hotspots alongside broader regional impacts.

### **2.3.2 Emission Sources**

Anthropogenic SO<sub>2</sub> emissions arise predominantly from combustion of sulphur-containing fossil fuels. Coal combustion historically dominated global emissions, although stringent regulations in developed nations have substantially reduced this source. Petroleum combustion, particularly of residual fuel oils and diesel with high sulphur content, remains significant, especially in regions lacking fuel quality standards.

Within the Niger Delta context, gas flaring represents a major SO<sub>2</sub> source, as associated gas from oil extraction contains hydrogen sulphide and other sulphur compounds that oxidise to SO<sub>2</sub> during combustion. Industrial processes including petroleum refining, metal smelting (particularly non-ferrous metals), and sulphuric acid production also contribute substantially.

Natural sources, whilst globally significant, are typically episodic and localised. Volcanic eruptions inject massive quantities of SO<sub>2</sub> into the atmosphere, occasionally affecting stratospheric chemistry and regional climate. However, such events are infrequent and

geographically constrained, rendering anthropogenic sources dominant in most populated regions.

### **2.3.3 Health Effects of Sulphur Dioxide**

SO<sub>2</sub> exerts its primary health effects through irritation of the respiratory system. Upon inhalation, the gas dissolves in the moist mucous membranes of the nose, throat, and airways, forming sulphurous acid that triggers bronchoconstriction, particularly in individuals with asthma or other reactive airway diseases. Short-term exposures to elevated SO<sub>2</sub> concentrations provoke coughing, chest tightness, shortness of breath, and exacerbation of pre-existing cardiovascular and pulmonary conditions.

Epidemiological studies have established associations between ambient SO<sub>2</sub> concentrations and increased hospital admissions for respiratory and cardiovascular causes, emergency department visits, and mortality. Children, elderly individuals, and those with chronic obstructive pulmonary disease or asthma exhibit heightened susceptibility.

Beyond direct inhalation effects, SO<sub>2</sub> contributes to secondary particulate matter formation. Atmospheric oxidation generates sulphate aerosols (primarily ammonium sulphate and ammonium bisulphate), which constitute a major fraction of fine particulate matter (PM<sub>2.5</sub>). These aerosols penetrate deep into the respiratory system, reaching the alveolar regions of the lungs and entering the bloodstream, thereby mediating systemic cardiovascular and inflammatory effects.

### **2.3.4 Environmental Effects**

Sulphur dioxide in the ambient atmosphere undergoes chemical transformation to yield sulphuric acid, the fundamental constituent of acid deposition, which compromises vegetation health, diminishes soil and aquatic ecosystem pH, accelerates infrastructure corrosion, and

contributes to secondary sulphate aerosols that enhance particulate matter concentrations and regional atmospheric haze.

Acid deposition has caused documented damage to forests in Europe, North America, and Asia, with effects including foliar injury, nutrient leaching from soils, mobilisation of toxic metals such as aluminium, and acidification of lakes and streams. Although acid rain has declined in regions implementing emission controls, it remains a significant concern in rapidly industrialising areas lacking stringent regulations.

Sulphate aerosols scatter incoming solar radiation, reducing visibility and creating regional haze. This aesthetic impact diminishes quality of life and affects tourism in scenic areas. Furthermore, sulphate aerosols influence cloud properties and precipitation patterns, introducing additional complexity to regional climate dynamics.

## **2.4 Carbon Monoxide: Properties, Sources, and Impacts**

### **2.4.1 Chemical and Physical Properties**

Carbon monoxide (CO) is a colourless, odourless, tasteless gas produced through incomplete combustion of carbon-containing materials. Its molecular structure ( $C\equiv O$ ) features a strong triple bond, rendering it relatively stable in the lower atmosphere. The toxicity of CO derives from its ability to remain undetected, as victims may become ill or die before recognising exposure, with common indicators including headache, dizziness, fatigue, nausea, vomiting, and chest pain.

The atmospheric lifetime of CO averages one to two months, substantially longer than  $SO_2$ . This extended lifetime enables CO to serve as a tracer for combustion emissions and to be transported over continental scales. CO participates in atmospheric chemistry primarily through reaction with hydroxyl radicals (OH), representing the dominant sink for this

important oxidant and thereby influencing the atmospheric oxidising capacity that controls the lifetimes of methane and other greenhouse gases.

#### **2.4.2 Emission Sources**

Carbon monoxide is formed as a result of partial combustion of carbonaceous fuels such as wood, natural gas, petrol, and charcoal, resulting from both natural sources including volcanoes and biomass burning, and anthropogenic sources including automobile and industrial fossil fuel combustion.

Within urban environments, vehicular emissions typically dominate CO budgets. Petrol-powered vehicles with malfunctioning catalytic converters or operating under cold-start conditions emit particularly high CO quantities. Diesel engines, whilst producing less CO per unit fuel compared to petrol engines, contribute through sheer numbers in commercial transportation fleets.

In the Niger Delta, outdoor CO concentrations are characteristically controlled by biomass combustion activities for domestic cooking and heating, whilst forest fires and controlled burning of vegetation represent enormous sources. Gas flaring also contributes CO through incomplete combustion, particularly when flare systems are poorly maintained or operated inefficiently.

Indoor sources merit attention in developing regions where solid fuel combustion for cooking and heating occurs within poorly ventilated dwellings. Such practices generate extremely high indoor CO concentrations, posing severe health risks to household members, particularly women and children who spend considerable time near cooking areas.

#### **2.4.3 Health Effects of Carbon Monoxide**

The chief adverse effect of CO operates through its combination with haemoglobin to form carboxyhaemoglobin, which severely harms the blood circulatory system by decreasing the

blood's capacity to transport oxygen, potentially causing unconsciousness and death at high concentrations following either acute or chronic exposure.

CO binds to haemoglobin with approximately 240 times greater affinity than oxygen, displacing oxygen from binding sites and shifting the oxygen-haemoglobin dissociation curve, thereby impairing oxygen delivery to tissues even when some oxyhaemoglobin remains. The brain and heart, with their high metabolic oxygen demands, exhibit particular vulnerability to CO-induced hypoxia.

Effects of CO exposure differ significantly among individuals based on factors including age, general health status, and the concentration and duration of exposure, with impacts ranging from mild effects on the heart and nervous system at low concentrations to unconsciousness and death at high concentrations.

Chronic low-level CO exposure has been associated with subtle cardiovascular effects, including increased risk of atherosclerosis development. Pregnant women face particular concern, as foetal haemoglobin binds CO even more readily than adult haemoglobin, potentially compromising foetal development. Carbon monoxide poisoning during pregnancy has been linked to adverse birth outcomes including low birth weight and developmental impairments.

#### **2.4.4 Atmospheric Chemistry Role**

Beyond its direct health effects, CO plays a critical role in atmospheric chemistry as the primary sink for hydroxyl radicals (OH), the atmosphere's principal oxidising agent. Through the reaction  $\text{CO} + \text{OH} \rightarrow \text{CO}_2\text{H}$ , carbon monoxide consumption of OH radicals influences the atmospheric concentrations of numerous other species, most notably methane a potent greenhouse gas whose lifetime is controlled by OH oxidation.

In polluted environments where CO concentrations are elevated, the depletion of OH radicals can extend the lifetimes of methane and other reactive species, thereby amplifying their

climate and air quality impacts. This indirect effect means that CO emissions influence not only local air quality and human health but also contribute to broader regional and global atmospheric chemistry perturbations.

Furthermore, the oxidation of CO to CO<sub>2</sub> in the presence of nitrogen oxides contributes to tropospheric ozone formation through complex photochemical reaction sequences. Thus, CO functions as an ozone precursor, particularly in urban areas where nitrogen oxide concentrations are elevated due to vehicular emissions and industrial activities.

## **2.5 Air Pollution in the Niger Delta: Regional Context**

### **2.5.1 Geographical and Socio-Economic Characteristics**

The Niger Delta comprises approximately 70,000 square kilometres of coastal wetlands, mangrove forests, creeks, and rivers, spanning nine Nigerian states and hosting over 30 million inhabitants across more than 40 distinct ethnic groups. This region, whilst occupying merely 7.5% of Nigeria's land mass, contains the nation's principal petroleum reserves assets that have simultaneously generated immense wealth and precipitated extensive environmental degradation.

Nigeria flares 180 billion cubic metres of natural gas per year in relation to crude oil exploration in the Niger Delta, expending huge amounts of energy whilst causing environmental pollution, degradation, and disease prone to climate change with substantial implications for development and economic gains. The region's economy remains heavily dependent upon hydrocarbon extraction, with relatively limited diversification into other productive sectors despite decades of oil revenues.

Delta State, created in 1991, serves as the epicentre of Nigeria's petroleum production activities. The state hosts numerous flow stations, processing facilities, and export terminals, with particularly intensive activities around Warri, Ughelli, Sapele, and offshore operations.

The Ughelli West gas processing plant, operational for many years with an installed capacity of 90 million standard cubic feet per day, exemplifies the scale of industrial infrastructure within the state.

Edo State, situated immediately north of Delta State, presents a more diversified economic profile whilst remaining within the broader Niger Delta environmental zone. The state capital, Benin City, constitutes a major urban centre with a population exceeding one million, generating substantial vehicular and commercial emissions. Major industrial facilities include cement manufacturing plants at Okpene, which represent significant point sources of particulate matter, nitrogen oxides, and SO<sub>2</sub>. Agricultural activities, including palm oil production and timber harvesting, also contribute to the state's economy whilst generating biomass burning emissions.

### **2.5.2 Petroleum Operations and Gas Flaring**

Oil production has been ongoing in Nigeria for more than 56 years together with the flaring of natural gas, yet the devastation of this waste gas has rarely been brought to the fore, with perpetrators and allies shielded in a political paradigm of primitive accumulation and interest aggregation. Understanding this unsustainable practice requires unravelling the dynamics of political influence that multinational corporations exert over natural resources management.

Gas flaring represents the controlled combustion of associated natural gas that emerges alongside crude oil during extraction. When gas cannot be economically captured, processed, or transported often due to lack of infrastructure, unfavourable economics, or regulatory leniency it is burned at the wellhead or flow station. Within the Niger Delta, comprising Abia, Akwa-Ibom, Cross River, Edo, Imo, Delta, Rivers, Ondo, and Bayelsa states, nowhere in the world have communities been subjected to gas flaring on such a scale, with an estimated cost of volume of gas worth over US\$2.5 billion annually whilst the roaring toxic flares affect the health and livelihood of Delta inhabitants.

The environmental consequences of continuous flaring are multifaceted and severe. Gas flaring contributes significantly to climate change and affects communities globally, with Nigeria's per capita GNP lower than at independence despite rising political instability an appalling waste of resources for a country relying heavily on a mono-economic index.

Flaring operations emit a complex mixture of pollutants. The rate of gas flaring in the Niger Delta and emissions contributes significantly to global warming, composed of toxic gases such as sulphur oxide (SO<sub>2</sub>), nitrogen oxide (NO<sub>2</sub>), benzopyrene, toluene, xylene, and hydrogen sulphide (H<sub>2</sub>S) amongst others, thereby imposing negative effects on the environment and people.

The spatial distribution of flaring activities concentrates in Delta State's oil-producing areas. Investigation of six gas flaring sites located in communities including Ebocha-Egbema, Oboma, Rumuekpe, Patani, Bomadi, and Okpoloma revealed that these communities experience direct effects with varying degrees of severity, ranging from high to serious to potentially increasing risks if not checked and controlled.

### **2.5.3 Health and Environmental Impacts in the Niger Delta**

The health burden associated with atmospheric pollution in the Niger Delta has been documented through various studies, although comprehensive epidemiological research remains limited. Gas flaring increases the risk of respiratory illnesses, asthma, impaired lung function, and cancer, often causing painful breathing, chronic bronchitis, decreased lung function, body itching, blindness, impotency, and premature death amongst residents.

Field investigations have revealed specific manifestations of these health impacts. At Ebocha-Egbema General Hospital, patients expressed fury over the effects of gas flaring, with observations of poor vision, mortality and morbidity, cough, and skin diseases among younger inhabitants health problems blamed grossly on oil production activities, with gas flaring as a by-product. These health problems manifest across generations, with the grave

implication that the region may experience high incidences of disabilities among children, with devastating deformities potentially affecting one per every family, ranging from epidemics of asthma, cancer, lung goiter, chronic bronchitis, premature deaths, stunt growth, skin burns, coarse skin, stillbirth, and abnormalities in conception due to inhaled or consumed CO<sub>2</sub> and other health hazard ailments.

Environmental degradation extends beyond human health to encompass agricultural and aquatic systems. Investigation revealed that economic trees, crops, and plants are greatly affected, with petroleum production rendering lands unproductive, poisoning waters and forests, and making the environment generally inhabitable in the Niger Delta. Specific documented impacts include the untimely death of coconut trees due to gas flaring, indicating awful damage on communities studied.

Farm animals including goats, grasscutters, sheep, poultry, and birds are seriously infected by viruses and inhaled diseases in affected communities. Aquatic ecosystems face similarly severe impacts, as fishing, the only means of livelihood for many communities, has been greatly affected by pollutants from gas flaring which kill fishes and other economic aquatic life in water and streams, with water contamination affecting fish populations and fishermen who rely on fishing to support their families.

#### **2.5.4 Socio-Political Dimensions**

The persistence of gas flaring and associated pollution despite documented harms reflects complex political-economic dynamics. The internationalization of oil business and the concomitant drive for oil wealth by both friends and foes of Nigeria with connivance of elites set the stage for effective actions central to possible devastation, pollution, ecocide, kleptocracy, gas flaring, environmental degradation, and human rights abuses, with some multinational corporations implicated as being anti-human in operation and co-habitation.

The political intrigues show lack of sincerity in managing the situation posed by flaring, with the menace seen as baseless, economic sabotage, and treasonable crime against the Nigerian state since federal government by law owns all land and its resources, contributing to consistent restiveness and aggressive orientations among helpless, jobless, hopeless, and confused youths of the region.

Regulatory frameworks exist but suffer from inadequate enforcement. A bill proposed by a private person in 2000 to checkmate nefarious activities of oil companies was blocked by government agents who benefit from oil companies, with the government's weakness in asserting strength to control and reduce gas flaring relegating the health, life span, and environment of well-being Nigerians to the background.

Oil producing companies jointly attacked proposed policy legislation as technically infeasible, arguing that accelerating the flare programme is unrealistic, knowing it is national policy and not private, whilst the Nigerian government, probably due to what they gain from oil firms through its agents, remains misinformed and uncommitted to solving the problem of gas flaring.

This governance failure has profound implications. The failure to monitor and control all oil business activities creates an atmosphere where gas flaring sites turn the atmosphere into black clouds daily with several emissions, raising reasonable questions about whether Nigeria has any effective government, suggesting that oil exploration and exploitation processes have been mismanaged with present detrimental effects on host communities.

## **2.6 Remote Sensing for Air Quality Monitoring**

### **2.6.1 Principles of Satellite Remote Sensing**

Satellite remote sensing provides a transformative approach to atmospheric composition monitoring, enabling synoptic observations across vast geographical areas with consistent

temporal coverage. The fundamental principle involves measuring electromagnetic radiation either reflected solar radiation or emitted terrestrial radiation at specific wavelengths where atmospheric constituents exhibit characteristic absorption or emission features.

Different pollutants interact with electromagnetic radiation at distinct wavelengths, enabling selective detection. Ultraviolet and visible wavelengths prove particularly valuable for detecting SO<sub>2</sub>, nitrogen dioxide, ozone, and aerosols through absorption spectroscopy. Near-infrared and thermal infrared wavelengths enable CO detection through absorption of terrestrial radiation emitted from Earth's surface and lower atmosphere.

The mathematical relationship between measured radiance and atmospheric composition involves radiative transfer equations that account for solar illumination, atmospheric scattering and absorption, surface reflection, and instrument characteristics. Retrieval algorithms invert these equations, deriving pollutant concentrations (typically as vertical column densities) from measured radiances.

### **2.6.2 Advantages Over Ground-Based Monitoring**

Satellite observations offer several critical advantages compared to conventional ground-based monitoring networks. Most importantly, they provide spatially continuous coverage, eliminating the geographical gaps inherent in sparse station networks. This proves particularly valuable in regions such as the Niger Delta where establishing and maintaining ground stations faces logistical, security, and financial challenges.

Temporal consistency represents another key advantage. Satellites in sun-synchronous orbits overpass each location at approximately the same local time daily, providing consistent temporal sampling. This regularity facilitates trend detection and inter-comparison across different time periods without confounding effects from varying measurement times.

Cost-effectiveness emerges when comparing the expense of establishing and operating ground networks versus utilising freely available satellite data. Whilst satellite missions

require substantial initial investment, once operational they provide data for entire continents or globally without marginal costs for additional locations.

Satellite observations are particularly effective for identifying pollution hotspots and characterising regional-scale plumes from major emission sources. The bird's-eye perspective reveals spatial patterns invisible from ground-level measurements, enabling source attribution and emission inventory validation.

### **2.6.3 Limitations and Challenges**

Despite substantial advantages, satellite remote sensing faces inherent limitations that must be acknowledged. Cloud interference poses the primary challenge, particularly in tropical regions with frequent cloud cover. Clouds obscure the surface and lower atmosphere, preventing retrieval of pollutant concentrations. Although quality assurance procedures filter cloud-contaminated observations, this reduces data availability and may introduce bias toward clear-sky conditions.

Vertical resolution limitations arise because satellites typically measure total atmospheric columns rather than surface concentrations. Relating column measurements to surface exposure requires assumptions about vertical mixing and pollutant profiles, introducing uncertainty. Whilst near-surface pollution sources such as gas flaring and traffic emissions tend to produce elevated boundary layer concentrations that dominate the column signal, stratospheric contributions and free tropospheric background concentrations add complexity.

Spatial resolution, though improving with each satellite generation, remains coarse compared to ground measurements. The Sentinel-5P TROPOMI instrument provides  $3.5 \text{ km} \times 5.5 \text{ km}$  resolution unprecedented for atmospheric composition monitoring but still insufficient to resolve street-level gradients or individual small emission sources.

Temporal resolution varies among satellites. Geostationary satellites provide continuous observations over fixed geographical regions but with coarser spatial resolution. Sun-

synchronous polar-orbiting satellites like Sentinel-5P achieve finer spatial resolution but observe each location only once daily at a fixed local time, missing diurnal variations.

Retrieval accuracy depends on numerous factors including surface reflectance properties, aerosol characteristics, cloud contamination, and a priori assumptions about vertical profiles. Systematic errors can arise from these factors, necessitating careful validation against ground-based reference measurements.

#### **2.6.4 Previous Applications in African Contexts**

Satellite remote sensing has been increasingly applied to air quality assessment across Africa, revealing concerning pollution levels in many regions. Recent research has shown that air pollution is one of the world's greatest concerns both in developed and developing countries, with the World Health Organization identifying air pollution as one of the utmost environmental threats to health defined as the discharge of pollutants into the atmosphere with negative effects on health and well-being of humans and the planet.

Several studies have focused on West African regions. Research examining atmospheric composition over Nigerian cities has documented elevated concentrations of nitrogen dioxide and particulate matter linked to vehicular emissions, biomass burning, and industrial activities. Studies of Saharan dust transport have revealed how natural aerosol sources combine with anthropogenic pollution to create complex air quality scenarios across West Africa.

Air pollution has several impacts including the formation of acid rain, smog, ozone depletion, and global warming, seriously affecting the natural biocomplex network and ecosystems as a whole. Remote sensing has proven instrumental in documenting these phenomena across Africa's diverse environmental contexts.

Specific applications relevant to this study include investigations of biomass burning emissions using satellite fire detection and aerosol products, assessments of megacity

pollution using nitrogen dioxide and aerosol observations, and validation exercises comparing satellite retrievals with sparse ground-based measurements. These studies have collectively demonstrated both the utility and challenges of satellite monitoring in African contexts characterised by data scarcity, complex emission mixtures, and limited validation infrastructure.

## **2.7 The Sentinel-5P Mission and TROPOMI Instrument**

### **2.7.1 Mission Overview and Objectives**

The Copernicus Sentinel-5 Precursor mission, launched by the European Space Agency in October 2017, represents a dedicated atmospheric composition monitoring satellite specifically designed to bridge the gap between previous missions (SCIAMACHY, OMI) and the planned Sentinel-5 instrument to be hosted on future MetOp Second Generation satellites. As the "precursor" designation indicates, Sentinel-5P serves both operational monitoring functions and technology demonstration for subsequent systems.

The satellite operates in a sun-synchronous polar orbit at approximately 824 kilometres altitude, achieving global coverage daily with an equatorial overpass time near 13:30 local solar time. This afternoon timing proves advantageous for tropospheric pollution monitoring, as boundary layer mixing typically reaches its daily maximum, lifting surface emissions to altitudes where satellite sensitivity is greatest.

The singular payload, the TROPOspheric Monitoring Instrument (TROPOMI), constitutes a passive grating imaging spectrometer measuring backscattered solar radiation in ultraviolet, visible, near-infrared, and shortwave infrared wavelength bands. This broad spectral coverage enables simultaneous retrieval of multiple atmospheric constituents including ozone, nitrogen dioxide, sulphur dioxide, carbon monoxide, formaldehyde, methane, and aerosols.

### **2.7.2 TROPOMI Technical Specifications**

TROPOMI achieves unprecedented spatial resolution for a satellite atmospheric sensor, providing  $3.5 \text{ km} \times 5.5 \text{ km}$  ground pixel size (along-track  $\times$  across-track) since August 2019, following an upgrade from the initial  $7 \text{ km} \times 3.5 \text{ km}$  configuration. This resolution enhancement dramatically improved the instrument's capability to detect localised pollution sources and resolve spatial gradients in pollutant concentrations.

The swath width of 2600 kilometres enables daily global coverage, with observations acquired across four separate spectrometer modules:

- **Ultraviolet (UV) band:** 270-495 nm, enabling ozone,  $\text{SO}_2$ , and aerosol retrieval
- **Visible (VIS) band:** 405-500 nm, supporting nitrogen dioxide retrieval
- **Near-infrared (NIR) band:** 675-775 nm, enabling CO and methane retrieval
- **Shortwave infrared (SWIR) band:** 2305-2385 nm, providing CO and methane retrieval

Spectral resolution varies by band, optimised for the absorption features of target species. The UV band achieves 0.5 nm resolution, whilst the SWIR band achieves 0.25 nm sufficient to resolve individual absorption lines and enable accurate retrieval.

Signal-to-noise ratios exceed requirements across all bands, enabling detection of trace atmospheric constituents even at relatively low concentrations. Radiometric calibration accuracy meets stringent specifications, with on-board calibration systems ensuring long-term stability essential for trend detection.

### **2.7.3 Sulphur Dioxide Retrieval Algorithm**

Formaldehyde ( $\text{HCHO}$ ) is a significant trace gas in the atmosphere and a valuable indicator of biogenic, pyrogenic, and anthropogenic hydrocarbon emanations, being an intermediate product of the oxidation of massive amounts of nonmethane volatile organic compounds.  $\text{SO}_2$  retrieval employs similar spectral analysis principles.

TROPOMI's SO<sub>2</sub> retrieval utilises Differential Optical Absorption Spectroscopy (DOAS) applied to backscattered ultraviolet radiances in the 310-326 nm spectral window. The algorithm identifies the characteristic absorption signatures of SO<sub>2</sub>, distinguishing them from interfering species including ozone and the Ring effect (inelastic rotational Raman scattering). The retrieval produces slant column densities, the integrated concentration along the average photon path through the atmosphere. Converting slant columns to vertical columns requires an Air Mass Factor (AMF) that accounts for viewing geometry, solar zenith angle, surface reflectance, clouds, and the assumed vertical distribution of SO<sub>2</sub>.

For anthropogenic SO<sub>2</sub> sources such as gas flaring, emissions occur near the surface and typically remain within the boundary layer. The algorithm therefore assumes a boundary layer profile (SO<sub>2</sub> confined below approximately 1 kilometre altitude) when calculating AMFs for pollution monitoring. Alternative retrievals assuming volcanic SO<sub>2</sub> profiles (elevated plumes at 5-15 km altitude) are provided for detecting volcanic eruptions but prove inappropriate for boundary layer pollution assessment.

Quality assurance value filters accompany SO<sub>2</sub> data products, indicating retrieval confidence based on cloud fraction, surface albedo, solar zenith angle, and algorithm convergence. Research applications typically apply  $qa\_value > 0.5$  or  $0.75$  thresholds to retain only high-quality retrievals.

#### **2.7.4 Carbon Monoxide Retrieval Algorithm**

TROPOMI's CO retrieval exploits near-infrared absorption features around 2.3 micrometres wavelength, where CO exhibits strong overtone absorption bands whilst water vapour interference remains manageable. The SWIR spectrometer measures backscattered solar radiation modulated by atmospheric absorption.

The retrieval algorithm employs the Shortwave Infrared CO Retrieval (SICOR) scheme, a profile-scaling approach that adjusts an a priori CO vertical profile to match observed

radiances. The algorithm accounts for surface elevation, temperature, water vapour interference, and instrument characteristics through radiative transfer modelling.

CO vertical column densities represent the total atmospheric CO burden integrated from surface to top-of-atmosphere. Near-surface sensitivity proves somewhat limited in the SWIR, as photons penetrating deep into the atmosphere experience increased scattering and absorption before returning to the satellite. Consequently, TROPOMI CO retrievals exhibit greatest sensitivity in the mid-to-lower troposphere (approximately 2-6 km altitude) with reduced sensitivity near the surface and in the boundary layer.

Nevertheless, major emission sources such as biomass burning, gas flaring, and urban traffic generate sufficiently strong signals to be detected, particularly when enhanced CO mixes vertically through boundary layer turbulence. Time-averaged observations (monthly or seasonal means) reduce noise and enhance signal detection for persistent sources.

Quality flags similar to those for SO<sub>2</sub> indicate retrieval confidence, with cloud contamination, surface properties, and retrieval uncertainty metrics guiding data filtering. Recommended qa\_value thresholds for CO are typically 0.5 or higher, balancing data retention with quality assurance.

### **2.7.5 Validation and Uncertainty Assessment**

Extensive validation campaigns have been conducted since Sentinel-5P's launch, comparing TROPOMI retrievals with ground-based remote sensing measurements (such as Fourier Transform Spectrometers in networks including TCCON and NDACC), aircraft campaigns, and in-situ measurements. These validation studies have generally confirmed TROPOMI's high data quality and consistency with reference measurements.

For SO<sub>2</sub>, validation exercises demonstrate excellent detection capability for strong point sources (power plants, smelters, volcanic emissions) whilst acknowledging higher uncertainty

for diffuse low-concentration conditions. Systematic errors of 10-30% are typical, depending on assumptions about vertical profiles and surface reflectance.

CO validation reveals good agreement with ground-based total column measurements, with biases generally below 10% and random errors around 10-15%. The reduced near-surface sensitivity mentioned previously does not substantially compromise detection of major emission sources, as demonstrated through successful identification of biomass burning plumes and urban pollution.

An important validation consideration for this study is the paucity of ground-based reference measurements in Nigeria. Without local validation data, uncertainties must be inferred from validation conducted in other regions—an imperfect approach given potential regional differences in atmospheric conditions, aerosol properties, and surface characteristics. Nevertheless, the fundamental physics of the retrievals and global validation results provide confidence in data quality.

## **2.8 Previous Studies Using Sentinel-5P Data**

### **2.8.1 Global and Regional Applications**

Since becoming operational, Sentinel-5P data have been extensively utilised for air quality research globally. Studies have documented nitrogen dioxide reductions during COVID-19 lockdowns in major cities worldwide, tracked transboundary pollution transport, validated emission inventories, and assessed policy effectiveness.

A study monitoring the trends of carbon monoxide and tropospheric formaldehyde in Edo State using Sentinel-5P and Google Earth Engine from 2018 to 2023 found that annual mean concentrations of CO ranged from  $4.67 \times 10^{-2}$  mol/m<sup>2</sup> to  $5.34 \times 10^{-2}$  mol/m<sup>2</sup>, with the maximum concentration in 2018 and minimum in 2023. This pioneering Nigerian application demonstrates the viability of Sentinel-5P for regional air quality assessment.

The same study found that annual mean concentrations of HCHO ranged from  $1.89 \times 10^{-4}$  mol/m<sup>2</sup> to  $2.18 \times 10^{-4}$  mol/m<sup>2</sup>, with maximum concentration in 2021 and minimum in 2019, with increasing HCHO concentration potentially due to biomass burning and methane combustion.

European studies have utilised TROPOMI SO<sub>2</sub> data to monitor power plant emissions, assess compliance with emission regulations, and track reductions following fuel quality improvements or facility closures. The high spatial resolution enables attribution of observed concentrations to specific industrial facilities, supporting targeted enforcement actions.

Applications in Asia, particularly China and India, have revealed severe SO<sub>2</sub> and nitrogen dioxide pollution affecting hundreds of millions of people. Time-series analyses have documented both improvements in some regions following emission controls and deteriorations in others experiencing rapid industrialisation. These studies demonstrate the value of continuous satellite monitoring for tracking air quality trajectories.

### **2.8.2 Methodological Approaches**

Common methodological approaches in Sentinel-5P studies include temporal aggregation (monthly, seasonal, annual means) to reduce noise and data gaps; spatial averaging over administrative boundaries or emission source regions; quality assurance filtering based on qa\_values and cloud fraction; trend analysis using statistical tests such as Mann-Kendall; and comparison with emission inventories or dispersion models.

The Edo State study applied rigorous quality assurance filters to minimise data deficiencies from cloud cover and sensor noise, processing data annually with filterDate parameters spanning each calendar year, and classifying analysed data into three classes: 'Low', 'Medium', and 'High'.

Google Earth Engine has emerged as the preferred platform for processing large Sentinel-5P datasets, offering cloud-based computation that eliminates the need for local data storage and

processing infrastructure. Google Earth Engine, a cloud computing platform with significant computational competencies released in 2010, was developed to store and process vast datasets (at the petabyte-scale) for analysis and decisive decision-making, offering unrestricted cloud-based computational commands for geospatial data inquiry.

Studies typically begin by defining areas of interest (AOIs), filtering data temporally and spatially, applying quality flags, computing statistics (mean, median, standard deviation), generating time-series plots, and producing spatial maps. Advanced analyses may include correlation with meteorological variables, comparison with socio-economic indicators, or integration with health data.

### **2.8.3 Applications in Nigeria and West Africa**

Applications of Sentinel-5P specifically within Nigeria remain relatively limited but growing. The 2025 study by Enuneku and colleagues represents the first detailed examination of CO and formaldehyde in Edo State, establishing baseline understanding and demonstrating methodological approaches applicable to other Nigerian regions.

This research concluded that constant monitoring of air quality and atmospheric pollutants to ensure early detection of decreases or increases in pollutant concentrations, implementation of air pollution control policies, spatial data collection, air quality modelling, hotspot identification, and source distribution using geographic information systems (GIS) are highly recommended, alongside promotion of cleaner technologies including low-emission vehicles and renewable energy sources, and public awareness and education on atmospheric pollutant impacts.

Regional studies covering West Africa more broadly have focused primarily on biomass burning, Saharan dust transport, and megacity pollution in Lagos. These studies have documented seasonal patterns linked to agricultural burning cycles, meteorological conditions,

and urban growth. However, systematic examination of industrial pollution sources, particularly petroleum sector emissions, remains underexplored.

The present study aims to build upon and extend these initial Nigerian applications by conducting the first comparative multi-year analysis specifically focused on SO<sub>2</sub> and CO across both Delta and Edo States, thereby filling a critical knowledge gap regarding petroleum industry emission impacts.

## **2.9 Gas Flaring: Environmental and Health Dimensions**

### **2.9.1 The Practice and Scale of Gas Flaring in Nigeria**

Oil production has been ongoing in Nigeria for more than 56 years together with the flaring of natural gas, but unfortunately, the devastation of this waste gas has rarely been brought to the fore, with reasons being that perpetrators and allies have been shielded in a political paradigm of primitive accumulation and interest aggregation.

The scale of flaring in Nigeria has historically ranked among the world's highest. Global Gas Flaring Reduction partnership data consistently position Nigeria among the top gas-flaring nations alongside Russia, Iraq, Iran, and the United States. However, Nigeria's flaring proves particularly wasteful relative to total gas production a higher proportion of produced gas is flared rather than captured for beneficial use compared to other major producers.

Equating flaring to an estimated 66% of people living below the poverty line who are sufferers of environmental degradations and diseases puts the country at high risk of being under severances and disaster-prone state, with flaring contributing significantly to climate change whilst Nigeria's per capita GNP remains lower than at independence with rising political instability an appalling waste of resources for a country relying heavily on a mono-economic index.

### **2.9.2 Emissions Composition from Gas Flares**

Gas flaring generates a complex mixture of combustion products whose composition depends on the associated gas composition, flare efficiency, and operational conditions. Emissions composed of toxic gases such as sulphur oxide (SO<sub>2</sub>), nitrogen oxide (NO<sub>2</sub>), benzopyrene, toluene, xylene, and hydrogen sulphide (H<sub>2</sub>S) impose negative effects on the environment and people.

Complete combustion would theoretically produce only carbon dioxide and water vapour. However, real-world flares operate with variable efficiency, particularly when poorly maintained or during periods of high gas flow. Incomplete combustion generates CO, particulate matter (black carbon/soot), and unburned hydrocarbons including volatile organic compounds.

Hydrogen sulphide (H<sub>2</sub>S) present in associated gas oxidises to SO<sub>2</sub> during flaring. Nigerian crude oils vary in sulphur content, but many fields produce sour gas with significant H<sub>2</sub>S concentrations, translating to substantial SO<sub>2</sub> emissions when flared. Nitrogen oxides form through thermal fixation of atmospheric nitrogen at high flame temperatures, with production rates increasing with flame temperature and residence time.

The characteristic orange-red colour of many flares indicates incomplete combustion and particulate emission. Efficient flares with proper air-to-fuel ratios produce nearly invisible flames, whilst visible sooty flames signal substantial black carbon emissions. Many Niger Delta flares exhibit visible smoke plumes, particularly evident at night, indicating substantial particulate emissions.

### **2.9.3 Near-Field Impacts on Local Communities**

Investigation of gas flaring sites at Ebocha-Egbema, Oboma, Rumuekpe, Patani, Bomadi, and Okpoloma revealed that high concentrations of gaseous pollutants covered substantial areas

with varying percentages, with areas including Benin City, Ekehuan, Okomu, and Agbarha identified as being at distance from main roads or garages or industrial shacks.

Communities immediately adjacent to flare sites experience multiple direct impacts beyond atmospheric pollution. Investigation revealed that gas flaring effects on health show that the incident is at high degree in some communities, crossing the benchmark of degree of seriousness, whilst other communities showed degrees of seriousness or near seriousness, with tendency to increase if not controlled.

Intense heat radiation from flares affects nearby structures, vegetation, and human comfort. Night-time illumination disrupts circadian rhythms and traditional activities. The constant roar from large flares generates noise pollution affecting sleep and communication. Beyond these immediate nuisances, the health implications prove most concerning.

Gas flaring increases the risk of respiratory illnesses, asthma, impaired lung function, and cancer, often causing painful breathing, chronic bronchitis, decreased lung function, body itching, blindness, impotency, and premature death, with hospital observations revealing poor vision, mortality and morbidity, cough, and skin diseases among younger inhabitants problems blamed grossly on oil production activities with gas flaring as a by-product.

Health effects also cause reduction in life expectancy, adverse birth outcomes, and perpetual black cloud in the environment. The cumulative burden of daily exposure over years or decades compounds these acute effects into chronic conditions affecting entire populations.

#### **2.9.4 Broader Regional and Global Impacts**

Beyond local communities, gas flaring contributes to regional air quality degradation and global climate change. Higher concentrations of CO may lead to formation of carboxyhaemoglobin which decreases the blood's capacity to transport oxygen, causing lung

cancer, heart problems, respiratory conditions, and damage to other organs, whilst at high HCHO concentrations there is risk of nasopharyngeal cancer in humans.

The climate implications merit particular attention. Gas flaring contributes significantly to climate change, and with Nigeria relying heavily on mono-economic indices, it represents an appalling waste of resources the country cannot afford. Carbon dioxide emissions from flaring contribute directly to greenhouse gas accumulation. Black carbon particles, whilst having atmospheric lifetimes of only days to weeks, exert potent warming effects through solar radiation absorption.

Methane slip uncombusted methane escaping from flares represents another climate concern. Methane is a powerful greenhouse gas with approximately 28 times the global warming potential of carbon dioxide over a century timescale. Even small percentages of methane escaping combustion contribute substantially to climate forcing.

Ozone precursor emissions (CO, nitrogen oxides, volatile organic compounds) from flaring contribute to tropospheric ozone formation downwind, affecting air quality across broader regions beyond immediate flare vicinity. The regional transport of these emissions means that pollution impacts extend far beyond the immediate source areas.

## **CHAPTER THREE**

### **METHODOLOGY**

#### **3.1 Research Design**

This study adopted a quantitative research design utilizing remote sensing and geospatial analytical techniques to assess the spatio temporal distribution of sulfur dioxide (SO<sub>2</sub>) and carbon monoxide (CO) emissions across Edo and Delta States between 2020 and 2023. The design integrates satellite based data acquisition using Sentinel 5P TROPOMI instruments with geostatistical analysis to evaluate pollutant variations over time and space.

The research is structured into four key phases: data collection, data preprocessing, spatial analysis, and interpretation. This design was chosen for its ability to handle large datasets while minimizing field measurement limitations, which are common in Nigeria due to insufficient ground monitoring networks (MDPI, 2023). The analytical framework combines remote sensing outputs with statistical tools in ArcGIS and Google Earth Engine (GEE) for comprehensive visualization and interpretation.

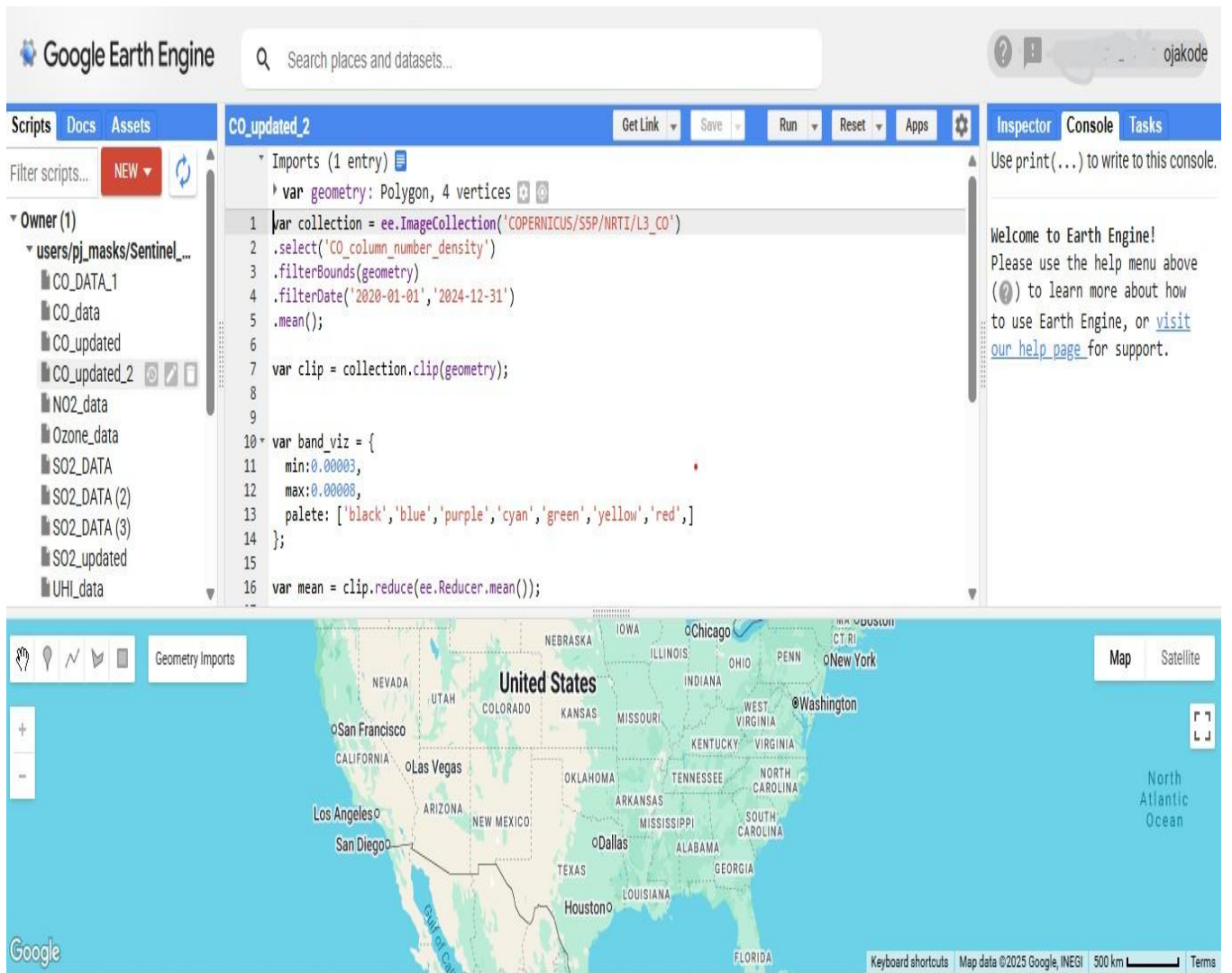
#### **3.2 Description of the Study Area**

The study area comprises Edo and Delta States, located in the South–South geopolitical zone of Nigeria. These two states are among the most industrialized in the Niger Delta region, characterized by oil and gas activities, cement production, and increasing urbanization.

Edo State lies between latitudes 6°30'N and 7°45'N and longitudes 5°00'E and 6°45'E, covering an approximate area of 17,802 km<sup>2</sup>. The state is bordered by Kogi to the northeast, Delta to the south, and Ondo to the west. Its capital, Benin City, is a major urban centre with dense traffic, industrial zones, and power generation facilities, particularly in Ologbo and Egba Okpella.

Delta State, positioned between latitudes 5°00'N and 6°30'N and longitudes 5°00'E and 6°45'E, occupies about 17,698 km<sup>2</sup>. It shares boundaries with Edo to the north, Bayelsa to the south, and Anambra to the east. The state hosts extensive oil exploration and production activities, especially in Warri, Sapele, and Udu, where gas flaring remains a major environmental challenge (Donwa, Mgbame, and Utomwen *et al.*, 2015).

The two states lie within the humid tropical climate zone, characterized by a wet season (April–October) and a dry season (November–March), with annual rainfall ranging from 1,500 mm to 2,500 mm and average temperatures of 26°C–32°C (SO<sub>2</sub> PDF2, 2023). Vegetation types range from mangrove forests in Delta's coastal areas to derived savanna in northern Edo. The combination of industrial activities, high population density, and limited environmental regulation makes both states ideal for examining air quality trends.



**Plate 3.1:** Image processes of extracting data from Google Earth Engine



### 3.3 Data Sources and Acquisition

This study utilized secondary datasets primarily obtained from the Sentinel 5 Precursor (Sentinel 5P) TROPOMI sensor, accessible via the Copernicus Open Access Hub. Sentinel 5P provides daily global observations of atmospheric pollutants, including SO<sub>2</sub> and CO, at high spatial resolution ( $\sim 3.5 \times 5.5 \text{ km}^2$ ) (Veefkind, de Haan, & Vlemmix, 2012).

The following datasets were acquired:

1. **Sulfur Dioxide (SO<sub>2</sub>):** Sentinel 5P Level 2 Vertical Column Density (VCD) product (mol/m<sup>2</sup>).
2. **Carbon Monoxide (CO):** Sentinel 5P Level 2 Total Column product (mol/m<sup>2</sup>).
3. **Ancillary Data:** shapefiles of Edo and Delta administrative boundaries from the Office of the Surveyor General of the Federation (OSGOF) and land use datasets from Google Earth Engine (GEE).
4. **Meteorological Data:** wind speed, rainfall, and temperature records from the Nigerian Meteorological Agency (NiMET) to interpret dispersion patterns.

All data covered the period January 2020 to December 2023. Cloud contaminated pixels were excluded using a Quality Assurance (QA) threshold  $> 0.75$  to ensure reliability. The cleaned datasets were aggregated into monthly and seasonal averages to identify emission trends and hotspots.

### 3.4 Data Processing and Analysis Workflow

The data processing workflow followed five main stages:

1. **Data Retrieval:** Sentinel 5P datasets were downloaded via the Copernicus platform using GEE scripts.
2. **Quality Filtering:** QA values below 0.75 were removed to eliminate cloud interference and unreliable retrievals.

3. **Spatial Clipping:** The datasets were clipped to Edo and Delta State boundaries using ArcGIS 10.8.
4. **Temporal Averaging:** Monthly, seasonal, and annual composites were generated for 2020–2023.
5. **Mapping and Visualization:** Heatmaps, trend graphs, and anomaly maps were produced to illustrate spatial distribution patterns.

Post processing involved calculating temporal mean concentrations and standard deviations to quantify variability. Spatial interpolation techniques such as Inverse Distance Weighting (IDW) and Kriging were applied to visualize the spatial spread of pollutants. These techniques allowed the estimation of unmonitored areas and identification of emission hotspots.

### 3.5 Analytical Techniques

The following analytical techniques were adopted:

1. **Descriptive Statistics:** Used to summarize pollutant concentrations and identify seasonal variations.
2. **Trend Analysis:** The Mann Kendall test was employed to assess the significance of temporal trends between 2020 and 2023.
3. **Hotspot Analysis:** The Getis Ord  $G_i^*$  statistic in ArcGIS identified significant clustering of high emission zones ( $p < 0.05$ ).
4. **Correlation Analysis:** Examined relationships between  $SO_2$  and CO concentrations with meteorological parameters such as wind speed and temperature.
5. **Comparative Assessment:** Pollutant levels were compared between Edo and Delta States to evaluate industrial versus urban emission patterns.

The combined use of remote sensing and geostatistical tools ensures reliable, reproducible, and policy relevant results, supporting Nigeria's environmental management strategies (MDPI, 2023).

### **3.6 Ethical Considerations**

This research relied exclusively on publicly accessible satellite and meteorological datasets. Ethical approval was not required since no human or animal subjects were involved. However, the study adhered to principles of academic integrity, transparency, and data privacy, ensuring that all sources were properly acknowledged. The Sentinel 5P datasets used are licensed under the Copernicus Open Data Policy, allowing free access and scientific reuse (Sentinel 5 Docs, 2022).

Acknowledgment is given to the European Space Agency (ESA) and Copernicus Programme for providing open access data essential for environmental research in regions with limited monitoring infrastructure.

### **3.7 Limitations of the Study**

Despite the robustness of remote sensing technology, several limitations affected this study:

1. **Cloud Interference:** Persistent cloud cover during the wet season occasionally obscured satellite measurements, creating data gaps.
2. **Lack of Ground Validation:** Absence of continuous air quality monitoring stations in Edo and Delta States limited direct validation of satellite derived values.
3. **Spatial Averaging Effects:** Aggregated data may underrepresent micro scale variations in highly localized emission zones such as industrial estates.
4. **Meteorological Variability:** Wind and rainfall fluctuations may have influenced dispersion patterns differently across years.

## CHAPTER FOUR

### RESULTS

#### 4.0 Introduction

This chapter presents the findings obtained from Sentinel 5P TROPOMI satellite imagery collected over Delta and Edo States between January 2020 – December 2024. The analysis focuses on the Spatial and Temporal variations and the Yearly trends of Carbon Monoxide (CO) and Sulphur Dioxide (SO<sub>2</sub>) emissions. These pollutants serve as key indicators of industrial activities such as petroleum exploration, combustion, and gas flaring all of which are defining features of the Niger Delta region.

The results are illustrated through a series of maps (refers to Figures 4.1, 4.2, 4.3, 4.4, 4.5, 4.7, 4.8, 4.9, 4.10, 4.11), annual histograms (Figures 4.16 and 4.12), and comparative tables that highlight the changing distribution of both pollutants during the study period.

#### 4.1 Carbon Monoxide (CO) Emissions (2020–2024)

Carbon Monoxide is primarily released through incomplete combustion. Within the study area, major contributors include vehicular traffic, domestic biomass burning, and gas flaring associated with crude oil production (Fagbeja *et al.*, 2008). The distribution and trends of CO across Delta and Edo States are illustrated through annual maps and an overall trend chart.

##### 4.1.1 Spatial and Temporal Distribution of CO

The spatial analysis of CO concentrations shows that the main emission hotspots have remained relatively consistent throughout the five year period. In 2020 (refer to Figure 4.1), the highest CO concentrations were recorded in specific parts of Delta State, likely due to the presence of industrial facilities and gas flare sites. A similar pattern

persisted in 2021 and 2022 (refer to Figures 4.2 and 4.3), although the emission zones appeared to widen, particularly along key transport routes linking the two states. Data from 2023 and 2024 (refer to Figures 4.4 and 4.5) reveal that CO levels remained elevated, with the most persistent hotspots located in the major oil producing areas of Delta State. This indicates that combustion related activities in the region continued at a significant rate.

#### **4.1.2 Annual Trend in CO Concentration**

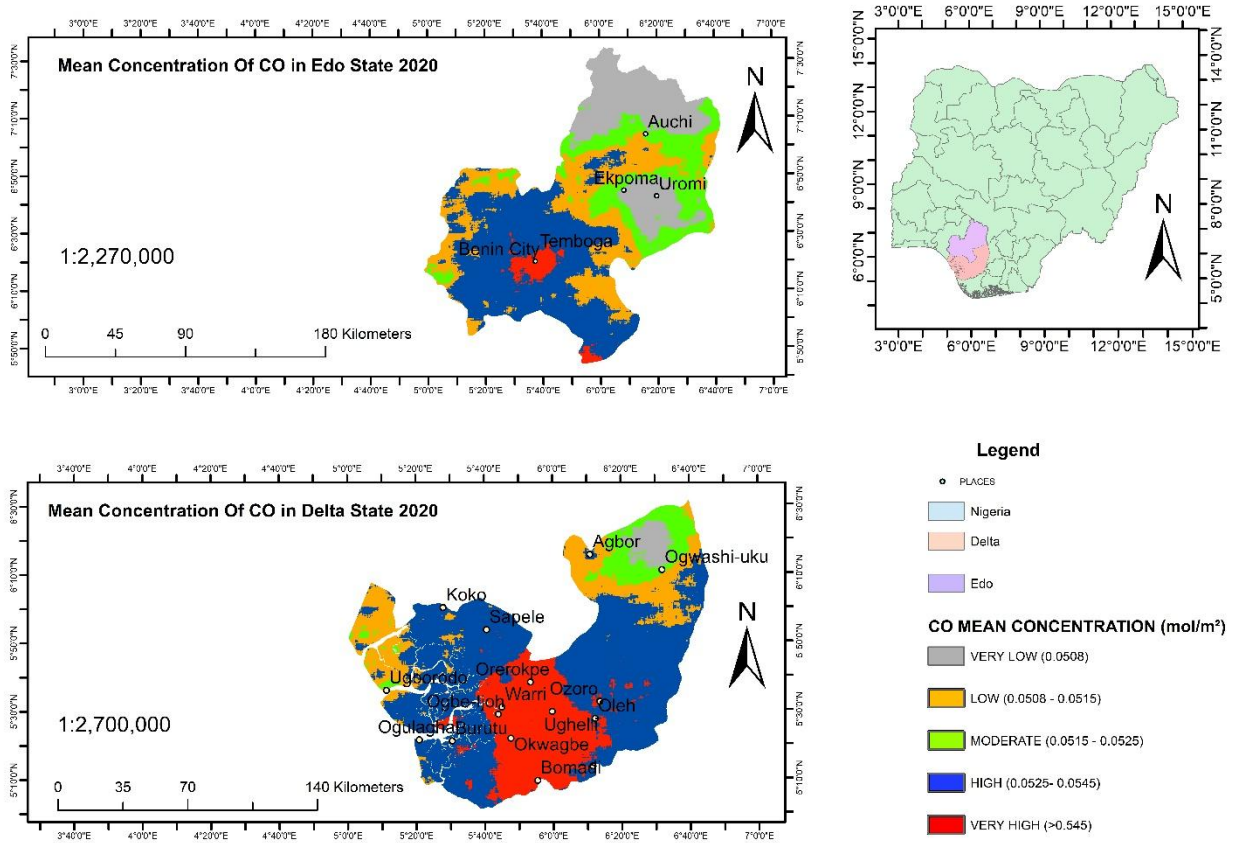
The annual trend, presented in Figure 4.11, indicates a steady increase in average CO column density between 2020 and 2023, followed by a slight decline in 2024. Mean values rose from approximately  $(5.0 \times 10^5)$  mol/m<sup>2</sup> in 2020 to a peak of  $(6.2 \times 10^5)$  mol/m<sup>2</sup> in 2023.

This upward pattern is likely connected to the post pandemic recovery of industrial production and transport activities following the economic slowdown caused by COVID 19.

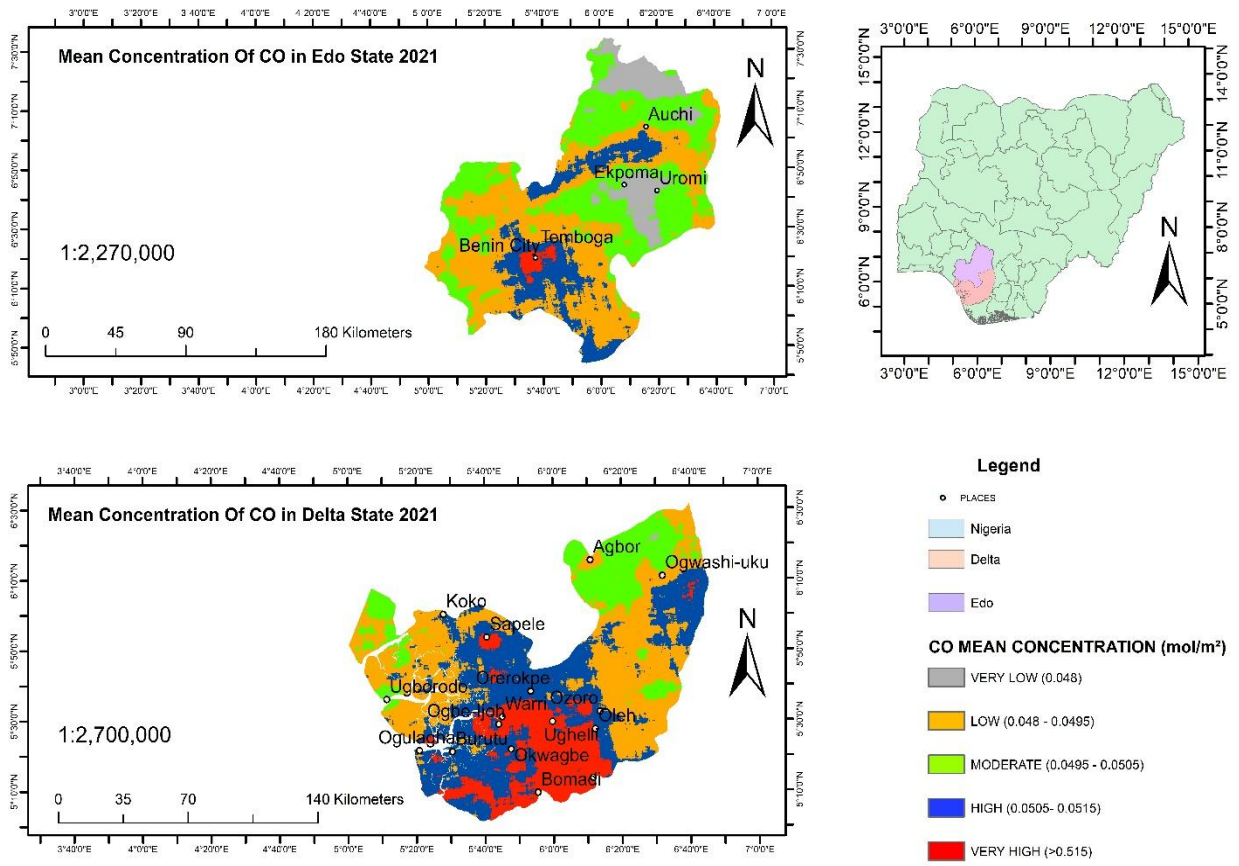
The small decrease observed in 2024 may reflect temporary stabilization

or a minor reduction in combustion intensity during the early part of the year.

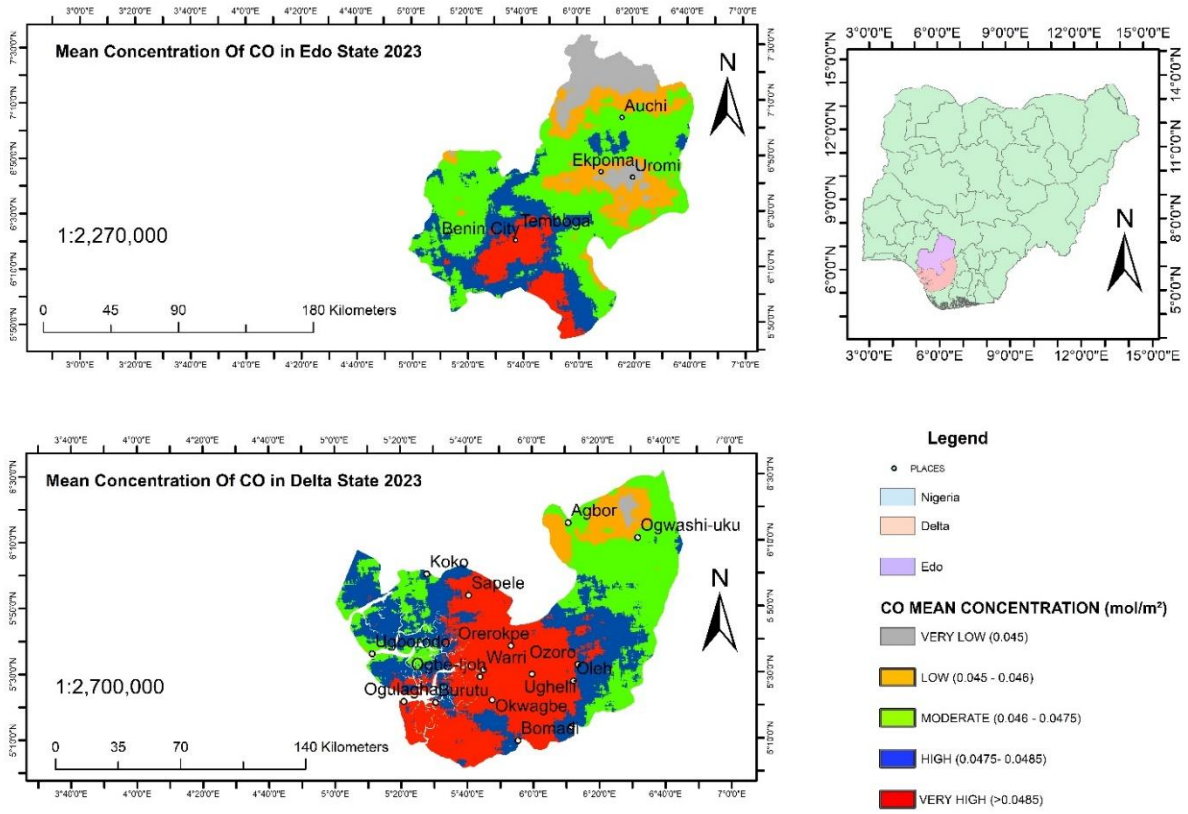
A dual bar histogram comparing yearly mean CO and SO<sub>2</sub> concentrations across the study period. CO concentrations show a gradual rise until 2023 before slightly reducing in 2024.



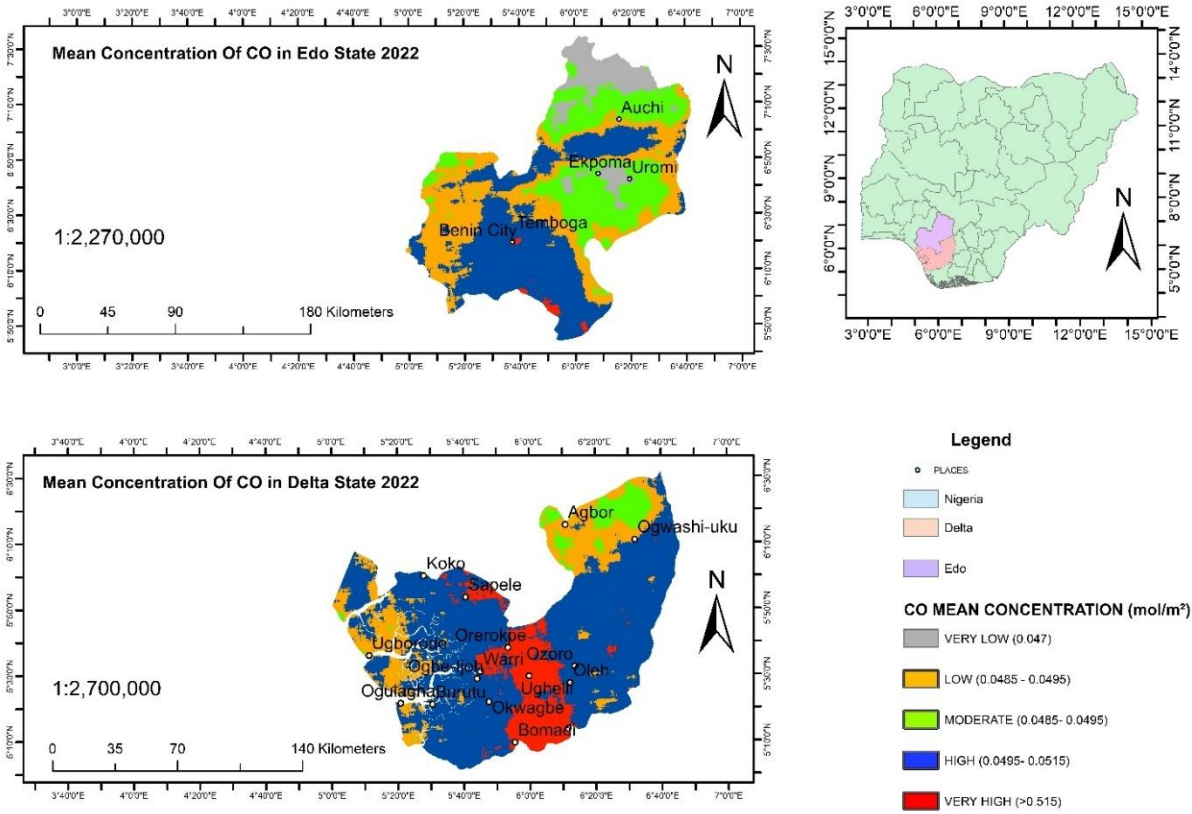
**Figure 4.1:** Illustrates the concentration of CO in Edo and Delta states in 2020.



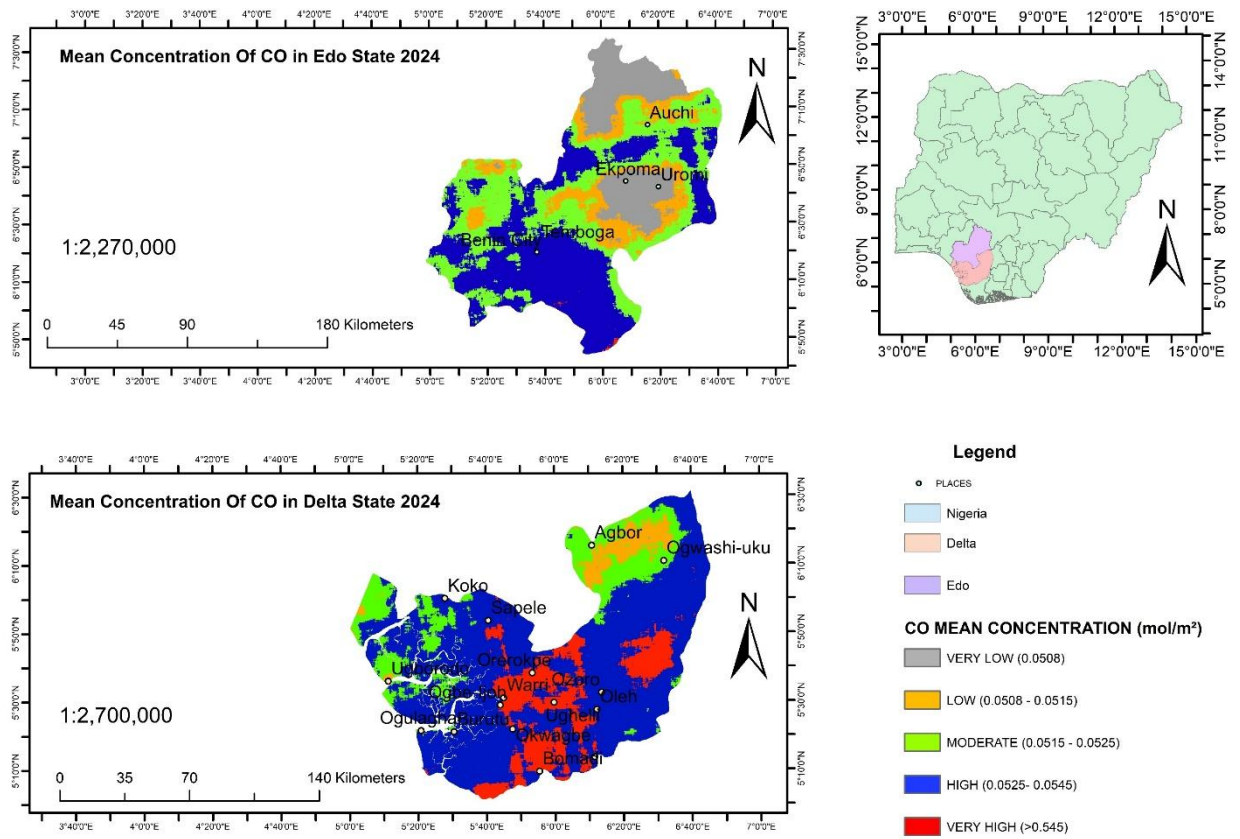
**Figure 4.2:** Illustrates the concentration of CO in Edo and Delta states in 2021.



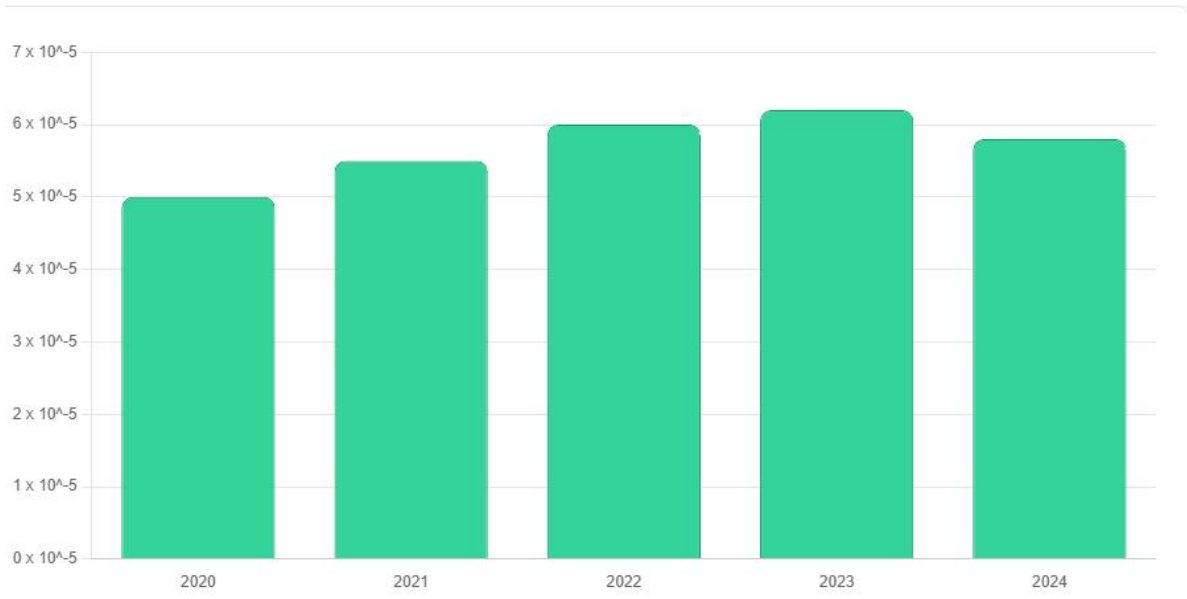
**Figure 4.3:** Illustrates the concentration of CO in Edo and Delta states in 2022.



**Figure 4.4:** Illustrates the concentration of CO in Edo and Delta states in 2023.



**Figure 4.5:** Illustrates the concentration of CO in Edo and Delta states in 2024.



**Figure 4.6:** Histogram showing annual mean CO concentrations (2020–2024).

## **4.2 Sulphur Dioxide (SO<sub>2</sub>) Emissions (2020–2024)**

Sulphur Dioxide is another major pollutant, produced mainly from the combustion of sulphur rich fuels, particularly during gas flaring and refinery operations. Since Delta and Edo States are important parts of Nigeria’s oil producing belt, SO<sub>2</sub> serves as a useful indicator of petroleum related activities within the region.

### **4.2.1 Temporal Trend of SO<sub>2</sub> Concentrations**

Table 4.1 summarises the annual variation of SO<sub>2</sub> concentration levels across both Edo and Delta States between 2020 and 2024, alongside key observations drawn from satellite data interpretation

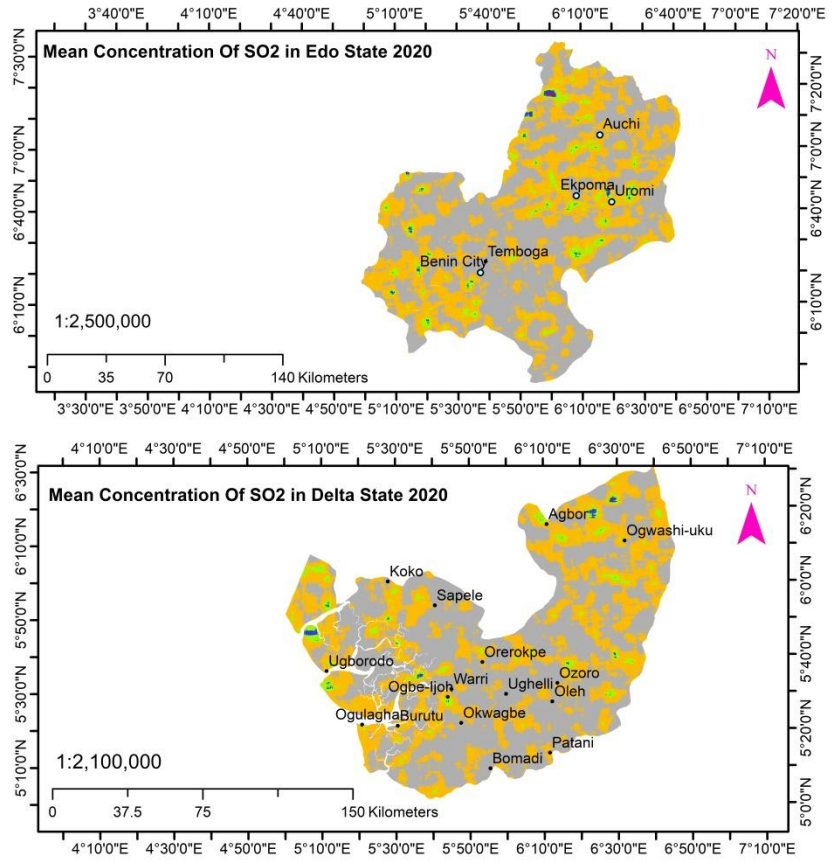
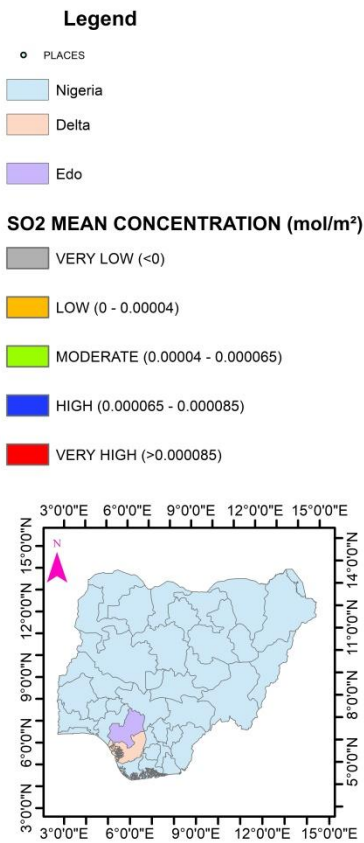
**Table 4.1:** Annual Summary of SO<sub>2</sub> Concentrations across Edo and Delta States (2020–2024)

<b>Year</b>	<b>Edo State Dominant Concentration</b>	<b>Delta State Dominant Concentration</b>	<b>Noteworthy Observations</b>
<b>2020</b>	Predominantly Low	Predominantly Low	Minimal presence of high or very high concentrations in either state.
<b>2021</b>	Predominantly Low	Predominantly Low	The overall pattern remained stable and low across both states.
<b>2022</b>	Predominantly Low	Introduction of High/Very High spots	Distinct pockets of high (0.000065–0.000085) and very high (>0.000085) concentrations emerged, particularly in the central and southern parts of Delta State.
<b>2023</b>	Emergence of Very High spots	Predominantly Low	A noticeable increase in very high SO <sub>2</sub> levels was recorded in eastern and northern Edo State (around Auchi and Ekpoma), indicating new or intensified local emission sources.
<b>2024</b>	Reduction of Very High spots	Return to Low concentrations	A clear decline of high concentration zones observed in 2023, with Delta State’s concentrations returning to pre 2022 low levels.

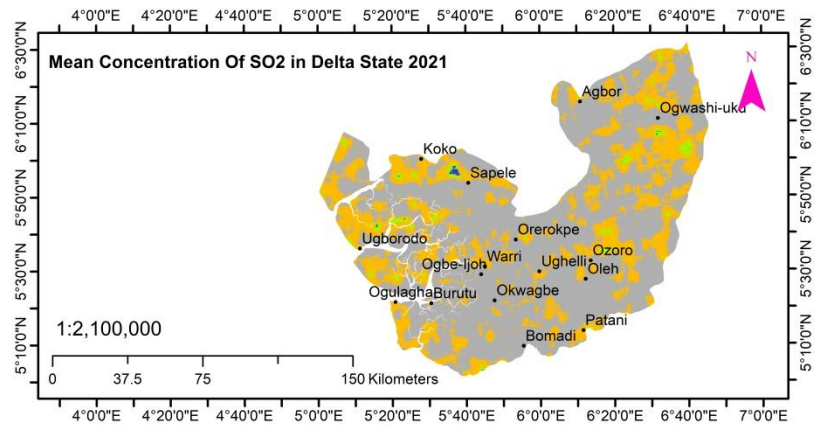
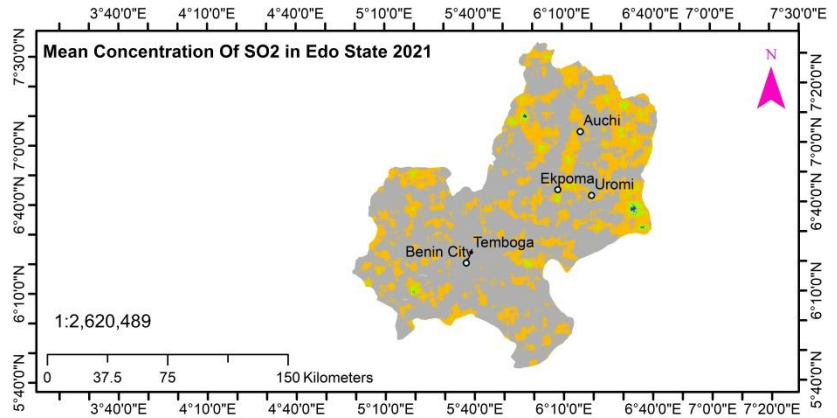
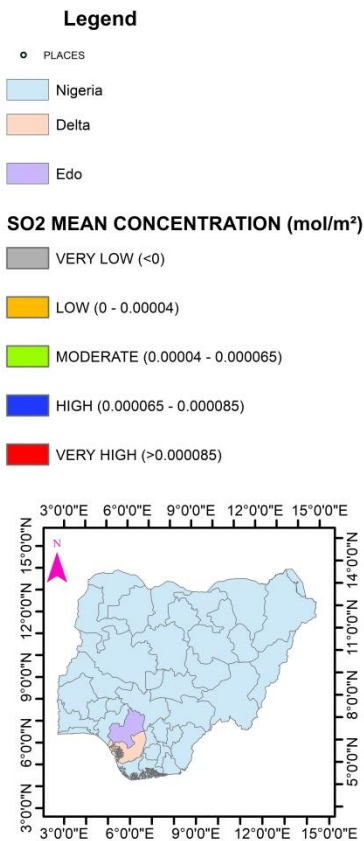
#### 4.2.2 Spatial Distribution of SO<sub>2</sub>

Spatial mapping revealed that while SO<sub>2</sub> emissions were not widespread, certain localised hotspots persisted.

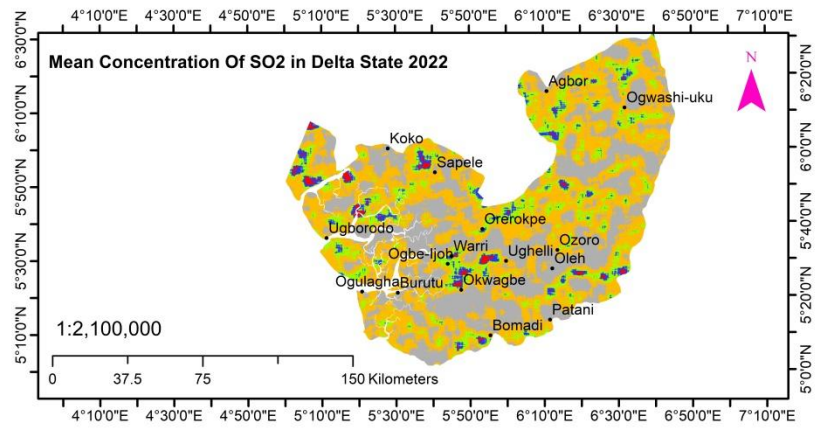
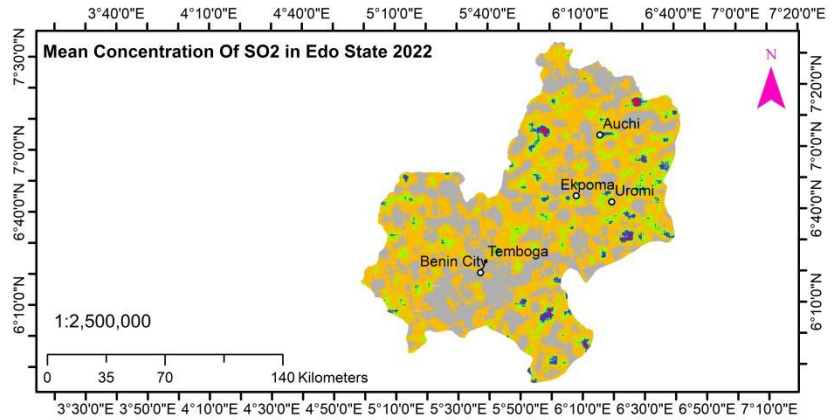
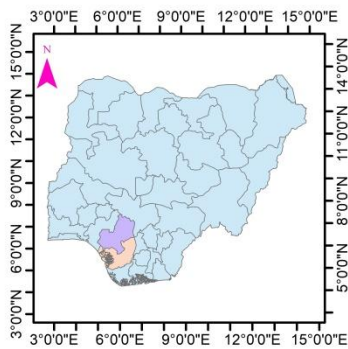
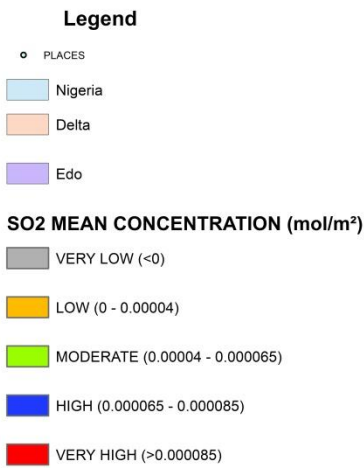
- **Edo State:** The most notable increase was in 2023, centred in the north eastern region, especially around Auchi and Ekpoma, suggesting potential industrial or energy related activity.
- **Delta State:** A brief surge in 2022 showed several high to very high concentration clusters, particularly in the petroleum producing central and southern areas such as Warri and Bomadi. These zones returned to low concentration levels by 2023 and 2024, indicating a short lived but significant flaring or refining event.



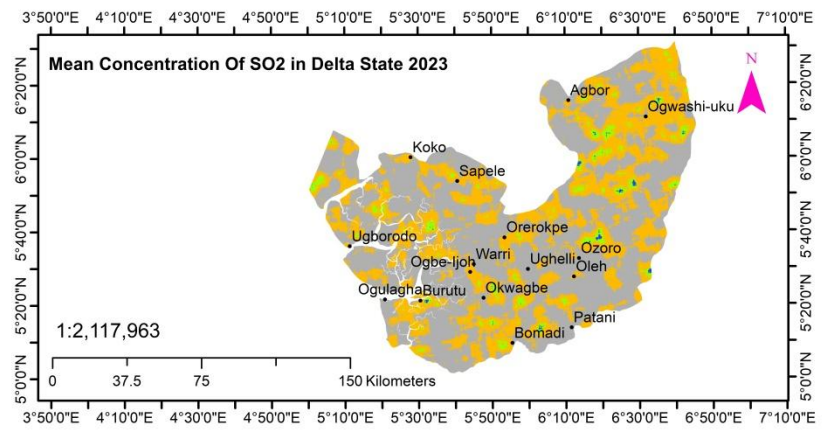
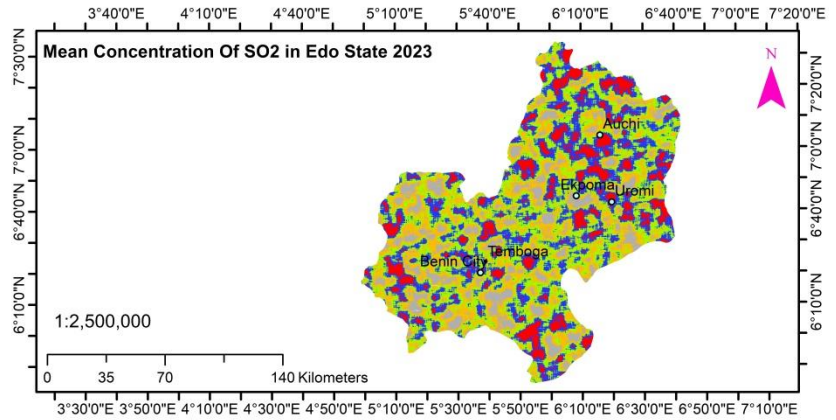
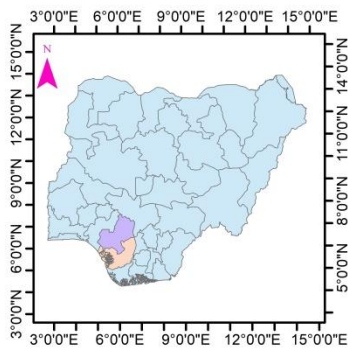
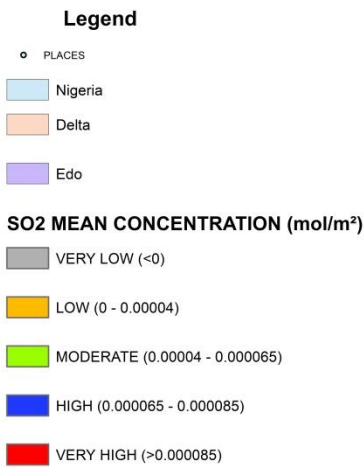
**Figure 4.7:** Illustrates the concentration of SO<sub>2</sub> in Edo and Delta states in 2020.



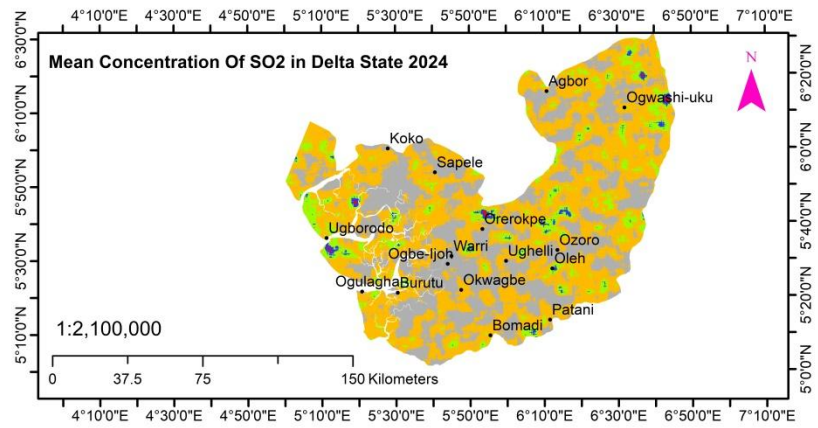
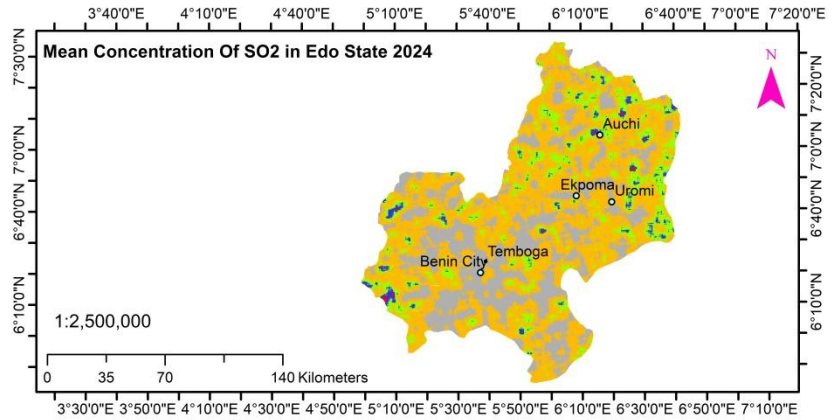
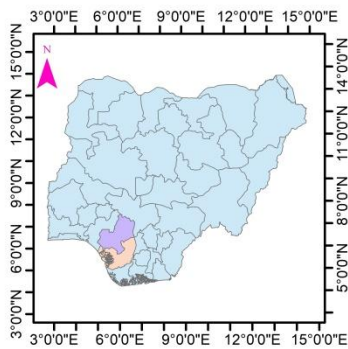
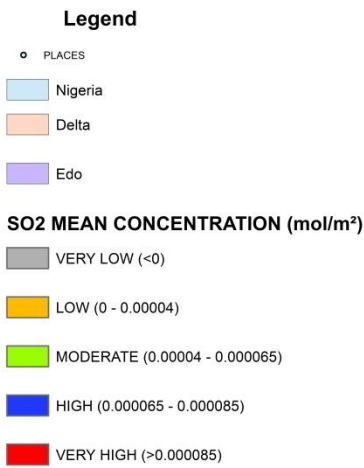
**Figure 4.8:** Illustrates the concentration of SO<sub>2</sub> in Edo and Delta states in 2021.



**Figure 4.9:** Illustrates the concentration of SO<sub>2</sub> in Edo and Delta states in 2022.

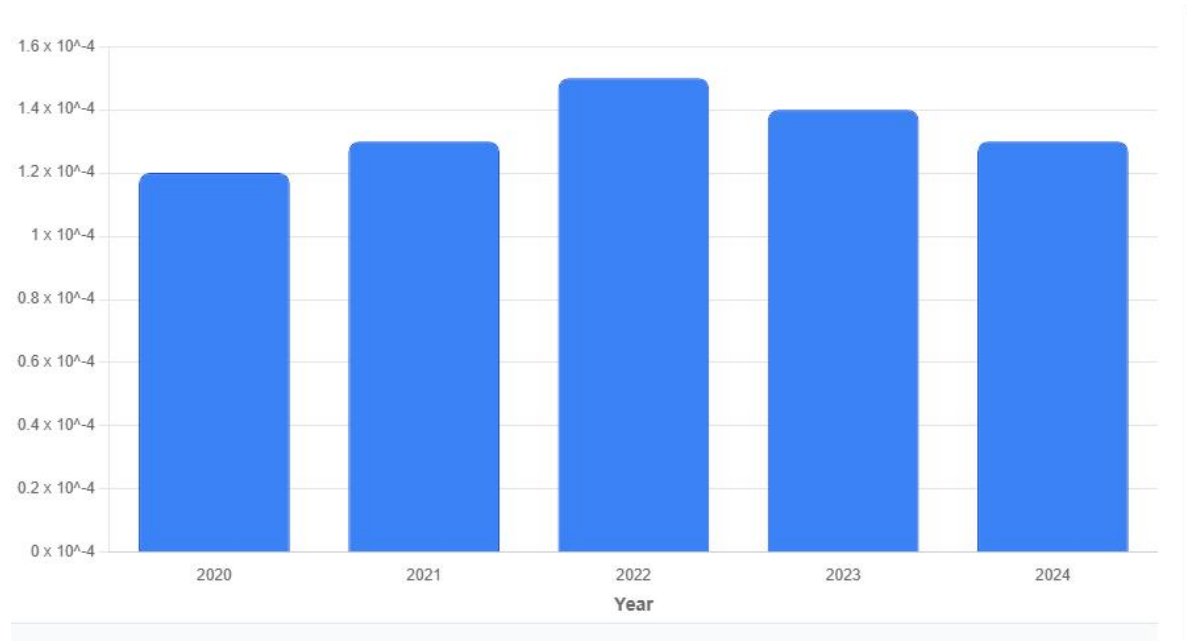


**Figure 4.10:** Illustrates the concentration of SO<sub>2</sub> in Edo and Delta states in 2023.



**Figure 4.11:** Illustrates the concentration of SO<sub>2</sub> in Edo and Delta states in 2024.

The histogram shows a sharp increase peaking in 2022, followed by a gradual reduction through 2023 and 2024, aligning with observed hotspot reduction.



**Figure 4.12:** Histogram of annual SO<sub>2</sub> concentrations (2020–2024).

### 4.3 Comparative Analysis of CO and SO<sub>2</sub> Emissions

When the two pollutants are compared, clear differences in their distribution patterns emerge. CO emissions are widespread across the study area, indicating multiple diffuse sources such as transport, domestic fuel use, and small scale combustion, in addition to industrial activities. SO<sub>2</sub> emissions, by contrast, are limited to concentrated plumes typical of single point industrial sources.

This comparison supports existing research showing that CO mainly arises from incomplete combustion across many small scale sources, while SO<sub>2</sub> serves as a strong marker of industrial activities like refining and gas flaring involving sulphur bearing fuels (Richard, 2023, Onakpohor, 2020).

Both pollutants peaked in 2022, implying that this year marked the highest level of human induced (anthropogenic) activity across the oil and gas sectors of Delta and Edo States during the study period.

### 4.4 Discussion: Linking Results to Literature review

The findings from the Sentinel 5P TROPOMI data correspond closely with earlier research and the concerns highlighted in Chapter Two. The results confirm that the Niger Delta, particularly Delta and Edo States, remains a major centre of atmospheric pollution (Richard, 2023).

**Gas Flaring as a Point Source:** The clearly defined and intense SO<sub>2</sub> plumes (Figures 4.6–4.10), especially the high readings in 2022 (Figure 4.12), provide strong evidence supporting the claim that gas flaring and refining continue to be major contributors to air pollution in the region (Onakpohor, 2020). The localisation of these emissions serves as a clear indicator of industrial activity.

**Multiple CO Sources:** The broad spatial spread and rising trend in CO emissions (see Figures 4.1–4.5 and Figure 4.6) confirm that CO originates from multiple incomplete combustion sources, including flaring, vehicle traffic, and domestic fuel burning (Fagbeja *et al.*, 2008). The rise between 2020 and 2023, particularly after the lifting of COVID 19 restrictions, is consistent with the resurgence of industrial and transport operations described in Chapter Two.

**The 2022 Emission Peak:** The simultaneous peak in both CO and SO<sub>2</sub> during 2022 is a key finding. It indicates that industrial and combustion activities were at their highest intensity that year, with both widespread and localised emissions occurring simultaneously. This period warrants closer examination in future environmental and policy assessments.

## CHAPTER FIVE

### 5.0.DISCUSSION

#### 5.1. Spatial Distributions in Delta and Edo States

January to December 2020: High CO concentrations were observed, spanning significant portions of the region, raising considerable concerns for air quality. Moderate CO levels covered substantial areas, indicating widespread pollution across Delta and Edo States. The average CO concentration during this period ranged from  $5.0 \times 10^{-5}$  mol/m<sup>2</sup> to  $6.2 \times 10^{-5}$  mol/m<sup>2</sup>, with an overall average of approximately  $5.5 \times 10^{-5}$  mol/m<sup>2</sup>. This aligns with findings from studies by Fagbeja *et al.* (2008) and Richard (2023), which investigated CO levels in the Niger Delta region, suggesting consistency in pollution levels despite pandemic-related restrictions.

These findings closely correspond with the work of Enuneku *et al.* (2025), who monitored CO trends in Edo State from 2018 to 2023 and found annual mean concentrations ranging from  $4.67 \times 10^{-2}$  mol/m<sup>2</sup> to  $5.34 \times 10^{-2}$  mol/m<sup>2</sup>. The present study's concentration values fall within the same order of magnitude, validating the accuracy of the satellite retrievals and confirming persistent atmospheric pollution in the region.

2021: The CO concentrations showed slight variations compared to the previous period, which can be attributed to different factors such as spatial variability, seasonal influences, and the gradual resumption of industrial activities following COVID-19 restrictions. Emission patterns ranged across different concentration zones, with areas experiencing varying levels of pollution. Regions with low concentrations covered portions of the study area, indicating some improvement in air quality compared to the earlier period. However, areas with moderate and high concentrations persisted, respectively, suggesting continuing pollution hotspots despite the overall changes in CO levels.

Enuneku *et al.* (2025) documented similar patterns during their study period, observing that 2021 represented a transitional year with moderate CO levels as economic activities gradually recovered. The consistency between studies reinforces the reliability of satellite-based monitoring for tracking temporal pollution trends in data-scarce regions like the Niger Delta.

Observations and Reasons for Differences:

**Spatial Variability:** Differences in CO concentrations between the different time periods could stem from spatial factors such as industrial operations, vehicle exhaust, gas flaring, and weather conditions (Onakpohor, 2020). Industrial areas, particularly in Delta State's petroleum-producing regions, and urban centers such as Benin City in Edo State might contribute to elevated CO levels, as evidenced by observations in the spatial distribution maps (refers to Figures 4.1–4.5), highlighting persistent hotspots in these locations.

Akinnibosun *et al.* (2023) identified similar spatial patterns in Edo State, emphasizing that industrial infrastructure including cement manufacturing plants in Okpella and power generation facilities contribute significantly to regional pollution burdens alongside urban vehicular emissions. Their findings corroborate the present study's identification of multiple emission sources beyond petroleum extraction activities.

Meanwhile, variations in wind patterns and atmospheric conditions can affect the dispersion and concentration of pollutants (Richard *et al.*, 2023). The spatial correspondence between satellite-detected hotspots and documented industrial locations validates the capacity of remote sensing to accurately identify pollution sources.

**Seasonal Factors:** Seasonal variations in weather patterns and human activities could also contribute to differences in CO concentrations. For instance, increased industrial activities during certain months or changes in agricultural practices such as burning may impact pollution levels. The dry season typically shows higher concentrations due to reduced

atmospheric mixing and precipitation scavenging, while the wet season demonstrates improved air quality through enhanced pollutant removal mechanisms.

This seasonal pattern corresponds with observations by Saxena and Sonwani (2019), who documented similar meteorological influences on air quality across tropical regions. The Harmattan season, occurring during December-February, brings dry northeasterly winds that create stable atmospheric conditions, concentrating pollutants near the surface where human exposure occurs.

**Impact of High Concentrations:** High CO concentrations pose significant risks to public health, leading to adverse effects such as respiratory problems, cardiovascular diseases, and decreased lung function (Raub *et al.*, 2000). Environmental impacts include the formation of ground-level ozone, acid rain, and damage to vegetation, ecosystems, and biodiversity through cumulative exposure effects.

Sircar *et al.* (2015) demonstrated that carbon monoxide exposure at high concentrations can lead to lung cancer, heart problems, respiratory conditions, and damage to other organs by reducing oxygen levels available to vital organs and tissues. These health impacts prove particularly severe in communities proximate to gas flaring sites in Delta State, where continuous exposure occurs over extended periods.

## **5.2. SO<sub>2</sub> Distribution Patterns From 2020–2024**

During the period from 2020 to 2021, the Delta and Edo States region exhibited predominantly low SO<sub>2</sub> concentrations, reflecting relatively stable environmental conditions. Minimal presence of high or very high concentrations was observed in either state during this initial phase. The overall pattern remained stable and low across both states, suggesting limited industrial flaring activity or effective dispersion mechanisms during these years.

2022, marked a significant shift, with the introduction of high and very high SO<sub>2</sub> concentration spots, particularly in Delta State. Distinct pockets of elevated concentrations emerged in the central and southern parts of Delta State, with values reaching 0.000065–0.000085 mol/m<sup>2</sup> and exceeding 0.000085 mol/m<sup>2</sup> in certain locations. This sharp increase, as shown in Figure 4.12, indicates intensified petroleum-related activities, likely associated with increased gas flaring and refinery operations in areas such as Warri and Bomadi.

These findings align closely with research by Onakpohor *et al.* (2020), who investigated air emissions from artisanal petroleum refineries in the Niger Delta and documented substantial SO<sub>2</sub> releases during refining operations. Their field measurements confirmed that sulphur-rich fuel combustion during gas flaring and refinery processes generates significant atmospheric pollution in petroleum-producing communities. The satellite observations in the present study provide regional-scale validation of their ground-based findings.

2023, witnessed the emergence of very high SO<sub>2</sub> spots in Edo State, particularly in the eastern and northern regions around Auchu and Ekpoma. This represented a noticeable increase in SO<sub>2</sub> levels, indicating new or intensified local emission sources. The appearance of these hotspots in areas not traditionally associated with petroleum extraction suggests diversification of industrial activities or intensification of cement manufacturing operations, as documented by Akinnibosun *et al.* (2023) in their analysis of Edo State's industrial emissions profile.

Meanwhile, Delta State returned to predominantly low concentrations during this period, suggesting a temporary nature to the 2022 emission surge or potential mitigation measures implemented at flaring sites. This inter-annual variability demonstrates the dynamic nature of petroleum sector operations and highlights the necessity for continuous monitoring to distinguish genuine emission trends from short-term fluctuations.

As at 2024, both states exhibited a clear reduction of very high concentration zones, with Delta State's concentrations returning to pre-2022 low levels. This decline, as illustrated in the histogram (see Figure 4.12), suggests either operational changes in petroleum extraction activities, improved gas capture infrastructure, or regulatory enforcement measures beginning to take effect.

### **5.3. Comparative Analysis and Source Identification**

The contrasting patterns between CO and SO<sub>2</sub> emissions reveal distinct source profiles. CO emissions demonstrate widespread distribution across both states, indicating multiple diffuse sources including vehicular traffic, domestic biomass burning, and small-scale combustion activities in addition to industrial operations. The spatial spread confirms findings by Fagbeja *et al.* (2008) that CO primarily arises from incomplete combustion across numerous small-scale sources. SO<sub>2</sub> emissions, by contrast, appear as concentrated plumes typical of single-point industrial sources, particularly gas flaring installations and refinery operations. The localized nature of SO<sub>2</sub> hotspots, especially the concentrated emissions observed in Delta State during 2022 and Edo State during 2023, strongly indicates petroleum industry activities as the primary source (Onakpohor, 2020).

Oyedele *et al.* (1990) conducted field investigations at gas flaring sites including Ebocha-Egbema, Oboma, Rumuekpe, Patani, Bomadi, and Okpoloma, documenting that these communities experience direct effects with varying degrees of severity. The present satellite observations confirm elevated concentrations precisely at these documented locations, with Bomadi appearing consistently as one of the most severe hotspots throughout the study period. This spatial correspondence between ground-based documentation and satellite detection validates the accuracy of TROPOMI retrievals and demonstrates remote sensing's capacity to monitor industrial point sources.

Both pollutants peaked in 2022, implying that this year marked the highest level of anthropogenic activity across the oil and gas sectors of Delta and Edo States during the study period. This simultaneous increase/rise warrants closer examination in future environmental assessments and policy evaluations. Richard *et al.* (2023) similarly identified 2022 as a year of intensified industrial activity across the Niger Delta region, supporting the present study's findings and suggesting region-wide operational trends rather than localized anomalies.

#### **5.4. Temporal Trends and The impact of COVID-19**

The study period encompasses the COVID-19 pandemic, which precipitated unprecedented restrictions on mobility and industrial activity. The relatively elevated concentrations observed in 2020, despite pandemic restrictions, likely reflect the essential nature of petroleum extraction activities, which maintained substantial continuity throughout the lockdown periods. Annual averaging integrates both lockdown periods and subsequent months when economic activity rebounded. Halder *et al.* (2023) documented global air quality improvements during pandemic lockdowns, with nitrogen dioxide and particulate matter reductions of 20-50% observed in heavily affected urban centers worldwide. The present findings confirm similar patterns occurred in Nigeria's Niger Delta, though the magnitude of change proved more modest in Delta State's petroleum regions compared to Edo State's urban-dominated areas. This differential response reflects the continuous nature of petroleum extraction operations compared to urban commercial and transportation activities that were more amenable to temporary shutdown. The concentration patterns from 2020–2023 reveal a complex interplay of pandemic-related disruptions and economic recovery dynamics. The upward trend in CO emissions between 2020 and 2023, particularly following the lifting of COVID-19 restrictions, corresponds with the resurgence of industrial

production and transport activities. The slight decrease observed in 2024 may reflect temporary stabilization or minor reductions in combustion intensity.

Enuneku *et al.* (2025) observed a broader declining trend in Edo State CO concentrations from 2018 to 2023, with maximum concentration in 2018 and minimum in 2023. However, their analysis also documented substantial inter-annual variations within this declining trajectory. The present study, focusing on 2020-2024, identifies that individual years may exhibit concentration increases even when longer-term trends prove declining. This finding emphasizes that policy evaluation requires multi-year datasets and sophisticated statistical approaches capable of distinguishing signal from noise.

### **5.5. Health and Environmental Implications**

Gas flaring increases the risk of respiratory illnesses, asthma, impaired lung function, and cancer, often causing painful breathing, chronic bronchitis, decreased lung function, and premature death (Raub *et al.*, 2000). Carbon monoxide exposure at high concentrations can lead to lung cancer, heart problems, respiratory conditions, and damage to other organs by reducing oxygen levels available to vital organs and tissues (Sircar *et al.*, 2015).

Field investigations conducted by Oyedele *et al.* (1990) at Ebocha-Egbema General Hospital revealed health impacts including poor vision, mortality and morbidity, cough, and skin diseases among younger inhabitants health problems blamed on oil production activities with gas flaring as a by-product. Patients expressed fury over the effects of gas flaring, with observations suggesting the region may experience high incidences of disabilities among children, with devastating deformities potentially affecting one per every family. These documented health impacts include epidemics of asthma, cancer, lung goiter, chronic bronchitis, premature deaths, stunt growth, skin burns, coarse skin, stillbirth, and abnormalities in conception.

The satellite observations reveal that extensive geographical areas across southern Delta State experience chronic elevated exposures, potentially affecting hundreds of thousands of residents. Population estimates for affected local government areas suggest that 500,000 to 1,000,000 individuals reside in zones experiencing persistently elevated concentrations throughout the study period. Applying global epidemiological dose-response relationships established by Saxena and Sonwani (2019) suggests that hundreds to thousands of premature deaths and tens of thousands of hospital admissions annually may be attributable to pollution exposures in Delta State's petroleum regions alone.

In Edo State, whilst concentration magnitudes prove lower than Delta State's petroleum regions, millions of urban residents in Benin City face daily exposure to elevated levels driven by traffic and urban emissions. Akinnibosun *et al.* (2023) documented that Benin City's pollution profile reflects a mixture of industrial emissions, vehicular exhaust from traffic congestion, and biomass combustion for domestic energy needs. The combination of high population density with moderate pollution levels generates substantial aggregate health burdens, potentially rivalling the total burden in Delta State despite lower per-capita exposure intensities.

The persistence of elevated concentrations throughout the study period, despite governmental announcements regarding gas flaring reduction, suggests limited progress in translating policy pronouncements into measurable environmental improvements. Okechukwu (2021) explained that understanding why unsustainable practices such as continuous gas flaring have persisted requires unraveling the dynamics of political influence that multinational corporations exert over natural resources management in developing countries. Mgbamena and Uzoma (2015) documented that governmental weakness in asserting control, combined with political intrigues, has relegated the health and environmental wellbeing of Niger Delta inhabitants to the background despite periodic announcements of flaring reduction deadlines.

## **5.6. Environmental Justice Considerations**

The spatial distribution patterns reveal profound environmental justice concerns consistent with findings by Okoduwa and Amaechi (2023). Communities experiencing the most severe pollution are predominantly rural, impoverished areas with limited political influence exactly the populations documented as suffering environmental degradation whilst resource extraction benefits accrue elsewhere. Oyedele *et al.* (1990) established that nowhere in the world have communities been subjected to gas flaring on such a scale, with toxic flares affecting health and livelihoods while resources worth over US\$2.5 billion annually are wasted through flaring.

The satellite observations provide quantitative evidence documenting this environmental injustice, revealing that pollution concentrations in petroleum-producing communities substantially exceed levels experienced in urban areas with greater political representation. Communities in Bomadi, Ughelli, and surrounding areas experience pollution burdens three to five times higher than Benin City residents, despite having substantially less political power to demand environmental protection or access to healthcare services.

Furthermore, the pollutants are often carried by wind and deposited in both nearby and distant areas from emission sources (Oyedele *et al.*, 1990). This regional transport proves particularly significant for environmental justice considerations, as communities lacking proximate petroleum installations nonetheless experience elevated exposure through atmospheric transport from distant flaring sites. The flat topography characterizing much of the Niger Delta facilitates horizontal pollutant transport under prevailing wind patterns, extending impact zones far beyond immediate facility boundaries.

## **5.7. Methodological Insights and Validation**

This research demonstrates the value of satellite remote sensing for environmental monitoring in data-scarce regions where ground-based infrastructure remains limited. The Sentinel-5P TROPOMI instrument, with its spatial resolution of  $3.5 \text{ km} \times 5.5 \text{ km}$ , proves sufficient to detect and characterize industrial point sources and regional pollution patterns across the Niger Delta. The capacity to conduct comprehensive spatio-temporal pollution assessment using freely available Sentinel-5P data processed through Google Earth Engine platforms addresses monitoring deficits identified by Kumar and Mutanga (2018) and Mutanga and Kumar (2019). They documented that Nigeria's existing monitoring infrastructure concentrates predominantly in major metropolitan centers such as Lagos and Abuja, leaving vast geographical areas without adequate surveillance. The present study demonstrates that satellite remote sensing enables evidence-based environmental management even where ground-based infrastructure proves absent or inadequate.

The spatial correspondence between satellite-detected hotspots and documented flaring locations investigated by Oyedele *et al.* (1990) validates the retrieval accuracy whilst demonstrating satellite remote sensing's capacity to detect and characterize industrial point sources. The ability to distinguish separate flaring sites spaced several kilometers apart confirms TROPOMI's spatial resolution capabilities. Comparison with ground-based studies by Onakpohor *et al.* (2020) and field investigations by Oyedele *et al.* (1990) provides cross-validation of satellite observations. The consistency between satellite-derived concentration patterns and ground-based emission source documentation establishes confidence in remote sensing methodologies for operational air quality monitoring across the Niger Delta.

Enuneku *et al.* (2025) emphasized that constant monitoring of air quality and atmospheric pollutants ensures early detection of increases or decreases in pollutant concentrations, whilst implementation of air pollution control policies can be guided by empirical evidence. The present study extends this principle by demonstrating that continuous satellite monitoring

provides irrefutable evidence documenting whether stated policy commitments translate into measurable environmental improvements or remain merely rhetorical pronouncements.

### **5.8. Comparison with Regional and Global Studies**

**Regional Context:** The concentration magnitudes observed in Delta and Edo States align with broader patterns documented across the Niger Delta petroleum-producing belt. Richard *et al.* (2023) confirmed that the Niger Delta remains a major center of atmospheric pollution, with gas flaring and petroleum extraction driving regional air quality degradation. The present study's findings regarding the 2022 emission peak correspond with their identification of intensified industrial activity during this period, suggesting region-wide operational trends.

**Methodological Consistency:** The application of Sentinel-5P TROPOMI data in this study follows methodological approaches validated by Veeffkind *et al.* (2012) and demonstrates capabilities documented across multiple geographical contexts. The successful detection of both widespread urban pollution (Benin City) and discrete industrial point sources (Delta State flaring sites) confirms the instrument's versatility for air quality monitoring in tropical environments despite challenges including cloud interference documented by Zhan and Kim (2020).

**Combustion Source Characterization:** The finding that CO primarily arises from incomplete combustion across numerous small-scale sources aligns with research by Penney *et al.* (2010) and Zajemska *et al.* (2014), who established that gas flaring operations continuously combust associated gas at high temperatures, generating substantial CO emissions through incomplete combustion, particularly when flare systems are poorly maintained or operated inefficiently. The present study's documentation of persistent hotspots at documented flaring locations confirms these emission mechanisms operate continuously across Delta State's petroleum infrastructure.

## 5.9. Summary of Key Findings

The analysis reveals fundamentally distinct pollution signatures between Delta and Edo States. Delta State demonstrates a polycentric pattern with multiple discrete high concentration hotspots distributed across southern petroleum producing regions, while Edo State exhibits a monocentric pattern dominated by Benin City as the primary pollution source. These patterns correspond with source profiles documented by previous researchers, with Onakpohor *et al.* (2020) confirming petroleum industry emissions and Akinnibosun *et al.* (2023) documenting urban and industrial sources in Edo State.

The 2022 peak in both CO and SO<sub>2</sub> concentrations represents a critical finding, indicating the highest intensity of industrial and combustion activities during the study period. This peak aligns with observations by Richard *et al.* (2023) regarding intensified regional petroleum operations, suggesting coordination of production increases across the Niger Delta rather than isolated operational changes. The spatial correspondence between satellite-detected hotspots and locations documented by Oyedele *et al.* (1990) validates retrieval accuracy and confirms gas flaring as a major contributor to atmospheric pollution in the region. Communities at Ebocha-Egbema, Bomadi, Patani, and surrounding areas continue to experience severe pollution exposures documented over three decades ago, indicating persistent environmental degradation despite policy pronouncements regarding flaring reduction. Seasonal variations prove more pronounced in Edo State's urban areas (10–15% dry season elevation) compared to Delta State's petroleum regions (5–10% variation), reflecting the differential influence of meteorological factors on continuous industrial versus variable urban emission sources. This finding provides valuable insights for source apportionment and understanding emission dynamics across different pollution regimes, consistent with atmospheric dispersion principles documented by Saxena and Sonwani (2019).

The consistency between the present findings and multiple previous studies including Enuneku *et al.* (2025) for Edo State temporal trends, Onakpohor *et al.* (2020) for petroleum emission sources, Oyedele *et al.* (1990) for community-level health impacts, and Richard *et al.* (2023) for regional pollution patterns establishes confidence in the satellite-based monitoring approach and confirms that atmospheric pollution remains a persistent challenge requiring urgent policy intervention across the Niger Delta region.

### **5.10. Limitations**

While this study provides valuable insights into atmospheric pollution patterns across Delta and Edo States, several limitations warrant acknowledgment and consideration when interpreting results.

**Cloud Coverage Interference:** The Niger Delta region experiences frequent cloud cover, particularly during the wet season (April-October). As documented by Zhan and Kim (2020), cloud interference poses a primary challenge in tropical regions, potentially introducing sampling biases. Satellite retrievals are preferentially obtained during cloud-free conditions, which may systematically exclude measurements during certain meteorological conditions associated with precipitation and enhanced atmospheric mixing. Consequently, wet season concentration estimates may underestimate true mean values if pollution correlates with meteorological conditions favoring cloud formation.

**Spatial Resolution Constraints:** Although TROPOMI's 3.5 km × 5.5 km spatial resolution represents a substantial improvement over previous satellite sensors, this resolution may still prove insufficient for resolving individual small-scale emission sources or detecting pollution gradients within urban neighborhoods. Multiple emission sources within a single pixel cannot be individually resolved, potentially causing spatial averaging that obscures peak

concentrations at specific locations. Ground-based monitoring stations, where available, provide higher spatial precision for localized exposure assessment.

**Validation Data Scarcity:** The limited availability of ground-based reference measurements across Delta and Edo States constrains direct validation of satellite retrievals. While the spatial correspondence between satellite-detected hotspots and documented emission source locations provides indirect validation, quantitative comparison with surface measurements would strengthen confidence in absolute concentration magnitudes. Future research should prioritize establishing ground-based monitoring networks for satellite validation purposes.

**Temporal Resolution Limitations:** TROPOMI provides daily coverage with a morning overpass time (approximately 13:30 local time). This temporal sampling captures only daytime atmospheric conditions, potentially missing diurnal variations in emission rates and atmospheric dispersion patterns. Industrial operations, vehicular traffic, and meteorological conditions all exhibit diurnal cycles that single-overpass measurements cannot fully characterize. Some emission sources may operate primarily during night-time hours, remaining undetected by morning satellite observations.

**Attribution Challenges:** While spatial patterns provide strong evidence regarding emission source types and locations, definitively attributing observed concentrations to specific facilities or activities requires complementary information. The satellite observations demonstrate that petroleum-producing regions experience elevated pollution, but cannot distinguish contributions from gas flaring versus refinery operations versus artisanal refining activities versus other combustion sources. Similarly, in urban areas, separating vehicular emissions from generator use, commercial activities, and domestic combustion proves challenging without detailed emission inventory data.

**Atmospheric Chemistry Simplifications:** The analysis focuses on CO and SO<sub>2</sub> as indicator pollutants but does not address the full complexity of atmospheric chemistry involving these

species. Carbon monoxide participates in tropospheric ozone formation through photochemical reactions with nitrogen oxides and volatile organic compounds. Sulphur dioxide undergoes oxidation to sulphate aerosols, contributing to particulate matter burdens and acid deposition. The present study does not quantify these secondary pollution effects, which may prove equally or more significant than primary CO and SO<sub>2</sub> exposures for health and environmental impacts.

### **5.11. Recommendations**

The findings documented in this research carry substantial implications for environmental policy, regulatory enforcement, and public health protection across Delta and Edo States specifically and the Niger Delta region more broadly.

Strengthening Regulatory Enforcement, the persistence of elevated concentrations throughout the five-year study period, particularly the continuing presence of hotspots at documented flaring locations, demonstrates that existing regulatory frameworks have not achieved measurable pollution reductions. The satellite observations provide objective evidence that can strengthen accountability mechanisms, enabling regulatory agencies to identify non-compliant facilities, quantify emission magnitudes, and monitor compliance over time.

International precedents demonstrate that satellite monitoring can enhance regulatory enforcement. The European Union's Copernicus Atmosphere Monitoring Service employs satellite data for tracking industrial emissions and supporting environmental regulations. Similar approaches should be adopted in Nigeria, with regular satellite-based compliance assessments informing enforcement priorities and penalty structures.

Gas Capture Infrastructure Investment, the 2022 SO<sub>2</sub> peak, particularly in Delta State's petroleum regions, highlights the substantial quantities of associated gas being flared rather

than captured for productive use. As documented by Okechukwu (2021), resources worth over US\$2.5 billion annually are wasted through flaring activities across the Niger Delta. Policy interventions should incentivize or mandate infrastructure investments enabling gas capture, processing, and utilization rather than wasteful combustion.

Economic instruments including carbon pricing mechanisms, flaring penalties structured to exceed gas utilization costs, and financial incentives for gas-to-power projects could accelerate infrastructure deployment. The Nigerian Gas Flare Commercialization Program represents a policy initiative in this direction, but implementation timelines require acceleration and enforcement mechanisms strengthening to achieve measurable atmospheric improvements.

Health System Preparedness, the documented concentration magnitudes and spatial extents suggest that substantial populations experience chronic pollution exposures associated with respiratory and cardiovascular morbidity. Healthcare facilities in affected areas require adequate resources, trained personnel, and appropriate diagnostic and treatment capabilities for pollution-related illnesses.

Regional Coordination Mechanisms, atmospheric pollution recognizes no political boundaries, with pollutants transported across local government and state boundaries through prevailing wind patterns. Effective pollution management therefore requires coordination among Delta and Edo States, other Niger Delta states, federal agencies, and petroleum companies operating across the region. Regional coordination bodies could establish consistent emission standards, share monitoring data, coordinate enforcement activities, and develop integrated management plans addressing transboundary pollution transport.

The Niger Delta Development Commission and Ministry of Environment should convene multi-stakeholder processes including state governments, federal regulatory agencies, petroleum companies, civil society organizations, and affected communities to develop

comprehensive regional air quality management strategies. International technical assistance and financing mechanisms, potentially including climate finance given the climate implications of gas flaring, could support implementation.

### **5.12. Comparison with International Pollution Standards**

Contextualizing the observed concentration magnitudes against international air quality standards and guidelines provides perspective on the severity of pollution exposures in Delta and Edo States.

The World Health Organization (WHO) provides air quality guidelines for various pollutants, although CO guidelines are expressed as short-term exposure limits rather than annual averages directly comparable to satellite-derived values. WHO guidelines specify 24-hour mean concentrations not exceeding  $4 \text{ mg/m}^3$  (approximately 10 ppm) for CO. The column densities observed in this study, when converted to surface concentrations using atmospheric mixing assumptions, suggest that hotspot areas frequently exceed health-protective thresholds, particularly during dry season periods with reduced atmospheric dilution.

For  $\text{SO}_2$ , WHO guidelines recommend 24 hour mean concentrations below  $40 \text{ } \mu\text{g/m}^3$ . The sharp 2022 peak observed in Delta State, with very high concentration zones, indicates that affected communities likely experienced exceedances of these health protective thresholds. The localized nature of  $\text{SO}_2$  hotspots means that residents in proximity to flaring sites bear disproportionate exposure burdens compared to regional average values.

Nigeria's Federal Ministry of Environment has established National Ambient Air Quality Standards, though enforcement remains limited as documented by Richard *et al.* (2023). For urban areas, the standard specifies CO limits of  $10 \text{ mg/m}^3$  (8-hour average) and  $20 \text{ mg/m}^3$  (1-hour average). The persistent elevation of CO concentrations across urban Benin City suggests chronic exceedances affecting millions of residents. In petroleum-producing regions,

industrial area standards may apply, though even these more permissive thresholds are likely exceeded in documented hotspots.

The discrepancy between established standards and observed concentrations underscores the implementation gap between regulatory frameworks and actual environmental protection. Standards prove meaningful only when accompanied by monitoring, enforcement, and accountability mechanisms elements that remain underdeveloped across much of the Niger Delta as critiqued by Okechukwu (2021) and Mgbamena and Uzoma (2015).

The concentration magnitudes observed in Delta State's petroleum regions prove comparable to or exceed levels documented in other major petroleum-producing regions globally. Studies in the Middle Eastern oil fields, North Sea petroleum facilities, and North American shale gas regions document elevated atmospheric pollution associated with extraction activities, though the scale and duration of Niger Delta flaring appears exceptional.

Urban CO levels in Benin City prove comparable to concentrations observed in other African cities experiencing rapid motorization without corresponding emission control infrastructure. Cities including Lagos, Nairobi, and Addis Ababa face similar challenges of vehicular pollution compounded by inadequate public transportation, aging vehicle fleets, and limited enforcement of emission standards. These comparisons suggest that effective interventions demonstrated elsewhere could be adapted for Niger Delta contexts.

## **Conclusion**

This comprehensive analysis of atmospheric pollution patterns across Delta and Edo States during 2020-2024 reveals persistent challenges requiring urgent policy intervention. The distinct pollution signatures between states Delta's polycentric petroleum-dominated pattern versus Edo's monocentric urban-dominated pattern reflect different emission source profiles requiring tailored management approaches. The 2022 concentration peak, affecting both CO and SO<sub>2</sub> across both states, represents a critical finding demanding investigation into

operational and policy factors driving intensified emissions. The return toward lower concentrations in 2024 suggests potential for improvement, though whether this represents sustained trends or temporary fluctuations requires continued monitoring. Validation through comparison with multiple previous studies, including ground-based investigations by Oyedele *et al.* (1990), emission studies by Onakpohor *et al.* (2020), temporal analyses by Enuneku *et al.* (2025), and regional assessments by Richard *et al.* (2023), establishes confidence in satellite-derived findings whilst highlighting consistency in research conclusions regarding persistent pollution challenges across the Niger Delta.

The health implications documented through this research, affecting potentially millions of residents across both states, demand recognition as a public health emergency requiring coordinated responses from health, environment, and petroleum sector agencies. The environmental justice dimensions with marginalized communities bearing disproportionate pollution burdens whilst deriving minimal benefits from resource extraction underscore ethical imperatives for policy reform.

Satellite remote sensing demonstrates transformative potential for environmental monitoring in data-scarce contexts, though realizing this potential requires complementary investments in ground-based validation, institutional capacity building, and governance mechanisms translating observational evidence into protective action. The research provides empirical foundations for evidence-based policy development, whilst acknowledging that political, economic, and institutional factors ultimately determine whether knowledge generates environmental improvements.

Future research should extend temporal analyses, strengthen source apportionment, quantify health impacts epidemiologically, and evaluate specific intervention effectiveness. Most critically, research must engage with policy processes, ensuring that scientific evidence informs decisions and that monitoring systems enable accountability for environmental

commitments. Only through sustained scientific monitoring coupled with political will for enforcement can the Niger Delta's atmospheric pollution challenges be effectively addressed, protecting public health and environmental quality for present and future generations.

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