MONITORING CONCENTRATION LEVELS OF CARBON MONOXIDE AND AEROSOLS IN ABA METROPOLIS, ABIA STATE, SOUTH-EASTERN NIGERIA - A CASE STUDY OF 2019-2024.

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NOVEMBER, 2025.

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AN UNDERGRADUATE DISSERTATION SUBMITTED TO THE DEPARTMENT OF ENVIRONMENTAL MANAGEMENT AND TOXICOLOGY, FACULTY OF LIFE SCIENCES, UNIVERSITY OF BENIN, BENIN CITY, EDO STATE, NIGERIA; IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR AWARD OF BACHELOR OF SCIENCE (B.Sc.) DEGREE IN ENVIRONMENTAL MANAGEMENT AND TOXICOLOGY.

NOVEMBER, 2025.

CERTIFICATION

This is to certify that this research titled **monitoring concentration levels of Carbon monoxide and aerosols in Aba metropolis, Abia state, South-Eastern, Nigeria - a case study of 2019-2024** was carried out by **Favour Osemwonyenmwen Elegon** and presented to the Department of Environmental Management and Toxicology, Faculty of Life Sciences, University of Benin, Benin City; in partial fulfillment of the requirement for award of Bachelor of Science (B.Sc.) in Environmental Management and Toxicology. It was conducted under stable 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.

Dr C. F. AMAECHI **DATE**

(PROJECT SUPERVISOR)

PROF. (Mrs) AISIEN E. T. **DATE**

(HEAD OF DEPARTMENT)

DECLARATION

I, Favour Osemwonyenmwen Elegon declare that monitoring concentration levels of Carbon monoxide and aerosols in Aba metropolis, Abia state, South-Eastern, Nigeria - a case study of 2019-2024 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.

FAVOUR OSEMWONYENMWEN ELEGON **DATE**

DEDICATION

I dedicate this project to God Almighty, the source of all knowledge and wisdom. His guidance, strength and grace have made this research journey possible. To my beloved parents, whose unwavering love, support, and prayers have been my greatest source of strength and inspiration. Your sacrifices and encouragement have shaped me into who I am today, and for that I am forever grateful.

ACKNOWLEDGMENT

I am deeply grateful to God Almighty, the source of all wisdom and strength, whose unfailing grace and guidance have sustained me throughout this journey. Without Him, this achievement would not have been possible. My heartfelt appreciation goes to my beloved parents, Mr. and Mrs. Elegon, for their endless love, sacrifices, prayers, and encouragement. To my dear siblings, Iredia, Nosa, and Philomena, thank you for your constant encouragement and for always believing in me. I also genuinely appreciate my best friend, Moses Omokhagbo Anthony, for always standing by me with steadfast support and companionship through this journey. My heartfelt gratitude goes to my project supervisor, Dr. C. F. Amaechi, for his patient guidance, invaluable advice, and unwavering support. I am also grateful to Mr. Kingsley, whose input and direction greatly enriched this work. My gratitude also goes to my Head of Department, Prof. (Mrs.) Aisien E. T., and my course adviser, Dr. A. F. Eghomwanre, for their leadership, guidance, and encouragement throughout my academic journey. I deeply appreciate my lecturers Dr. Nosa, Dr. Jeff, Dr. Ekene, and all other amiable lecturers whose teachings, insights, and dedication have shaped me academically and intellectually. To my dear friends , Stella Okoh, Abbey Osato, Asuzu Favour, Ufuoma Ighoteguono , Obasuyi Ozazee, Izeyozarbor Israel, Okoli Nmesoma ,Desmond and Lola—thank you for your friendship, motivation, and support always. To those whose names I may have inadvertently omitted, please accept my sincere gratitude as your contributions are equally valued. Finally, I acknowledge myself for the resilience and determination that brought me this far, and I recognize the countless researchers whose works formed the foundation and inspiration for this study. God bless you all.

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ABSTRACT

Aba, a major commercial hub in southeastern Nigeria, faces growing air pollution pressures, particularly from carbon monoxide (CO) and aerosols. Sentinel-5P satellite data processed on Google Earth Engine were used to track their concentrations from 2019 to 2024, with annual, monthly, and spatial patterns assessed alongside inter-annual variation. CO peaked at 0.0562 mol/m² in 2024 and was lowest in 2023 at 0.0489 mol/m². February consistently recorded the highest monthly values, reflecting intensified dry-season emissions and limited atmospheric dispersion. Aerosols followed a similar seasonal cycle, peaking in February, with the highest concentration in 2024 (0.1683) and the lowest in 2020 (-0.7115). Spatial analysis revealed persistent hotspots in central and northern Aba, especially around Ariaria International Market, Aba Industrial Zone, and Ngwa Road Market, while outlying areas such as Asa Umu Nka and Crystal Park Avenue maintained lower levels. Statistical testing showed that CO differences were significant in the early years (2019–2020, 2021–2022) and highly significant in the later period (2023–2024 and the 2019–2024 comparison), while no significant changes occurred in 2020–2021 or 2022–2023. Aerosols, by contrast, recorded highly significant differences from 2019 to 2022, but no significant changes in the later years, except for a strong 2019–2024 contrast. Despite these fluctuations, both pollutants remained persistently elevated in densely populated and economically active zones, underscoring continued risks to health and environmental quality. The findings confirm the value of Sentinel-5P and Google Earth Engine for urban air quality assessment and highlight the need for targeted emission control and stronger regulatory oversight.

CHAPTER ONE

1.0 INTRODUCTION

1.1. BACKGROUND OF STUDY

Across the globe, rising environmental concerns have become increasingly interconnected with human health, economic productivity, and sustainable development (Manisalidis *et al.*, 2020; Gul and Das, 2023; Borge *et al.*, 2023). Atmospheric pollution is among the most pressing environmental threats today, with the World Health Organization linking it to over seven million premature deaths each year (Manisalidis *et al.*, 2020; Gul and Das, 2023; WHO, 2024). This burden disproportionately affects low- and middle-income nations where limited resources hinder effective responses. The impacts of atmospheric pollution extend far beyond human health, disrupting ecosystems, reducing biodiversity, and undermining global efforts to stabilize the climate (Lovett *et al.*, 2009; Ghorani-Azam *et al.*, 2016; Izah *et al.*, 2023). Contributing factors include a wide range of natural and anthropogenic sources from vehicular emissions and industrial processes to biomass burning and natural events such as dust storms and wildfires (Burnett *et al.*, 2018; IARC, 2016; Odubo and Kosoe, 2024). Rapid urbanization and unchecked industrial growth have exacerbated these problems in many regions, triggering a sharp increase in pollution-related diseases such as asthma, cardiovascular disorders, and cancer (WHO, 2021; Lelieveld *et al.*, 2019; Mathew *et al.*, 2024).

While developed countries have managed to mitigate these impacts through strong environmental regulations and advanced monitoring technologies (Ross *et al.*, 2012; Jonidi Jafari *et al.*, 2021), fast-growing economies continue to face serious obstacles. In countries like China and India, air quality often reaches hazardous levels due to traffic congestion, coal combustion, and biomass burning. Major cities such as Beijing and New Delhi regularly record $PM_{2.5}$ levels far above WHO's recommended limits (Lelieveld *et al.*, 2019; Mathew *et al.*, 2024). In Latin America, industrial hubs like Mexico City and São Paulo face ongoing pollution problems tied to transportation and manufacturing activities (Gómez-Peláez *et al.*, 2020; Coloballes, 2020).

Across Africa, similar challenges persist. Rapid population growth, expanding cities, and widespread reliance on biomass fuels contribute to a complex air quality situation (Abera *et al.*, 2021; Petkova *et al.*, 2013; Jiying *et al.*, 2023; Atuyambe *et al.*, 2024). Despite the growing urgency, the continent still lacks widespread air quality monitoring infrastructure. Indoor air pollution remains a major concern in rural and peri-urban areas where charcoal and wood are still widely used (Abera *et al.*, 2021; Petkova *et al.*, 2013). Outdoor pollution from vehicle emissions and dust from unpaved roads also adds to the problem (United Nations Environment Programme, 2019). Cities like Accra, Johannesburg, Nairobi, and Cairo regularly struggle with pollution from inefficient transport systems, industrial activity, and poor waste management (Abera *et al.*, 2021; Atuyambe *et al.*, 2024).

Nigeria, Africa's most populous country, is facing a severe air pollution crisis, particularly in its urban and industrial centers (Ladan, 2013; Amegah and Agyei-Mensah, 2016; Abaje *et al.*, 2020). Heavy use of fossil fuels, the rise of informal industries, and weak environmental oversight have created pollution hotspots with significant health consequences (Awofeso, 2011; Obanya *et al.*, 2018; Fakinle *et al.*, 2020). Cities such as Lagos, Port Harcourt, Abuja, and Kano show patterns of rapid, unregulated urbanization, heavy traffic, and constant emissions from generators and Industrial processes (Adeyanju and Manohar, 2017; Merem *et al.*, 2018; Amaechi *et al.*, 2024a; Lala *et al.*, 2025). These cities frequently report elevated levels of carbon monoxide (CO) and Aerosols, all of which contribute to respiratory and cardiovascular illnesses (Amaechi *et al.*, 2023; Olowoporoku *et al.*, 2011; Sadiq *et al.*, 2022; The Guardian, 2016). In southeastern Nigeria, Onitsha has gained notoriety for its extremely high $PM_{2.5}$ levels (The Guardian, 2016; Kalu and Zakirova, 2019), while Aba is emerging as a pollution hotspot due to its expanding industrial sector and lack of environmental controls.

Aba, a major commercial and manufacturing hub in southeastern Nigeria, is subject to intense environmental pressures driven by high vehicular density, diesel generator use, informal industrial activity, and frequent waste burning (Akuagwu and Ozeh, 2013; Nwosu and Ewurum, 2018; Diagi *et al.*, 2025; Okey-Wokeh *et al.*, 2020). The cumulative effect of these activities has significantly deteriorated air quality, yet real-time, continuous monitoring remains largely absent, impeding a full understanding of pollution dynamics and public health risks (Akuagwu and Ozeh, 2013; Nwosu and Ewurum, 2018; Diagi *et al.*, 2025).

Previous studies have documented air pollution in Aba predominantly through ground-based methods. Akuagwu and Ozeh (2013) employed electrochemical gas sensors and gravimetric techniques across six strategic locations, revealing frequent exceedances of WHO standards for CO and SO_2. Anietimfon and Anaekwe (2015) measured SO_2 concentrations using the West-Gaeke method, while Nwosu and Ewurum (2018) assessed air quality near the Enyimba dumpsite using portable gas detectors and gravimetric samplers, identifying elevated concentrations of CO, H_2S, CH_4, and PM. Diagi *et al.* (2025) focused on CO and particulate matter using handheld sensors across different urban land uses. Although these studies underscore the severity of pollution, they are limited by localized, short-term sampling, restricting comprehensive spatial and temporal assessments. In a related effort, Abulude *et al.* (2023) utilized satellite-derived data from Plume Labs to monitor air quality in southeastern towns, including Aba. However, their reliance on generalized air quality indices (PAQI) and a 60-day observation window limited pollutant-specific analysis and temporal continuity.

To overcome these limitations, satellite-based remote sensing offers a scalable, cost-effective solution. The Sentinel-5P satellite, developed by the European Space Agency (ESA), delivers near-daily, high-resolution data on key atmospheric pollutants (ESA, 2021; Oxoli *et al.*, 2020; Mathew *et al.*, 2024). With its Tropospheric Monitoring Instrument (TROPOMI), Sentinel-5P captures detailed concentrations of CO and aerosols with a level of spatial and temporal resolution unattainable by conventional ground-based approaches (ESA, 2021; Oxoli *et al.*, 2020; Mathew *et al.*, 2024; Reshi *et al.*, 2024; Veefkind *et al.*, 2012; Enuneku *et al.*, 2025; Okoduwa and Amaechi, 2023).

This study applies Sentinel-5P data to assess CO and aerosol pollution over Aba from 2019 to 2024, offering the first longitudinal, city-wide remote sensing-based analysis of air quality in the region. By bridging spatial and temporal monitoring gaps, this research provides critical insights into pollution trends and their environmental and health implications.

1.2 STATEMENT OF PROBLEM

The deterioration of air quality remains a serious concern for public health and environmental sustainability, particularly in developing countries where pollution-related illnesses account for over seven million premature deaths annually (WHO, 2024; Manisalidis *et al.*, 2020; Okoye, 2025). In urban centers like Aba metropolis, located in southeastern Nigeria, the problem is becoming increasingly urgent (Akuagwu and Ozeh, 2013; Anietimfon and Anaekwe, 2015; Kalu and Zakirova, 2019). Known for its high level of industrial, vehicular, and commercial activities, Aba is a major contributor to atmospheric pollutants, particularly carbon monoxide (CO) and aerosols (Akuagwu and Ozeh, 2013; Anietimfon and Anaekwe, 2015; Nwosu and Ewurum, 2018). These pollutants are commonly linked to harmful health outcomes, including respiratory infections, cardiovascular diseases, and reduced life expectancy (Croitoru *et al.*, 2020; Manisalidis *et al.*, 2020; WHO, 2024) . Major sources of these emissions include industrial processes, dense traffic, fossil fuel combustion, and the widespread use of diesel-powered generators (Akuagwu and Ozeh, 2013; Anietimfon and Anaekwe, 2015; Akuagwu *et al.*, 2016; Nwosu and Ewurum, 2018). While many developed countries have managed to improve air quality through regulatory frameworks and technological monitoring systems, urban centers in Nigeria continue to suffer from rising pollution levels due to rapid urban growth, weak enforcement of environmental laws, and limited adoption of advanced monitoring tools (Jonidi-Jafari *et al.*, 2021; Croitoru *et al.*, 2020; Amaechi *et al.*, 2023; Amaechi *et al.*, 2024a; Amin Kodiya *et al.*, 2025). In the case of Aba, there is a noticeable absence of systematic air quality monitoring and reliable datasets (Akuagwu and Ozeh, 2013; Nwosu and Ewurum, 2018; Jonidi-Jafari *et al.*, 2021). This lack of real-time and long-term environmental data makes it difficult to evaluate pollution levels, trace emission sources, or implement effective mitigation strategies (Jonidi-Jafari *et al.*, 2021). Despite evidence linking air pollution to severe health consequences, Aba lacks the infrastructure and policy support needed to address these challenges (Akuagwu and Ozeh, 2013; Nwosu and Ewurum, 2018; Jonidi-Jafari *et al.*, 2021). Modern methods such as satellite-based remote sensing, which have proven effective in other regions, remain underused (Jelili *et al.*, 2020). As a result, critical decisions regarding environmental management and public health interventions are being made without sufficient data support. Therefore, there is an urgent need for accurate, location-specific assessments of air quality in Aba metropolis to guide effective policy formulation, improve environmental planning, and reduce health risks associated with exposure to pollutants like CO and aerosols.

1.3 AIM AND OBJECTIVES OF STUDY

Aim

The aim of this study is to assess tropospheric Carbon monoxide (CO) and aerosol concentrations in Aba metropolis, Abia State, Nigeria.

Objectives

1. To use GIS imagery to establish CO and aerosols variations

2. To carry out temporal and spatial assessment for the selected air quality parameters (CO and aerosols).

3. To determine CO and aerosols emissions for the years under review.

1.4 JUSTIFICATION OF STUDY

In Nigeria, particularly in urban and industrial centers like Aba, air pollution is becoming an increasing concern for both public health and the environment (Nwosu and Ewurum, 2018). High levels of pollutants, including CO and aerosols, have been linked to severe respiratory diseases, cardiovascular conditions, and decreased overall life expectancy (WHO, 2021). Given the rapid urbanization and industrial expansion in Aba, the city faces increasing pollution from vehicular emissions, industrial discharges, and the widespread use of diesel generators for power supply (Akuagwu and Ozeh, 2013; Nwosu and Ewurum, 2018). However, there is a lack of continuous and systematic air quality monitoring, making it difficult for policymakers to implement data-driven interventions. Existing studies on air pollution in Aba have primarily relied on short-term and localized monitoring, often using traditional ground-based stations, which are limited in coverage and often suffer from maintenance challenges (Akuagwu and Ozeh, 2013; Anietimfon and Anaekwe, 2015; Nwosu and Ewurum, 2018). The use of advanced remote sensing technologies, such as Sentinel-5P satellite data, remains significantly underutilized in Nigeria's air quality management framework. This presents a major research gap, as satellite-based monitoring offers extensive spatial and temporal coverage, allowing for a more comprehensive assessment of pollution patterns over time (Oxoli *et al.*, 2020; Mathew *et al.*, 2024). Additionally, while numerous studies have assessed air pollution in major Nigerian cities like Lagos, Abuja and Port Harcourt (Adeyanju and Manohar, 2017; Nwachukwu *et al.*, 2019; Croitoru *et al.*, 2020; Amaechi *et al.*, 2023; Amaechi *et al.*, 2024a; Amin Kodiya *et al.*, 2025), there remains a significant gap in research focusing on medium-sized commercial hubs like Aba. The unique pollution dynamics of Aba, driven by its industrial activities and energy dependence, warrant a dedicated study to understand air quality variations and health implications. Furthermore, there has been little effort to integrate Geographic Information Systems (GIS) and Google Earth Engine (GEE) into air quality studies in Aba, despite their potential in visualizing pollution trends and aiding policy development (Reshi *et al.*, 2024). This study seeks to bridge these gaps by leveraging Sentinel-5P satellite data to analyze long-term trends in CO and aerosol concentrations in Aba from 2019 to 2024. The findings will provide valuable insights into pollution sources, seasonal variations, and exposure risks, ultimately guiding urban planners, environmental policymakers, and public health officials in developing targeted air quality management strategies. Without urgent action, the air pollution crisis in Aba will continue to threaten public health, economic productivity, and environmental sustainability.

CHAPTER TWO

2.0. LITERATURE REVIEW

2.1. AIR AND AIR QUALITY

Air is a critical component of the Earth's atmosphere, sustaining life and maintaining ecological balance (Ashraf and Mohd Hanafiah, 2019). It is a complex mixture of gases, primarily composed of nitrogen (78%) and oxygen (21%), with trace amounts of carbon dioxide, argon, and water vapor (Ashraf and Mohd Hanafiah, 2019). These components play vital roles in biological processes such as respiration and photosynthesis, which are essential for life on Earth (Ashraf and Mohd Hanafiah, 2019). The quality of air directly influences environmental sustainability, human health, and the global climate system. Clean air is necessary for maintaining the health of ecosystems, supporting agricultural productivity, and ensuring overall environmental stability (Ashraf and Mohd Hanafiah, 2019; von Schneidemesser *et al.*, 2020). According to the World Health Organization (WHO), exposure to polluted air significantly contributes to the global burden of disease, making air quality a pressing public health concern (Kjellstrom *et al.*, 2006; Kalender and Alkan, 2019; WHO, 2024).

Historically, the composition of air remained relatively constant before industrialization. However, human activities have increasingly introduced pollutants into the atmosphere, disrupting its natural balance (von Schneidemesser *et al.*, 2020). Modern air quality challenges stem from both natural and anthropogenic sources (Prajapati *et al.*, 2023). Natural contributors include volcanic eruptions and wildfires, which release significant amounts of particulate matter and gases into the atmosphere (Kjellstrom *et al.*, 2006; Kalender and Alkan, 2019). On the other hand, human-induced pollution arises from industrial emissions, transportation, deforestation, and urbanization, all of which contribute to air quality deterioration (Prajapati *et al.*, 2023). Air also interacts with various physical and chemical processes in the atmosphere, serving as a medium for the dispersion of pollutants that affect both local and global climates (Ashraf and Mohd Hanafiah, 2019; von Schneidemesser *et al.*, 2020; Prajapati *et al.*, 2023). Understanding its composition and dynamics is fundamental to assessing air quality and implementing effective pollution control strategies (Ashraf and Mohd Hanafiah, 2019; von Schneidemesser *et al.*, 2020; Prajapati *et al.*, 2023).

Air quality refers to the degree to which the air in a particular environment is clean or polluted, measured by the concentration of specific pollutants and their effects on human health and the environment (Kjellstrom *et al.*, 2006; Kalender and Alkan, 2019; Meda *et al.*, 2022). It is a critical environmental indicator that directly impacts public health, ecological balance, and economic productivity (Siddiqua *et al.*, 2022; Meda *et al.*, 2022). The United Nations Environment Programme has identified deteriorating air quality as a major challenge worldwide, particularly in urban and industrialized regions (Kjellstrom *et al.*, 2006; Kalender and Alkan, 2019; United Nations Environment Programme, 2021). The assessment of air quality involves monitoring pollutants such as Aerosols (particulate matter), nitrogen oxides (NO_x), sulfur dioxide (SO_2), ozone (O_3), and carbon monoxide (CO) (Meda *et al.*, 2022; Siddiqua *et al.*, 2022; Nakhjiri and Kakroodi, 2024). The WHO has established guidelines for acceptable levels of these pollutants, beyond which they pose severe health risks. For example, exposure to fine particulate matter ($PM_{2.5}$) has been linked to respiratory diseases, cardiovascular issues, and premature mortality (WHO, 2024; Siddiqua *et al.*, 2022; Meda *et al.*, 2022) .

Globally, air quality varies based on geographic location, human activity, and meteorological conditions (Sonwani and Saxena, 2016; Nakhjiri and Kakroodi, 2024). Developed nations often have stringent regulatory frameworks and advanced monitoring systems that help maintain better air quality. In contrast, many developing countries struggle with increasing air pollution due to rapid urbanization, industrialization, and weak regulatory enforcement. In Africa, air quality concerns are escalating as urban centers expand, traffic congestion worsens, and industrial emissions increase (Agbo *et al.*, 2021). Nigeria, for example, faces significant air quality challenges, particularly in major cities such as Lagos and Port Harcourt. Studies indicate that urban air quality indices in these areas frequently exceed WHO-recommended limits, exposing millions of residents to hazardous pollutants (Yakubu, 2018; Ndukwe *et al.*, 2022; Nicholas *et al.*, 2024). Maintaining good air quality is essential for sustainable development and public health. Effective management requires regular air quality monitoring, the enforcement of environmental policies, and public awareness initiatives to reduce pollution and mitigate its adverse effects (Agbo *et al.*, 2021).

2.2. AIR POLLUTION

Air pollution refers to the presence of harmful substances in the atmosphere that pose risks to human health, ecosystems, and infrastructure (Kjellstrom *et al.*, 2006; Kalender and Alkan, 2019; WHO, 2021). These pollutants can be either natural or anthropogenic, affecting the quality of the air we breathe and the overall environmental balance (Kjellstrom *et al.*, 2006; Kalender and Alkan, 2019; Smith and Taylor, 2020). Globally, air pollution is recognized as a major public health and environmental crisis, with millions of premature deaths annually linked to poor air quality (United Nations Environment Programme, 2021).

The World Health Organization (2021) identifies air pollution as one of the leading environmental risks to human health, contributing to approximately seven million premature deaths each year. Major sources include industrial activities, vehicular emissions, agricultural practices, and natural events such as wildfires and volcanic eruptions (Anderson *et al.*, 2020). Air pollution manifests in both outdoor (ambient) and indoor environments, with the former being a significant concern in urban and industrial areas (Johnson *et al.*, 2020; Siddiqua *et al.*, 2022; Nakhjiri and Kakroodi, 2024).

Air pollution has evolved into a global concern due to its transboundary nature (Zhang *et al.*, 2017). Pollutants released in one region can travel across borders through atmospheric currents, impacting regions far from their original source (Chen *et al.*, 2018). For instance, industrial emissions from Europe have been detected over the Arctic, demonstrating the far-reaching effects of air pollution (Abdelmajeed and Juszczak, 2024). This global dispersion of pollutants necessitates international collaboration to address air quality challenges.

In Africa, air pollution is becoming a pressing environmental and public health issue (Agbo *et al.*, 2021). Rapid urbanization, industrial growth, and population increase contribute to deteriorating air quality (Adedeji *et al.*, 2022). According to Petkova *et al.* (2013) African cities experience some of the highest levels of particulate matter globally, with major urban centers such as Lagos, Nairobi, and Cairo exceeding WHO air quality guidelines. The absence of stringent environmental policies and limited monitoring capacity further exacerbate the situation (Okonkwo and Uche, 2020). A significant contributor to air pollution in Africa is biomass burning for cooking and heating, which releases large amounts of particulate matter and carbon monoxide (Johnson *et al.*, 2020; Agbo *et al.*, 2021). Additionally, industrial emissions, vehicular exhaust, and open waste burning are major sources of air pollutants (Smith and Taylor, 2020).

The effects of air pollution are more severe in low-income urban communities, where access to clean energy and healthcare is limited (Abdelmajeed and Juszczak, 2024).

Nigeria faces critical air pollution challenges due to rapid industrialization, urbanization, and weak environmental regulations (Adedeji *et al.*, 2022; Lala *et al.*, 2023). Studies show that air pollution levels in major Nigerian cities consistently exceed WHO limits, contributing to increased respiratory diseases and other health complications (Chukwu *et al.*, 2022; Lala *et al.*, 2023). Port Harcourt, located in Rivers State, is particularly affected by black soot resulting from illegal oil refining and gas flaring (Okonkwo and Uche, 2020; Chukwu *et al.*, 2022; Lala *et al.*, 2022). This persistent pollution has led to community protests and calls for regulatory intervention (Smith and Taylor, 2020). In Northern Nigeria, including Kano State, air pollution is driven by agricultural activities and dust storms (Adedeji *et al.*, 2022). Although the industrial footprint is lower compared to southern states, seasonal dust from the Sahara Desert contributes to elevated particulate matter concentrations (Okonkwo and Uche, 2020; Chukwu *et al.*, 2022; Lala *et al.*, 2022). Addressing air pollution in Nigeria requires a multi-faceted approach, including improved monitoring systems, stringent environmental policies, and public awareness campaigns (Smith and Taylor, 2020).

2.3. TYPES OF AIR POLLUTANTS

Air pollutants are substances present in the atmosphere that can cause harm to human health, ecosystems, and the built environment (WHO, 2021). These pollutants originate from both natural and anthropogenic sources and are classified based on their chemical composition, physical state, and the manner in which they enter the atmosphere (Anderson *et al.*, 2020).

Understanding the types of air pollutants is essential for developing effective strategies to mitigate their impact on public health and the environment (Johnson *et al.*, 2020).

Air pollutants are generally categorized into primary and secondary pollutants (Smith and Taylor, 2020). Primary pollutants are emitted directly into the atmosphere from identifiable sources, while secondary pollutants form through chemical reactions involving primary pollutants and other atmospheric components (Chen *et al.*, 2018).

2.3.1. Primary Air Pollutants

Primary air pollutants are substances released directly from sources such as industrial activities, vehicles, and natural processes (Singh *et al.*, 2025). The most common primary pollutants include particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). Particulate matter also called aerosols consists of tiny solid and liquid particles suspended in the air. It is classified by size, with PM_{10} referring to particles with diameters less than 10 microns and $PM_{2.5}$ referring to finer particles with diameters less than 2.5 microns (WHO, 2021). Major sources of PM include vehicle emissions, industrial processes, and dust storms (Singh *et al.*, 2025). These fine particles pose significant health risks as they penetrate deep into the respiratory tract, causing respiratory and cardiovascular diseases (Johnson *et al.*, 2020).

Carbon monoxide (CO), a colorless and odorless gas, is produced from the incomplete combustion of carbon-based fuels (Smith and Taylor, 2020). Motor vehicles, biomass burning, and industrial processes are the primary contributors to CO emissions (Anderson *et al.*, 2020). When inhaled at high concentrations, CO reduces oxygen delivery to body tissues, which can lead to cardiovascular complications and neurological impairments (Singh *et al.*, 2025).

Similarly, sulfur dioxide (SO_2), a pungent gas, is primarily emitted through the burning of fossil fuels, particularly coal and oil, as well as through industrial activities like petroleum refining (Johnson *et al.*, 2020). Exposure to SO_2 causes respiratory irritation and contributes to the formation of acid rain, which severely affects ecosystems (Singh *et al.*, 2025).

Nitrogen oxides (NO_x), including nitric oxide (NO) and nitrogen dioxide (NO_2), are another significant group of primary air pollutants. These gases are produced through high-temperature combustion processes, especially in vehicles and power plants (WHO, 2021). NO_x gases play a crucial role in the formation of ground-level ozone and smog, which exacerbate respiratory conditions and contribute to environmental degradation (Okonkwo and Uche, 2020). Volatile organic compounds (VOCs) are organic chemicals that easily evaporate at room temperature. These compounds originate from vehicle emissions, industrial processes, and household products such as paints and solvents (Chen *et al.*, 2018). VOCs play a key role in the formation of ground-level ozone and present health risks ranging from respiratory irritation to cancer (Abdelmajeed and Juszczak, 2024). While the emission sources and health impacts of carbon monoxide and aerosols are well established, their atmospheric behavior and concentration levels are significantly influenced by meteorological parameters, which control their dispersion, transformation, and removal processes.

Meteorological parameters strongly affect CO and aerosol concentrations by controlling dispersion, chemical transformation, and removal. High temperatures enhance photochemical reactions, increasing secondary aerosol formation (Seinfeld and Pandis, 2016). Under intense sunlight and elevated atmospheric temperatures, volatile organic compounds and CO participate in photochemical reactions, generating secondary organic aerosols, thereby elevating overall particulate matter levels (Seinfeld and Pandis, 2016). Low wind speeds trap CO and aerosols near emission sources, leading to higher localized pollutant concentrations, while strong winds enhance horizontal and vertical dispersion, reducing surface-level concentrations (Jacobson, 2012). Humidity also plays a critical role; high humidity conditions promote particle growth through aqueous-phase reactions, leading to larger aerosol sizes and modified chemical compositions (Zhang *et al.*, 2015). Solar radiation accelerates CO oxidation into carbon dioxide, while simultaneously promoting the formation of oxidants that contribute to secondary aerosol production (Finlayson-Pitts and Pitts, 2000). Additionally, rainfall acts as an atmospheric cleansing mechanism, removing aerosols and soluble gases through wet deposition and temporarily improving air quality (Pope and Dockery, 2006). Consequently, variations in temperature, wind speed, humidity, solar intensity, and precipitation patterns drive significant spatiotemporal variations in CO and aerosol levels across different regions and seasons, influencing both air quality and public health outcomes.

2.3.2. Secondary Air Pollutants

Secondary air pollutants are not emitted directly but form through chemical reactions between primary pollutants and other atmospheric compounds (Anderson *et al.*, 2020). These pollutants are particularly harmful due to their ability to disperse widely and their persistent effects on health and the environment (Singh *et al.*, 2025). Among the most significant secondary pollutants is ground-level ozone (O_3), which forms when nitrogen oxides (NO_x) react with volatile organic compounds (VOCs) in the presence of sunlight (Zhao and Wang, 2022). Ozone is a major component of photochemical smog and is associated with serious health risks, including respiratory distress and reduced lung function (Singh *et al.*, 2025). In Nigeria, urban areas such as Lagos and Port Harcourt experience elevated ozone levels due to traffic congestion and industrial emissions (Okonkwo and Uche, 2020).

Sulfuric and nitric acids, which are precursors to acid rain, also form as secondary pollutants. These acids result from the chemical reaction of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) with water vapor in the atmosphere (Kjellstrom *et al.*, 2006; Kalender and Alkan, 2019; Chen *et al.*, 2018). Acid rain has detrimental environmental impacts, including damage to ecosystems, the corrosion of infrastructure, and the acidification of water bodies, which disrupts aquatic life (Abdelmajeed and Juszczak, 2024). Another significant secondary pollutant is peroxyacetyl nitrate (PANs), which are byproducts of photochemical reactions involving VOCs and NO_x (Smith and Taylor, 2020). PANs contribute to eye irritation, respiratory problems, and reduced agricultural productivity (Anderson *et al.*, 2020).

The formation of secondary pollutants underscores the complexity of air pollution, as they often arise from interactions between various primary pollutants and environmental conditions. Their widespread distribution and lasting effects make them a major concern for both public health and environmental sustainability (Nyakuma *et al.*, 2022).

2.4. SOURCES OF AIR POLLUTANTS

Air pollutants originate from a wide range of natural and anthropogenic (human-made) sources, each contributing to varying levels of air contamination (WHO, 2021). Identifying these sources is crucial for developing effective air quality management strategies and mitigating their adverse effects on human health and the environment (Smith and Taylor, 2020). Air pollutants can be categorized based on their origin into natural and anthropogenic sources (Johnson *et al.*, 2020).

2.4.1. Natural Sources of Air Pollutants

Natural sources of air pollution are those that occur without human intervention. While these pollutants are part of natural ecological processes, their concentration can have significant environmental and health impacts (Anderson *et al.*, 2020). Volcanic eruptions are a major natural source, releasing large quantities of gases and particulate matter, including sulfur dioxide (SO_2), carbon dioxide (CO_2), and ash (Meda *et al.*, 2022; Siddiqua *et al.*, 2022; Nakhjiri and Kakroodi, 2024). These emissions can cause respiratory problems and contribute to the formation of acid rain, which negatively affects ecosystems and infrastructure (Mahmud *et al.*, 2023). Dust storms, particularly in arid and semi-arid regions, also contribute to air pollution by releasing fine particulate matter (PM) into the atmosphere (Okonkwo and Uche, 2020). Northern Nigeria, experiences significant dust pollution during the Harmattan season, which affects air quality and visibility (Yakubu, 2018).

Wildfires are another natural source of air pollutants, generating particulate matter, carbon monoxide (CO), and volatile organic compounds (VOCs) (Smith and Taylor, 2020). These pollutants degrade air quality and pose respiratory risks, especially in regions prone to seasonal fires (Zhao and Wang, 2022). Biogenic emissions from plants and other biological sources release volatile organic compounds (VOCs) through natural processes (Anderson *et al.*, 2020). Although these emissions are typically low, they contribute to the formation of secondary pollutants like ground-level ozone (Chen *et al.*, 2018). Oceans and seas also act as natural sources of air pollution by releasing aerosols, including salt particles and organic compounds, into the atmosphere (Johnson *et al.*, 2020). These particles play a crucial role in influencing cloud formation and atmospheric chemistry, impacting climate and weather patterns (Siddiqua *et al.*, 2022).

2.4.2. Anthropogenic Sources of Air Pollutants

Anthropogenic sources, resulting from human activities, are the primary contributors to air pollution globally (WHO, 2021). These sources are increasing due to industrialization, urbanization, and the expansion of transportation systems (Okonkwo and Uche, 2020). Among the most significant anthropogenic sources are industrial activities, including fossil fuel combustion, manufacturing processes, and mining operations. Power plants and industrial facilities burn coal, oil, and natural gas, releasing pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM) (Chen *et al.*, 2018). In Nigeria, the oil and gas industry in Rivers State is a major source of air pollution due to gas flaring and oil refining, releasing hazardous air pollutants (Adedeji *et al.*, 2022). Mining operations also contribute to air pollution by releasing particulate matter and heavy metals, which negatively impact air quality and public health (Zhao and Wang, 2022).

Transportation is another significant anthropogenic source, with vehicle emissions contributing to carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) from fuel combustion (Smith and Taylor, 2020). In densely populated urban areas such as Lagos, vehicular traffic is a primary source of air pollution, leading to severe health and environmental issues (Mahmud *et al.*, 2023). Aviation and shipping also add to atmospheric pollution by emitting greenhouse gases and particulate matter, which exacerbate climate change and local air quality degradation (Anderson *et al.*, 2020).

Agricultural practices significantly contribute to air pollution through crop residue burning and livestock emissions. The practice of burning agricultural residues releases carbon monoxide (CO), particulate matter (PM), and other pollutants (Johnson *et al.*, 2020). This is a common practice in rural areas of Nigeria, where it contributes to regional air pollution and environmental degradation (Adedeji *et al.*, 2022). Livestock emissions, particularly methane (CH_4) produced through enteric fermentation and waste decomposition, are a potent greenhouse gas that contributes to global warming (Okonkwo and Uche, 2020).

Residential and commercial activities, such as biomass and solid fuel burning, also play a significant role in air pollution. In many developing regions, including Nigeria, households burn wood, charcoal, and other solid fuels for cooking and heating (Smith and Taylor, 2020). This practice generates indoor air pollution, which is linked to respiratory diseases and other health complications (WHO, 2021). Additionally, waste incineration in urban Nigeria produces toxic pollutants, including dioxins, furans, and heavy metals, due to inadequate waste management infrastructure (Mahmud *et al.*, 2023; Chen *et al.*, 2018).

Energy generation through gas flaring is a major source of air pollution in oil-producing regions like Rivers State. Gas flaring releases substantial quantities of carbon dioxide (CO_2), sulfur dioxide (SO_2), and black carbon, which have been linked to severe air quality degradation and health problems (Adedeji *et al.*, 2022). This practice not only harms local communities but also contributes to global climate change by adding greenhouse gases to the atmosphere (Okonkwo and Uche, 2020).

2.5. INFLUENCE OF METEOROLOGY PARAMETERS ON AIR POLLUTANTS

Meteorological parameters play a critical and multifaceted role in influencing carbon monoxide (CO) and aerosol concentrations by governing the mechanisms of atmospheric dispersion, chemical transformation, and removal processes (von Schneidemesser *et al.*, 2020; Prajapati *et al.*, 2023). Temperature, wind speed, humidity, solar radiation, and precipitation collectively shape the spatiotemporal dynamics of these pollutants (Seinfeld and Pandis, 2016). High ambient temperatures significantly enhance photochemical activity in the atmosphere, promoting the transformation of primary pollutants into secondary pollutants. Specifically, elevated temperatures accelerate the formation of secondary aerosols through thermally driven photochemical reactions involving volatile organic compounds (VOCs) and CO (Seinfeld and Pandis, 2016; von Schneidemesser *et al.*, 2020; Prajapati *et al.*, 2023). These reactions are particularly active during periods of intense solar radiation and high atmospheric temperatures, wherein VOCs and CO interact in the presence of sunlight to form secondary organic aerosols (SOAs). The resulting SOAs contribute substantially to fine particulate matter ($PM_{2.5}$), thereby deteriorating air quality (Seinfeld and Pandis, 2016). Wind speed is another crucial parameter; low wind velocities hinder pollutant dispersion, allowing CO and aerosols to accumulate near their emission sources (Seinfeld and Pandis, 2016). This stagnation can lead to elevated local concentrations, particularly in urban or industrial regions with dense emissions (Seinfeld and Pandis, 2016). In contrast, higher wind speeds enhance both horizontal and vertical mixing of air masses, facilitating the dilution and transport of pollutants away from the surface and reducing their concentration in the breathing zone (Jacobson, 2012; Siddiqua *et al.*, 2022; Nakhjiri and Kakroodi, 2024). This dynamic dispersion effect can lead to significant spatial variability in pollutant levels, even within relatively small geographic areas. Humidity, particularly relative humidity, further modulates aerosol behavior (Zhang *et al.*, 2015). Under high humidity conditions, aerosols can absorb moisture, resulting in hygroscopic growth. This growth leads to increased particle size and mass, alters their optical and chemical properties, and enhances their potential health impacts (Zhang *et al.*, 2015; Siddiqua *et al.*, 2022; Nakhjiri and Kakroodi, 2024). Moreover, aqueous-phase reactions in humid conditions enable the formation of secondary aerosols through pathways that are less active in drier air, thus contributing further to particulate matter loadings (Choudhary *et al.*, 2015; Wassie, 2020). Solar radiation acts as a primary driver for photochemical processes in the troposphere. It accelerates the oxidation of CO into carbon dioxide (CO_2), a less harmful gas in terms of immediate health effects (Choudhary *et al.*, 2015; Wassie, 2020). Simultaneously, solar radiation facilitates the production of photochemical oxidants, such as ozone and hydroxyl radicals, which play a central role in the formation of secondary aerosols (Finlayson-Pitts and Pitts, 2000; Siddiqua *et al.*, 2022; Nakhjiri and Kakroodi, 2024). These oxidants not only transform VOCs into SOAs but also engage in complex chemical cycles that sustain and amplify aerosol formation under favorable meteorological conditions. Rainfall, on the other hand, serves as a natural atmospheric cleansing agent (Mahmud *et al.*, 2023; Nicholas *et al.*, 2024). Through wet deposition processes, rain effectively removes both aerosols and soluble gaseous pollutants from the atmosphere (Mahmud *et al.*, 2023; Nicholas *et al.*, 2024). This scavenging effect leads to a temporary reduction in pollutant concentrations and an improvement in air quality following precipitation events (Pope and Dockery, 2006). However, the extent and duration of this cleansing effect depend on rainfall intensity, duration, and the nature of the pollutants involved.

Therefore, the interaction between meteorological factors and atmospheric pollutants is highly dynamic and nonlinear (Siddiqua *et al.*, 2022; Nakhjiri and Kakroodi, 2024). Variations in temperature, wind patterns, humidity levels, solar intensity, and precipitation collectively drive substantial temporal and spatial fluctuations in CO and aerosol concentrations (Mahmud *et al.*, 2023; Nicholas *et al.*, 2024). These fluctuations not only affect visibility and atmospheric chemistry but also have profound implications for human health, particularly in regions with vulnerable populations or inadequate pollution control measures (Mahmud *et al.*, 2023; Nicholas *et al.*, 2024). Understanding these meteorological influences is thus critical for accurate air quality forecasting, health risk assessment, and the development of effective mitigation strategies (Mahmud *et al.*, 2023; Nicholas *et al.*, 2024).

2.6. IMPACTS OF AIR POLLUTION

Air pollution has far-reaching consequences that extend beyond environmental degradation. Its effects are multifaceted, encompassing human health, the environment, the economy, and the social fabric of affected communities (WHO, 2021). The severity of these impacts depends on pollutant concentration, exposure duration, and population vulnerability (Smith and Taylor, 2020). Globally, air pollution contributes to millions of premature deaths and places significant burdens on public health systems (Anderson *et al.*, 2020). In developing nations such as Nigeria, the lack of effective air quality monitoring and regulatory enforcement exacerbates these effects (Mahmud *et al.*, 2023; Nicholas *et al.*, 2024).

2.6.1. Health Impacts of Air Pollution

Exposure to air pollution is a major public health concern, linked to both acute and chronic health conditions (WHO, 2021). Air pollutants, particularly fine particulate matter (PM2.5), ozone (O_3), and nitrogen oxides (NO_x), can enter the respiratory system and trigger a wide range of health problems (Chen *et al.*, 2018). Air pollution is a significant contributor to respiratory illnesses, including asthma, chronic obstructive pulmonary disease (COPD), and acute respiratory infections (Johnson *et al.*, 2020). Long-term exposure to fine particulate matter increases the risk of developing and exacerbating these conditions (Abdelmajeed and Juszczak, 2024). Studies conducted in Nigeria's urban centers, particularly Lagos and Port Harcourt, reveal a high prevalence of respiratory issues associated with vehicular and industrial emissions (Okonkwo and Uche, 2020; Chukwu *et al.*, 2022; Nyakuma *et al.*, 2022; Lala *et al.*, 2023).

Particulate matter and gaseous pollutants such as carbon monoxide (CO) and nitrogen oxides (NO_x) are also linked to cardiovascular diseases, including heart disease, hypertension, and stroke (Adedeji *et al.*, 2022). Research indicates that long-term exposure to $PM_{2.5}$ increases the likelihood of cardiac arrhythmias and heart attacks (Kumar *et al.*, 2020; Gul and Das, 2023). This is particularly concerning in Nigeria, where high levels of air pollution from industrial sources and gas flaring exacerbate cardiovascular risks (Smith and Taylor, 2020). In addition to respiratory and cardiovascular diseases, air pollution is a known cause of cancer. Airborne carcinogens such as benzene, polycyclic aromatic hydrocarbons (PAHs), and heavy metals increase the risk of lung and other cancers (Chen *et al.*, 2018). The International Agency for Research on Cancer (IARC) classifies outdoor air pollution as a Group 1 carcinogen (WHO, 2021).

Emerging evidence suggests that air pollution affects brain development and cognitive function (Smith and Taylor, 2020). Children exposed to high levels of pollutants demonstrate lower IQ scores and an increased prevalence of neurodevelopmental disorders (Anderson *et al.*, 2020). In Nigerian cities, the combined effects of traffic emissions and poor air quality present a growing public health concern (Okonkwo and Uche, 2020). Additionally, prenatal exposure to air pollution is associated with adverse birth outcomes, including low birth weight, preterm birth, and infant mortality (Johnson *et al.*, 2020). Pregnant women exposed to elevated levels of particulate matter and nitrogen oxides face increased risks of pregnancy complications (Chen *et al.*, 2018). Studies in northern Nigeria highlight the impact of household air pollution from biomass burning on maternal and child health, raising serious public health concerns (Adedeji *et al.*, 2022; Nyakuma *et al.*, 2022).

2.6.2. Environmental Impacts of Air Pollution

Air pollution has profound consequences for ecosystems, biodiversity, and atmospheric processes (Smith and Taylor, 2020). Pollutants disrupt ecological balance and contribute to climate change through the emission of greenhouse gases (Anderson *et al.*, 2020). Sulfur dioxide (SO_2) and nitrogen oxides (NO_x) react with atmospheric moisture to form sulfuric and nitric acids, which fall as acid rain (Choudhary *et al.*, 2015; Wassie, 2020). Acid rain alters soil chemistry, reduces agricultural productivity, and harms aquatic ecosystems (Choudhary *et al.*, 2015). In Nigeria's Niger Delta region, acid rain resulting from gas flaring accelerates soil degradation, making agricultural activities more challenging (Adedeji *et al.*, 2022).

Greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and black carbon trap heat in the atmosphere, contributing to global warming (Abdelmajeed and Juszczak, 2024). Gas flaring in Nigeria releases substantial amounts of CO_2 and methane, exacerbating both regional and global climate change (Smith and Taylor, 2020). This further intensifies extreme weather patterns, including droughts and floods, which threaten local communities. Additionally, particulate matter and ground-level ozone contribute to reduced visibility and the formation of photochemical smog (Chen *et al.*, 2018). Nigerian cities, particularly Port Harcourt, experience persistent smog linked to industrial activities and vehicular emissions, posing a significant environmental and public health risk (Anderson *et al.*, 2020; Ndukwe *et al.*, 2022).

Air pollution also causes damage to vegetation and wildlife. Pollutants such as ozone and heavy metals impair plant growth and reduce biodiversity (WHO, 2021). In agricultural regions of Nigeria, air pollution reduces crop yields and disrupts local ecosystems (Awewomom *et al.*, 2024). The accumulation of pollutants in plant tissues and water sources further threatens wildlife and their natural habitats, compounding the ecological damage.

2.6.3. Economic Impacts of Air Pollution

The economic burden of air pollution is substantial, with costs arising from healthcare expenses, productivity losses, and environmental degradation (Smith and Taylor, 2020). Increased incidences of respiratory and cardiovascular diseases elevate healthcare costs for individuals and governments (Johnson *et al.*, 2020). In Nigeria, the treatment of air pollution-related illnesses imposes a significant financial burden on public health systems, straining already limited resources (Adedeji *et al.*, 2022). Moreover, air pollution reduces workforce productivity due to increased absenteeism and premature mortality (Mahmud *et al.*, 2023). Studies suggest that poor air quality leads to a decline in worker efficiency, resulting in significant economic losses (Abdelmajeed and Juszczak, 2024).

In addition to health and productivity costs, air pollution causes severe damage to infrastructure. Acid rain and particulate matter accelerate the deterioration of buildings, bridges, and cultural monuments (Okonkwo and Uche, 2020). In Nigeria, the economic cost of repairing pollution-related damage to infrastructure is substantial, particularly in urban areas where industrial activities are concentrated (Chen *et al.*, 2018). Furthermore, pollutant deposition damages crops and reduces agricultural yields (Smith and Taylor, 2020). In regions affected by gas flaring, soil acidification and reduced crop viability contribute to economic hardship, undermining the livelihoods of local farmers (Anderson *et al.*, 2020).

2.6.4. Social and Cultural Impacts of Air Pollution

Air pollution influences social and cultural practices, community health, and overall quality of life (Smith and Taylor, 2020). Severe environmental degradation can lead to the displacement of communities, particularly in areas affected by industrial pollution (Adedeji *et al.*, 2022). In the Niger Delta, pollution-induced land degradation forces migration and disrupts traditional livelihoods, exacerbating social instability (Yakubu, 2018; Ndukwe *et al.*, 2022; Nicholas *et al.*, 2024). This displacement not only affects the physical well-being of communities but also weakens social cohesion and cultural identity.

Environmental justice issues also arise from air pollution, as marginalized communities often bear the brunt of its impacts due to their proximity to industrial zones and their lack of political influence (Abdelmajeed and Juszczak, 2024). In Nigeria, socioeconomically disadvantaged groups face greater health risks from pollution, reflecting broader patterns of environmental inequality (Okonkwo and Uche, 2020). Air pollution also accelerates the decay of cultural monuments and heritage sites, threatening the preservation of historical artifacts (Smith and Taylor, 2020). Acid rain and particulate matter have caused damage to important historic structures in Nigeria's urban centers, posing challenges to cultural conservation efforts (Chen *et al.*, 2018).

2.7. METHODS OF MONITORING AIR QUALITY

Monitoring air quality is essential for assessing pollution levels, understanding pollution sources, and implementing effective mitigation strategies (WHO, 2021). Accurate air quality monitoring allows policymakers to develop evidence-based interventions to protect public health and the environment (Chen *et al.*, 2018). Different methods are used to monitor air pollutants, ranging from simple handheld devices to advanced satellite-based remote sensing technologies (Johnson *et al.*, 2020).

2.7.1. Handheld Meters

Handheld air quality meters are portable devices used to measure real-time concentrations of specific air pollutants. These devices are valuable for on-the-ground monitoring, especially in localized areas where fixed monitoring stations may not be available or practical (Anderson *et al.*, 2020). They are commonly used for rapid assessments, research purposes, and regulatory compliance checks (Rahman, 2023).

Handheld meters vary based on the pollutants they measure. Particulate matter monitors are designed to measure the concentration of airborne particles, specifically PM2.5 and PM10, which are significant indicators of air pollution (Smith and Taylor, 2020). Gas detectors use electrochemical sensors to detect gases such as carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) (Rahman, 2023). Volatile organic compound (VOC) sensors measure organic gases released from industrial processes, which pose health risks and contribute to environmental degradation (Rahman, 2023).

Handheld meters offer several advantages. Their portability allows for rapid deployment across multiple locations, making them ideal for quick assessments and emergency responses (Abdelmajeed and Juszczak, 2024). They are also more cost-effective compared to stationary monitoring stations, making them accessible for smaller-scale projects and developing regions (Rahman, 2023). Additionally, these devices provide real-time data, enabling immediate decision-making and faster responses to pollution events (Chen *et al.*, 2018).

Despite these advantages, handheld meters have limitations. Their limited range makes them suitable only for small-scale monitoring, and they are not effective for assessing pollution over large geographic areas (Anderson *et al.*, 2020). They also require regular calibration to maintain measurement accuracy, which can be resource-intensive and time-consuming (Johnson *et al.*, 2020).

In Nigeria, handheld meters are commonly used by researchers and environmental agencies to monitor air pollution levels in urban and industrial areas (Mahmud *et al.*, 2023).

2.7.2. Monitoring Stations

Monitoring stations are fixed sites equipped with advanced sensors to measure multiple air pollutants continuously (Larson *et al.*, 2017; Deshmukh *et al.*, 2020; New York State Department of Environmental Conservation, 2024). These stations play a critical role in providing long-term data for tracking pollution trends, understanding seasonal variations, and ensuring regulatory compliance (World Health Organization, 2021; Smith and Taylor, 2020).

Different types of monitoring stations serve various purposes (Deshmukh *et al.*, 2020). Ambient air monitoring stations measure pollutants in the outdoor environment, including particulate matter, nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) (Anderson *et al.*, 2020). Industrial emission monitoring stations are located near industrial sites to track emissions from factories and other heavy industries (Chen *et al.*, 2018). Traffic monitoring stations are placed in areas with high vehicular activity to assess pollutants generated by vehicle emissions (Singh *et al.*, 2021).

Monitoring stations provide several benefits (Deshmukh *et al.*, 2020; New York State Department of Environmental Conservation, 2024). They enable continuous, 24/7 data collection, which supports comprehensive long-term trend analysis and a better understanding of air pollution patterns (Larson *et al.*, 2017; Singh *et al.*, 2021). The high-precision instruments used in these stations offer accurate and reliable pollutant measurements, ensuring the credibility of collected data (Singh *et al.*, 2021). Additionally, these stations play an essential role in regulatory compliance by providing data to enforce environmental laws and monitor pollution thresholds (Abdelmajeed and Juszczak, 2024).

However, monitoring stations have notable limitations. They are expensive to install and maintain, which poses challenges for developing countries like Nigeria (US Environmental Protection Agency, 2023).

2.7.3. Remote Sensing

Remote sensing is a method of air quality monitoring that uses satellites and aerial platforms to collect large-scale data from the atmosphere (Fioletov *et al.,* 2016). This approach is essential for monitoring pollution across extensive regions, including remote and inaccessible areas where ground-based measurements may not be feasible (World Health Organization, 2021; Johnson *et al.*, 2020).

Remote sensing is categorized by the platform used to capture data. Satellite-based remote sensing relies on instruments aboard satellites such as Sentinel-5P and MODIS, which measure atmospheric pollutants from space (Smith and Taylor, 2020). Aerial platforms, including aircraft and drones, collect high-resolution air quality data over specific regions, providing a closer perspective than satellite systems (Anderson *et al.*, 2020).

Remote sensing offers several advantages. It provides wide geographic coverage, enabling the monitoring of pollution across large areas and regions with limited accessibility (Chen *et al.*, 2018). This method is also non-intrusive, allowing data collection without the need for physical instruments on the ground (Anenberg *et al.*, 2020). Furthermore, remote sensing provides access to historical data, which is invaluable for long-term climate research and pollution trend analysis (Abdelmajeed and Juszczak, 2024).

Despite its benefits, remote sensing has certain limitations (Fioletov *et al.,* 2016). The spatial resolution of satellite-based measurements is lower compared to ground-based monitoring stations, which may affect the precision of localized pollution assessments (Anenberg *et al.*, 2020). Additionally, atmospheric interference from weather conditions such as cloud cover can reduce data accuracy, particularly for pollutants near the surface (Anenberg *et al.*, 2020). Remote sensing provides a comprehensive overview of air pollution dynamics, supporting policy-making and environmental management efforts (Fioletov *et al.,* 2016).

2.7.3.1. Sentinel-5P

Sentinel-5 Precursor (Sentinel-5P) is a satellite launched by the European Space Agency (ESA) to monitor atmospheric composition globally (ESA, 2021). As part of the Copernicus program, it provides high-resolution data on pollutants such as ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), methane (CH_4), and aerosols (Ali *et al.*, 2024; Anwer and Anwer, 2025). This data is essential for assessing pollution trends, informing environmental policies, and supporting public health interventions (ESA, 2021).

The satellite's primary instrument, the TROPOspheric Monitoring Instrument (TROPOMI), captures atmospheric pollutants using ultraviolet, visible, near-infrared, and shortwave infrared spectrometry (Ali *et al.*, 2024; Anwer and Anwer, 2025). With a spatial resolution of 3.5 km × 7 km, Sentinel-5P can identify localized pollution sources and track emission hotspots (ESA, 2021). The satellite measures NO_2 from vehicular and industrial emissions (ESA, 2021), O_3 as a key component of ground-level smog (Ali *et al.*, 2024; Anwer and Anwer, 2025), SO_2 from volcanic activity and coal combustion (ESA, 2021), CO as an indicator of incomplete fossil fuel combustion (Ali *et al.*, 2024; Anwer and Anwer, 2025), CH_4 from agriculture, landfills, and the oil and gas sector (ESA, 2021), and aerosols that influence air quality and climate change (Ali *et al.*, 2024; Anwer and Anwer, 2025). The data is publicly available through the Copernicus Open Access Hub, facilitating pollution analysis and regulatory evaluations (ESA, 2021).

Sentinel-5P plays a crucial role in air quality monitoring by identifying pollution hotspots and assessing the environmental impacts of human activities (ESA, 2021). During the COVID-19 lockdowns, it detected significant reductions in NO_2 concentrations due to decreased industrial and vehicular activity (Bauwens *et al.*, 2020). In urban areas such as Lagos, Port Harcourt, Benin city, Kano and Abuja Sentinel-5P data has revealed elevated levels of CO, Aerosols, NO_2 and SO_2 from vehicular traffic and industrial emissions (Okoduwa and Amaechi, 2023; Mahmud *et al.*, 2023; Amaechi *et al.*, 2024b; Amaechi *et al.*, 2024c). In the Niger Delta, the satellite has identified high SO_2 concentrations from gas flaring, supporting regulatory efforts to mitigate air pollution (Mahmud *et al.*, 2023).

Beyond pollution monitoring, Sentinel-5P contributes to public health research by linking long-term exposure to pollutants like NO_2 and $PM_{2.5}$ with respiratory and cardiovascular diseases (Mahmud *et al.*, 2023). The satellite also supports climate change studies by tracking greenhouse gases such as CH_4 and CO, which are essential for climate modeling and mitigation strategies (Bauwens *et al.*, 2020).

Despite its advantages, Sentinel-5P has some limitations. Its spatial resolution, though improved compared to previous satellites, may not capture fine-scale pollution variations in highly urbanized or geographically complex areas (Ali *et al.*, 2024; Anwer and Anwer, 2025). Atmospheric interference, such as cloud cover, can also affect measurement accuracy, leading to gaps in data collection (Bauwens *et al.*, 2020). Additionally, analyzing and interpreting Sentinel-5P data requires advanced computational resources and technical expertise, which may pose challenges for some research institutions and policymakers (Mahmud *et al.*, 2023). Despite these constraints, Sentinel-5P remains a critical tool for monitoring air pollution and guiding environmental policies in Nigeria and globally (Amaechi *et al.*, 2024c; Halder *et al.*, 2023; Bendib and Boutrid, 2024; Singh *et al.*, 2025).

Jones (2021) utilized Sentinel-5P data to track transboundary air pollution across Southeast Asia. Their study focused on identifying pollution plumes originating from biomass burning and industrial emissions and tracing their cross-border transport. The researchers analyzed TROPOMI data from 2018 to 2021, focusing on Thailand, Malaysia, and Indonesia. They integrated satellite data with atmospheric transport models to trace pollution dispersion and quantified pollutant concentrations over time. The study found that NO_2 and carbon monoxide (CO) plumes from Indonesian peatland fires regularly affected neighboring countries. During peak burning seasons, NO_2 levels increased by 50% in downwind areas, with significant pollution detected over urban centers in Malaysia and southern Thailand. Jones (2021) advocated for using Sentinel-5P to monitor cross-border pollution and enforce international agreements on transboundary haze. They emphasized that satellite monitoring improves early warning systems and enhances regional cooperation on air quality management.

Behera *et al.* (2021) investigated the impact of COVID-19 lockdowns on air quality in India from 2019 to 2021. The study aimed to measure changes in pollutant concentrations during different phases of the lockdown and assess whether temporary reductions had lasting effects. They used Sentinel-5P TROPOMI satellite data to track NO_2, CO, and aerosol levels across major Indian cities and industrial hubs. The study compared pre-lockdown, lockdown, and post-lockdown air quality trends, linking pollution changes to reductions in vehicular and industrial activities. They found that NO_2 and CO levels dropped by over 50% in urban centers during the lockdown, with the most significant reductions in highly industrialized regions. Aerosol concentrations also declined, improving visibility and reducing respiratory health risks. However, pollution levels rebounded after restrictions eased, with some cities exceeding pre-pandemic concentrations due to the rapid resumption of economic activities. They concluded that COVID-19 lockdowns demonstrated the potential for rapid air quality improvement when emissions sources are controlled. The study recommended long-term strategies such as stricter industrial regulations, cleaner transportation systems, and sustainable urban planning to maintain air quality gains.

Shabbir (2023) analyzed cross-border air pollution trends in the Punjab and Haryana regions of India and Pakistan from 2019 to 2022. The study focused on how COVID-19 lockdowns influenced NO_2 and CO levels and how pollutants moved across national borders. They used Sentinel-5P TROPOMI data to examine spatio-temporal variations in NO_2 and CO concentrations. The study tracked pollution changes before, during, and after lockdowns, assessing emissions sources such as industrial activities, vehicular traffic, and agricultural burning. They found that NO_2 and CO levels decreased by over 40% during lockdowns, particularly in industrial areas. The study also revealed that pollution levels rebounded quickly as restrictions eased, driven by increased vehicle use and post-lockdown economic activities. Additionally, researchers observed significant transboundary pollution transport between India and Pakistan, highlighting the need for coordinated air quality management. They concluded that temporary air quality improvements during lockdowns emphasized the importance of long-term emission control policies. The study recommended collaborative air pollution management between India and Pakistan, stricter industrial regulations, and sustainable agricultural practices to mitigate pollution.

Maurya *et al.* (2022) investigated the impact of stubble burning on air quality using Sentinel-5P TROPOMI data from 2019 to 2023. The study focused on NO_2, CO, and aerosols, assessing pollution trends during and after the burning season. They used satellite observations to monitor pollutant levels in agricultural regions where stubble burning is a common practice. The study examined seasonal variations and assessed how pollution spread beyond the source areas. They found that NO_2 and CO concentrations increased significantly during post-harvest stubble burning, with peaks in October and November. Aerosol levels also spiked, leading to deteriorating air quality and visibility issues. The study identified that pollutants traveled beyond agricultural zones, affecting nearby cities and contributing to regional air pollution. They concluded that stubble burning is a major contributor to seasonal air quality degradation. The study recommended alternative farming practices, stricter enforcement of burning bans, and real-time air quality monitoring to mitigate pollution.

Hassaan *et al.* (2023) assessed air pollution vulnerability in the Nile Delta, Egypt, from 2019 to 2023. The study focused on identifying pollution hotspots and determining how population density influences air quality risks. They used Sentinel-5P satellite imagery to monitor NO_2, CO, and aerosol concentrations across urban and industrial zones. The study analyzed how meteorological factors and land use patterns affected pollution dispersion. They found that Cairo and other urban centers in the Nile Delta had the highest NO_2 concentrations, primarily due to industrial emissions and vehicular traffic. CO and aerosol levels were elevated in residential areas with high population density. Pollution worsened during winter due to temperature inversions trapping pollutants near the surface. The study also revealed that industrial zones contributed significantly to air pollution, particularly along the Nile River. They concluded that densely populated areas in the Nile Delta face serious air quality challenges. The study recommended enforcing stricter industrial emissions controls, expanding public transportation, and increasing air quality monitoring efforts.

Omokpariola *et al.* (2024) analyzed air quality trends in Nigeria from 2018 to 2022, focusing on NO_2, CO, and aerosols. The study aimed to identify short-term pollution patterns and assess the impact of regulatory measures and economic activities on air quality. They used Sentinel-5P and 3A/B satellite data to monitor air pollutants across Nigeria's urban, industrial, and rural regions. The study examined seasonal variations and linked changes in pollution levels to economic activities, meteorological factors, and policy interventions. They found that NO_2 and CO levels steadily increased in Lagos, Kano, and Port Harcourt, mainly due to industrial expansion and rising vehicle emissions. Aerosol concentrations remained high in northern Nigeria, particularly during the dry season when harmattan winds transported dust across the region. In 2020, pollution levels dropped briefly due to COVID-19 lockdowns but rebounded in 2021 as restrictions eased. The study highlighted a general increase in pollutant concentrations over the five years. They concluded that air pollution in Nigeria is worsening, driven by rapid urbanization and weak regulatory enforcement. The study recommended stricter emissions controls, improved air quality monitoring, and stronger environmental policies to mitigate pollution levels.

Okoduwa and Amaechi (2023) focused on monitoring and mapping carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) concentrations in Benin City, a rapidly growing urban area in Southern Nigeria. The primary objective was to track the temporal and spatial variations of these pollutants over a four-year period (2019–2022) and to analyze their relationship with human activities and environmental policies. Okoduwa and Amaechi (2023) employed Google Earth Engine (GEE) and Sentinel-5P (S5P) TROPOMI satellite data to capture pollutant concentrations. This approach allowed for continuous spatial monitoring and high-resolution mapping of CO, SO_2, and NO_2 levels. The researchers applied descriptive statistics and a paired sample t-test to evaluate differences in pollutant levels across the four years. They specifically analyzed annual variations and compared concentrations across different years to identify significant trends. Their results revealed significant fluctuations in pollutant levels, with CO peaking in 2020 at 0.0554 mol/m^2 and SO_2 also reaching its highest value in 2020 at 0.0000866 mol/m^2. Conversely, NO_2 levels were highest in 2021 at 0.0000797 mol/m^2. Statistical analysis showed a significant difference in CO levels between 2019 and 2020, reflecting an increase during the early phase of the COVID-19 pandemic. For NO_2, substantial differences emerged between 2019 and 2020 and between 2020 and 2021, suggesting a changing pattern of vehicular emissions and industrial output during and after the lockdown period. However, no significant changes occurred between 2021 and 2022 for either pollutant. Okoduwa and Amaechi

(2023) concluded that human activities, particularly industrial emissions and vehicular traffic, heavily influence air pollution patterns in Benin City. They also noted that the COVID-19 lockdown did not significantly reduce pollution levels, which contrasts with findings from other regions where strict lockdown measures led to lower emissions. The authors emphasized the need for continuous satellite monitoring to track pollution trends and inform environmental regulations aimed at improving air quality.

Amaechi *et al.* (2023) assessed the impact of the fuel subsidy removal policy on air quality in the Federal Capital Territory (FCT), Abuja, focusing on changes in carbon monoxide (CO) and nitrogen dioxide (NO_2) concentrations. Their objective was to determine whether removing fuel subsidies—which led to higher fuel prices—had a measurable effect on air pollution levels. Amaechi *et al.* (2023) adopted a remote sensing approach using Google Earth Engine (GEE) and Sentinel-5P TROPOMI satellite data to measure CO and NO_2 levels before and after the fuel subsidy removal. This longitudinal analysis compared pollutant concentrations across the FCT during the pre-subsidy and post-subsidy periods. By quantifying these differences, they evaluated how fuel price changes affected emission levels. Their results demonstrated a reduction in both CO and NO_2 concentrations following the removal of fuel subsidies. CO levels decreased from 0.0486–0.0415 mol/m^2 before the subsidy removal to 0.0395–0.0333 mol/m^2 after the policy was enacted. Similarly, NO_2 levels fell from 0.000125–0.0000597 mol/m^2 to 0.0000838–0.000051 mol/m^2. This reduction suggests that increased fuel costs may have led to lower vehicle usage and subsequently reduced emissions from fossil fuel combustion. Amaechi *et al.* (2023) concluded that fuel subsidy removal had a positive environmental impact by reducing CO and NO_2 emissions. The study highlighted the complex relationship between economic policies and environmental outcomes, suggesting that higher fuel prices may discourage unnecessary vehicle use, leading to improved air quality. The authors recommended that policymakers consider sustainable energy alternatives and investment in public transportation to maintain these environmental benefits while mitigating the social impacts of rising fuel costs.

Amaechi *et al.* (2024) compared air quality in Lagos and Kano, Nigeria's two largest commercial centers, between 2018 and 2023. The study aimed to identify key differences in pollution levels and sources contributing to air quality deterioration in both states. They used Sentinel-5P TROPOMI satellite data and ground-based monitoring stations to analyze NO_2, CO, and PM concentrations. The study examined seasonal variations and assessed pollution dispersion influenced by meteorological factors. They found that Lagos recorded higher NO_2 and CO levels due to its dense traffic and industrial activity. Kano, despite lower vehicle density, experienced significantly high PM concentrations, especially during the dry season, due to harmattan dust and biomass burning. Pollution levels peaked in both states during the harmattan months and declined slightly in the rainy season. The study revealed that both states exceeded WHO air quality guidelines throughout the study period. They concluded that Lagos and Kano face severe air pollution from different sources. Lagos suffers primarily from vehicle and industrial emissions, while Kano's air quality is worsened by dust and biomass burning. The study recommended stricter emissions regulations, improved urban planning, and enhanced air quality monitoring in both states.

Amaechi *et al.* (2024) examined how COVID-19 lockdown measures affected air quality in Lagos State, Nigeria, between 2019 and 2021. The study aimed to measure changes in pollutant concentrations before, during, and after lockdown restrictions. They used Sentinel-5P TROPOMI satellite data and air quality monitoring stations across Lagos to track NO_2, CO, and particulate matter (PM) levels. The study compared pollution levels across different land-use zones, including industrial, commercial, and residential areas. They found that NO_2 and CO levels declined significantly during lockdown periods, with reductions of over 40% in high-traffic areas. PM concentrations also dropped, particularly in congested regions. However, the study showed that pollution levels rebounded rapidly once restrictions eased, surpassing pre-pandemic levels due to increased economic activity. They concluded that while COVID-19 restrictions temporarily improved air quality, long-term pollution control measures are necessary. The study recommended promoting remote work, strengthening vehicle emission regulations, and expanding public transport infrastructure.

Amaechi *et al.* (2024) assessed nitrogen dioxide (NO_2), carbon monoxide (CO), and aerosol concentrations in Kano State, Northwestern Nigeria, from 2019 to 2023. The study aimed to identify pollution trends and determine key contributing factors. They used Sentinel-5P TROPOMI satellite data and ground-based monitoring stations to measure pollutant levels across Kano's urban, industrial, and residential zones. The study analyzed seasonal variations and meteorological influences on pollutant dispersion. They found that NO_2 and CO levels were highest in industrial areas and major road networks, exceeding WHO air quality standards. Aerosol concentrations remained consistently high, particularly during the dry season when harmattan winds intensified pollution levels. The study also revealed a year-on-year increase in pollutant concentrations, driven by population growth, increased industrialization, and vehicle emissions. They concluded that Kano State faces severe air pollution challenges, with significant health risks for residents. The study recommended stricter emission controls, better urban planning, and increased investment in air quality monitoring to mitigate pollution levels.

2.8. CASE STUDIES ON ABA METROPOLIS

Akuagwu and Ozeh (2013) undertook a comprehensive evaluation of air quality in Aba metropolis, assessing CO, SO_2, NO_2, and particulate matter (PM). The study spanned across six strategic locations representing industrial, commercial, and residential zones. The researchers used electrochemical gas sensors for gaseous pollutants and gravimetric methods for PM measurements. Additionally, meteorological parameters such as temperature, humidity, and wind speed were recorded to analyze their influence on pollutant distribution. The results indicated that CO and SO_2 concentrations frequently exceeded WHO air quality guidelines, particularly in densely populated commercial and industrial areas. For instance, CO levels were consistently above 50 ppm in the industrial zones, posing a direct health threat. NO_2 levels were also elevated, though slightly lower in residential areas. Seasonal variations were apparent, with pollutant levels peaking during the dry season due to reduced atmospheric dispersion and increased vehicular emissions. Akuagwu and Ozeh (2013) attributed these findings to rapid urbanization, poor environmental enforcement, and unregulated emissions from vehicles and industries. The authors emphasized the need for regular environmental monitoring, public education on pollution risks, and policy reforms to manage the worsening air quality. They concluded that without urgent intervention, the health risks associated with air pollution in Aba would continue to escalate, affecting both human health and the environment.

Anietimfon and Anaekwe (2015) investigated ambient air sulfur (IV) oxide (SO_2) concentrations in Aba, a large commercial city in southeastern Nigeria. Using the West-Gaeke method, they measured SO_2 levels across different locations from March to December 2013, encompassing both wet and dry seasons. The study found that the mean SO_2 concentration during the dry season was 0.180 ppm, while the wet season recorded a slightly lower average of 0.149 ppm, indicating a 9.42% reduction due to rain attenuation. The highest concentration (0.259 ppm) was observed at Asa Nnentu Market during the dry season, while the lowest (0.082 ppm) occurred at Plot 204 Obohia Road during the wet season. These concentrations significantly exceeded the Federal Environmental Protection Agency (FEPA) limits of 0.001–0.01 ppm, signaling serious air pollution concerns in Aba. The study attributed the elevated SO_2 levels to industrial emissions, vehicular traffic, and the burning of fossil fuels. The authors emphasized the urgent need for regulatory interventions and continuous air quality monitoring to mitigate public health risks.

Nwosu and Ewurum (2018) conducted an air quality assessment at Enyimba dumpsite, one of the largest waste disposal areas in Aba, to evaluate the impact of waste decomposition and open-air burning on ambient air quality. The study measured several pollutants, including carbon monoxide (CO), Sulphur(IV) oxide (SO_2), nitrogen dioxide (NO_2), hydrogen sulfide (H_2S), methane (CH_4), and particulate matter (PM). Air samples were collected from different points around the dumpsite using portable gas detectors and gravimetric samplers to analyze pollutant concentrations. Their results revealed significantly elevated pollutant levels at and around the dumpsite, especially during periods of active waste burning. CO concentrations peaked at 66.8 ± 8.3 ppm, while H_2S levels—a gas known for its toxicity and characteristic rotten egg odor—were also alarmingly high. Methane, a potent greenhouse gas, was present in considerable quantities due to the anaerobic decomposition of organic waste. Nwosu and Ewurum (2018) attributed these high pollutant levels to poor waste management practices, particularly the open-air burning of refuse. The study emphasized that such pollution poses serious health hazards, including headaches, dizziness, respiratory distress, and increased cancer risk due to prolonged exposure. The authors concluded that improving waste disposal methods, establishing air quality monitoring systems, and implementing stronger environmental regulations are crucial for safeguarding public health and mitigating pollution.

Diagi *et al.* (2025) conducted a thorough investigation into the levels of carbon monoxide (CO) and particulate matter (PM) across the Aba metropolis, a densely populated commercial hub in southeastern Nigeria. The study aimed to determine the extent of air pollution caused by vehicular emissions, industrial activities, and domestic combustion. Sampling was carried out in commercial, industrial, and residential areas, with a rural location serving as the control point. Akataobi used electrochemical sensors to measure CO concentrations and applied gravimetric methods to quantify PM levels. The findings revealed that CO concentrations ranged from 11.0 to 81.0 ppm, with Waterside Junction recording the highest average CO concentration (66.8 ± 8.3 ppm), far above the World Health Organization (WHO) permissible limit of 9.0 ppm for an eight-hour exposure. Particulate matter levels were similarly elevated, particularly in areas with intense vehicular movement and industrial emissions. The control site, located in a rural environment, consistently recorded the lowest levels of both pollutants (15.3 ± 4.3 ppm for CO), reinforcing the link between human activities and air pollution. Diagi *et al.* (2025) identified vehicular emissions, burning of tires and refuse, and industrial discharges as the primary sources of elevated CO and PM levels. The study highlighted the potential health risks associated with prolonged exposure to these pollutants, including respiratory illnesses, cardiovascular diseases, and reduced lung function. Akataobi concluded by recommending stricter environmental policies, enhanced public awareness, and better traffic management to curb air pollution in the metropolis.

Anaekwe (2020) focused on the concentration of Sulphur(IV) oxide (SO_2) in the air across Aba's commercial zones, recognizing the health risks associated with elevated SO_2 exposure. The study employed spectrophotometry—a precise analytical method for detecting gas concentrations—

across different locations, including industrial areas, major traffic points, and residential districts. Sampling took place over several months to capture potential variations in pollutant levels. Anaekwe (2020) found that SO_2 concentrations consistently exceeded the WHO guideline of 0.5 ppm for short-term exposure. The highest SO_2 levels were recorded near industrial complexes and high-traffic areas, where fuel combustion and vehicular exhaust are most prevalent. Residential areas exhibited lower concentrations but still surpassed acceptable limits. Seasonal trends showed that SO_2 levels increased during the dry season, a pattern attributed to reduced atmospheric dispersion. The study linked incomplete combustion of fossil fuels, industrial processing, and traffic congestion as the primary sources of SO_2 pollution. Anaekwe (2020) warned that prolonged exposure to high SO_2 levels can cause respiratory irritation, worsening of asthma symptoms, and lung function impairment, particularly among vulnerable populations like children and the elderly. The study recommended continuous air quality monitoring, enforcement of emission controls, and public health awareness initiatives to protect the local population.

Abulude *et al.* (2023) conducted a comprehensive study to monitor air quality in four towns (Owerri, Awka, Aba, and Nsukka) in Southeast Nigeria using satellite-based sensors. The study utilized data from Plume Labs, which was collected twice daily over a 60-day period. The air quality in these towns was assessed using the Plume Air Quality Index (PAQI), which categorizes pollution levels from “Low” to “Airpocalypse,” based on World Health Organization (WHO) standards. The findings indicated that pollution levels in these towns consistently exceeded WHO’s 24-hour daily limits, posing severe health risks. This elevation in air pollutants was attributed to anthropogenic activities such as vehicular emissions, industrial processes, and biomass combustion. The study underscores the importance of integrating satellite monitoring with traditional ground-level assessments to capture spatial and temporal pollution variations accurately. Furthermore, the authors advocate for the application of Internet of Things (IoT) technologies to enhance real-time air quality monitoring and data dissemination for public awareness and policy intervention.

Existing studies on air quality in Aba metropolis, including those conducted by Akuagwu and Ozeh (2013), Anietimfon and Anaekwe (2015), Nwosu and Ewurum (2018), Diagi *et al.* (2025), Anaekwe (2020), and Abulude *et al.* (2023), reveal significant gaps in temporal coverage, spatial comprehensiveness, and methodological approaches. Most of these studies are based on short-term ground-based measurements collected over limited periods, making them inadequate for capturing long-term pollution trends and seasonal variations. Additionally, these studies do not account for recent pollution patterns or provide a consistent dataset across multiple years. Furthermore, satellite-based monitoring, which offers broader spatial coverage and continuous data collection, has only been minimally explored (Abulude *et al.*, 2023), and no study has focused specifically on long-term CO and aerosol dynamics in Aba.

This research, addresses these gaps by offering longitudinal data spanning six years, providing a comprehensive assessment of CO and aerosol levels. Utilizing Sentinel-5P satellite data allows for consistent, high-resolution monitoring across both urban and peri-urban areas, overcoming the limitations of point-based ground measurements. This study will also identify seasonal variations, long-term trends, and spatial pollution hotspots, contributing to a more robust understanding of air quality in Aba and supporting evidence-based policymaking for environmental regulation.

CHAPTER THREE

3.0 METHODOLOGY

3.1 DESCRIPTION OF STUDY AREA

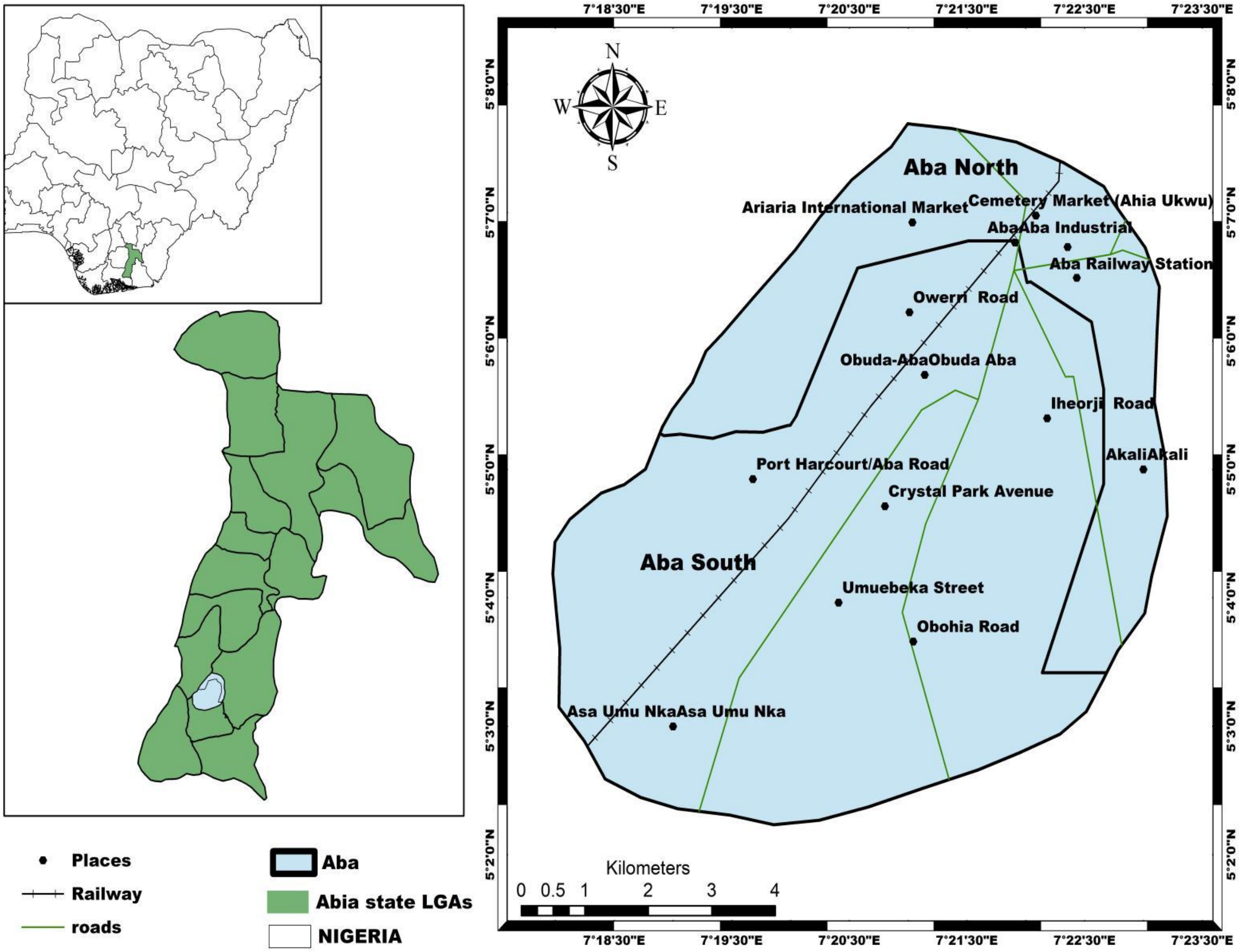

Figure 3.1: Map of Aba, Abia State, South Eastern Nigeria.

Aba Metropolis is one of the most commercially vibrant and industrially active cities in southeastern Nigeria (Abaje *et al.*, 2020; Ajayi *et al.*, 2024). Located in Abia State, Aba has grown significantly due to its economic potential, industrial base, and central position in the region (Abaje *et al.*, 2020; Ajayi *et al.*, 2024). The city is made up of Aba North and Aba South Local Government Areas (Okey-Wokeh *et al.*, 2020; Tanko *et al.*, 2022). Aba South contains the central business district, while Aba North includes residential and peripheral commercial areas (Abaje *et al.*, 2020; Ajayi *et al.*, 2024). Aba is geographically located between 5°04′N to 5°08′N latitude and 7°20′E to 7°25′E longitude (Okey-Wokeh *et al.*, 2020; Ajayi *et al.*, 2024). It shares boundaries with Osisioma Ngwa to the south, Obingwa to the east, and Ugwunagbo to the west. The city spans about 72 square kilometers (Okey-Wokeh *et al.*, 2020; Ajayi *et al.*, 2024). Its location supports regional trade links to cities like Umuahia, Owerri, Port Harcourt, and Ikot Ekpene (Okey-Wokeh *et al.*, 2020; Tanko *et al.*, 2022). This strategic positioning also results in high vehicular movement and intense industrial activity (Akuagwu *et al.*, 2016; Kanu *et al.*, 2023). Aba's population has risen rapidly over recent decades. According to the National Population Commission (2017), it now exceeds one million residents (Okey-Wokeh *et al.*, 2020; Tanko *et al.*, 2022; Akuagwu *et al.*, 2016; Kanu *et al.*, 2023). This growth, driven by rural-urban migration and economic opportunities, has led to urban challenges like congestion, air pollution, and inadequate infrastructure (Okey-Wokeh *et al.*, 2020; Tanko *et al.*, 2022). Economically, Aba is known as the "*Japan of Africa*" due to its concentration of small and medium-scale industries in textiles, leatherwork, and metal fabrication (Abaje *et al.*, 2020; Ajayi *et al.*, 2024). These industries support livelihoods but also contribute to air pollution through emissions of particulate matter and gases (Nwogu and Umezuruike, 2018; Abulude *et al.*, 2023). The city experiences a tropical rainforest climate with a bimodal rainfall pattern and high humidity (Abaje *et al.*, 2020; Ajayi *et al.*, 2024). The wet season lasts from March to October, while the dry season spans November to February (Abaje *et al.*, 2020; Ajayi *et al.*, 2024). Rainfall ranges from 1,800 mm to 2,400 mm annually, peaking from June to September (NIMET, 2022). Temperatures range between 26°C and 32°C, with humidity levels often above 80 percent during the rainy season (NIMET, 2022). These conditions influence the behavior of atmospheric pollutants, allowing CO and aerosols to accumulate under poor dispersion scenarios (Nwogu and Umezuruike, 2018; Abulude *et al.*, 2023). Topographically, Aba is flat to gently undulating, with elevations between 50 and 75 meters above sea level (Awuchi *et al.*, 2023; Alichi and Michael, 2025). The limited elevation and minimal wind flow reduce pollutant dispersal (Nwogu and Umezuruike, 2018; Abulude *et al.*, 2023). The Aba River, flowing through the southern part of the city, drains into the Imo River (Awuchi *et al.*, 2023; Alichi and Michael, 2025). However, poor drainage maintenance and illegal waste dumping often cause flooding during the rainy season, further spreading pollutants (Kanu *et al.*, 2023; Awuchi *et al.*, 2023; Alichi and Michael, 2025). Aba's economy is powered by trade and light manufacturing (Akuagwu *et al.*, 2016; Kanu *et al.*, 2023). The Ariaria International Market, located in Aba South, draws traders from across Nigeria and West Africa (Abaje *et al.*, 2020; Ajayi *et al.*, 2024). Local industries include plastic production, breweries, garment making, and metalwork (Abaje *et al.*, 2020; Ajayi *et al.*, 2024). These activities emit CO, NO_2, SO_2, VOCs, and aerosols (Nwogu and Umezuruike, 2018; Abulude *et al.*, 2023), contributing significantly to poor air quality, especially in densely built-up areas.

3.2 RESEARCH DESIGN

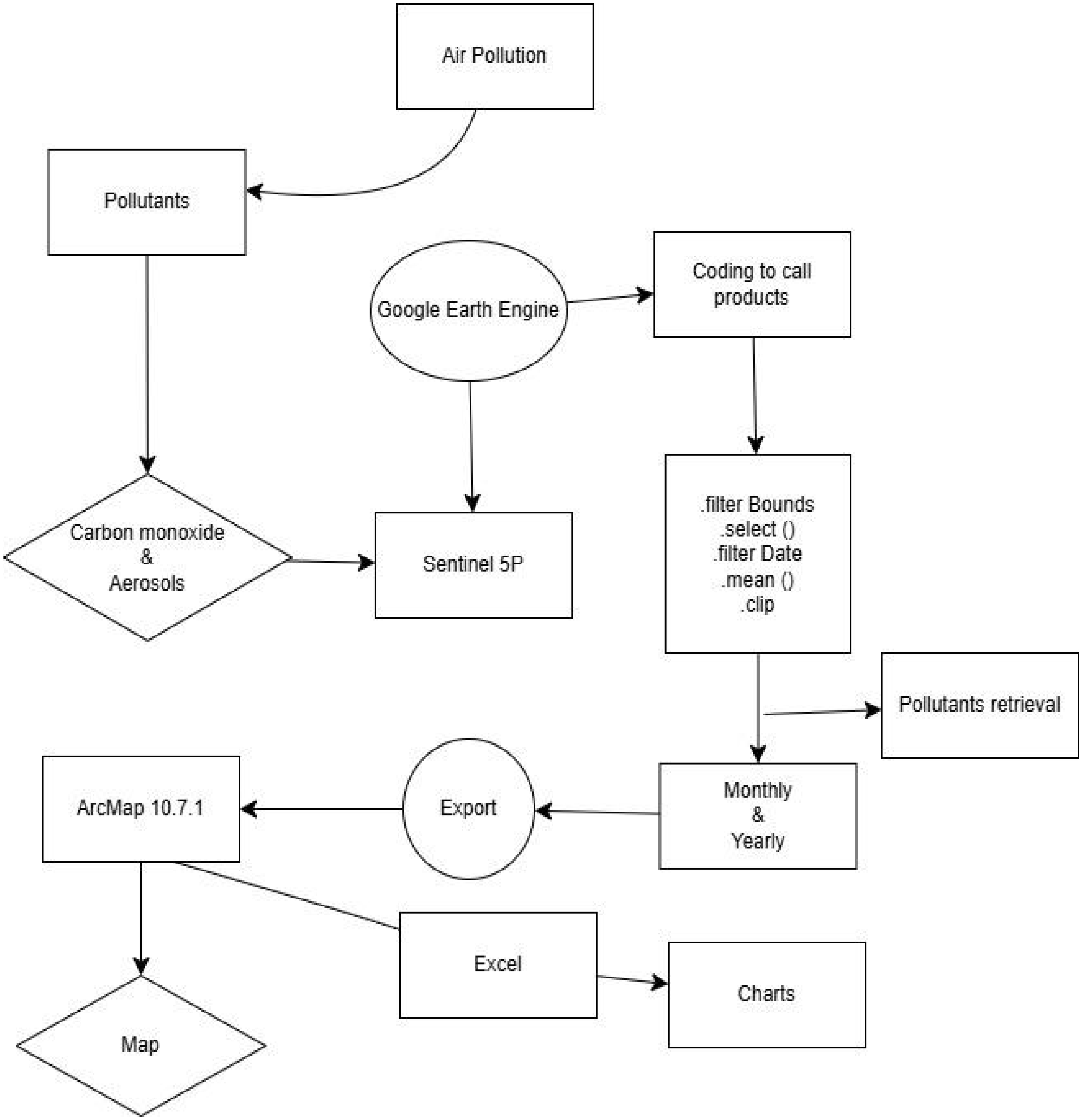

Figure 3.2: Schematic illustration of the research design.

3.3 DATA SOURCE/COLLECTION

This study focuses on Carbon Monoxide (CO) and Aerosol pollution in Aba, utilizing secondary data from the Sentinel-5 Precursor (Sentinel-5P) satellite, which was specifically developed to monitor atmospheric pollutants, due to its high spatial resolution and wide spatial coverage, unlike ground-based monitors that offer limited spatial representation. The satellite's high spatial resolution allows for detailed tracking of pollution patterns across different locations and over time (ESA, 2018). The dataset spans from 2019 to 2024, offering a clear picture of annual variations in CO and aerosol concentrations in the city. Sentinel-5P, launched in October 2017 under the European Space Agency's (ESA) Copernicus Programme, is equipped with the Tropospheric Monitoring Instrument (TROPOMI), which is capable of detecting a wide range of atmospheric pollutants including CO and aerosols (ESA, 2018; Chandra and Singh, 2023). TROPOMI captures data across ultraviolet, visible, near-infrared, and short-wave infrared bands, which enables the satellite to measure key atmospheric parameters with high precision (ESA, 2018). Its spatial resolution of 3.5×7 km^2 and daily global coverage make it suitable for identifying pollution hotspots and observing seasonal fluctuations (Omrani *et al.*, 2020).

Data from Sentinel-5P have been used in multiple studies to investigate the relationship between air pollution and human activities. For instance, Chandra and Singh (2023) analyzed pollution levels in Uttar Pradesh, India, across different COVID-19 lockdown phases, while Amaechi *et al.* (2023) used it to evaluate the effects of fuel subsidy removal on air quality in Abuja. The satellite has also supported assessments of air quality shifts during major events like pandemic lockdowns (Behera *et al.*, 2021; Amaechi *et al.*, 2024), provided evidence to support emission control measures (Omrani *et al.*, 2020), and contributed to climate modeling efforts by supplying reliable data on pollutant concentrations (Safarianzengir *et al.*, 2020).

3.4 DATA PROCESSING/ANALYSIS

Google Earth Engine (GEE) served as the primary platform for data acquisition and analysis. This cloud-based tool is designed for processing and visualizing geospatial datasets, including those from Sentinel-5P (Amaechi *et al.*, 2023; Amaechi *et al.*, 2024). Through GEE, researchers accessed relevant CO and aerosol datasets by filtering based on pollutant type, timeframe, and geographic coverage (Amaechi *et al.*, 2023; Amaechi *et al.*, 2024).

The platform's analytical capabilities allowed for detailed temporal analysis of CO and aerosol concentration trends over the study period. For example, Behera *et al.* (2021) and Amaechi *et al.* (2024) demonstrated how GEE could be used to assess pollution drops during lockdowns in India. GEE also supported spatial visualization, enabling the creation of high-resolution maps that highlight pollution hotspots, similar to Amaechi *et al.*'s (2023) study of air quality in Abuja.

3.5 METHOD OF ANALYSIS

This study employs a systematic methodology, integrating advanced geospatial tools with detailed data analysis, to comprehensively assess the spatial and temporal variations of CO and aerosol concentrations in Aba Metropolis. The process begins with accessing Sentinel-5P datasets from the GEE data catalog, specifically selecting CO and aerosol concentration data for the 2019–2024 period. These datasets are then precisely filtered based on temporal and spatial parameters to focus on the Aba metropolitan area. Within GEE's JavaScript scripting environment, custom code is developed to extract relevant bands for CO and aerosol measurements, incorporating functions for date filtering, cloud masking to remove obscured data, and calculating monthly and annual average pollutant concentrations.

Although CO is measured in mol/m², aerosols do not have a defined standard SI unit. The selection of January 1, 2019, as the start date for data collection is based on the availability of consistent Sentinel-5P datasets across all parameters, as detailed in the Earth Engine Data Catalog. While UV Aerosol Index data became accessible from July 4, 2018, and Carbon Monoxide and aerosol data were available from June 28, 2018, using 2019 as the baseline ensures complete and uniform annual datasets throughout the study period.

CO and aerosols were chosen due to their direct link with the predominant emission activities in Aba, particularly vehicular traffic, industrial discharges, and waste combustion (Akuagwu and Ozeh, 2013; Anietimfon and Anaekwe, 2015; Nwosu and Ewurum, 2018). These pollutants are also recognized by international air quality frameworks and health risk assessments as reliable indicators of urban pollution (Smith and Bolton, 2024).

Following processing in GEE, the resulting raster datasets are exported as GeoTIFF files, ensuring the preservation of spatial resolution and georeferencing information. These files are subsequently imported into ArcGIS 10.7.1 for further spatial analysis and visualization. In ArcGIS, the raster datasets are converted into shapefiles using the “Raster to Polygon” tool, which facilitates the overlay of pollutant concentration data with administrative boundaries and other vector layers representing the Aba metropolitan area. To enhance data interpretability, pollutant concentrations are classified into three distinct categories: high, moderate, and low. A color-coded scheme is applied, using red for high concentrations, yellow for moderate levels, and green for low concentrations, which aids in identifying pollution hotspots and understanding spatial distribution patterns.

Finally, attribute data from the shapefiles are extracted and exported to Microsoft Excel for in-depth statistical analysis. Monthly and annual averages of CO and aerosol concentrations are calculated to assess temporal trends and identify periods of elevated pollution. The statistical analysis includes computing descriptive statistics such as mean, median, and standard deviation to summarize the data. A paired sample t-test is also applied to evaluate whether differences in pollutant concentrations between consecutive years are statistically significant. This test is appropriate for the study because pollutant levels across years are interrelated, influenced by ongoing trends in emissions, policy interventions, and climatic variables. It helps isolate true changes in pollution levels from random year-to-year variation by accounting for internal dependencies within the dataset.

To effectively visualize trends and support the interpretation of results, time-series plots and charts are generated, providing clear insights into the dynamics of air quality in Aba Metropolis.

Table 3.1. CO, and aerosols dataset obtained from Sentinel-5P

Band Name	**Dataset**	**Unit**	**Min**	**Max**	**Description**
CO_column_number_density	**OFFL/L3_CO**	**mol/m^2**	**-34.43**	**5.71**	**Vertically integrated CO column density.**
absorbing_aerosols_index	**OFFL/L3_AER_AI**		**-21**	**39**	**A measure of the prevalence of aerosols in the atmosphere.**

CHAPTER FOUR

4.0. RESULTS

4.1. CARBON MONOXIDE RESULTS PRESENTATION

Table 4.1.1. Annual minimum, maximum, mean and standard deviation of CO concentration from 2019–2024.

CARBON MONOXIDE	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
MINIMUM	0.0499	0.0548	0.0525	0.0497	0.0489	0.0548
MAXIMUM	0.0509	0.0557	0.0535	0.0511	0.0501	0.0562
MEAN	0.0504	0.0553	0.0532	0.0505	0.0496	0.0558
STANDARD DEVIATION	0.0002	0.0002	0.0002	0.0003	0.0002	0.0003

Table 4.1.1, which outlines the annual minimum, maximum, mean, and standard deviation of CO concentrations, the year 2019 recorded a minimum of 0.0499 and a maximum of 0.0509, with a mean of 0.0504 and a standard deviation of 0.0002. This indicates relatively stable and low concentrations of CO during that year. In 2020, despite global lockdowns due to the COVID-19 pandemic, CO levels increased slightly, with a minimum of 0.0548, a maximum of 0.0557, and a mean of 0.0553. The standard deviation remained consistent at 0.0002, suggesting minimal fluctuations within the year. This counterintuitive rise in 2020 could be due to localized factors, such as continued use of generators and limited but concentrated urban emissions. The year 2021 experienced a mild decrease, with a mean of 0.0532 and a range between 0.0525 and 0.0535, maintaining the same standard deviation of 0.0002. In 2022, the CO concentration slightly rose again with a mean of 0.0505, ranging from 0.0497 to 0.0511, and a slightly higher standard deviation of 0.0003, pointing to increased variability, possibly due to renewed industrial and vehicular activities. By 2023, the mean dropped to 0.0496—the lowest among the six years—with a minimum of 0.0489 and a maximum of 0.0501, coupled with a stable deviation of 0.0002. This decline aligns with the impact of Nigeria’s fuel subsidy removal, which reduced fuel consumption and emissions. In 2024, CO concentration rose once more, reaching the highest mean of 0.0558, with a minimum of 0.0548 and a peak of 0.0562. The standard deviation increased to 0.0003, indicating a recovery period characterized by intensified activities and emissions.

Table 4.1.2. Monthly concentration of CO from 2019–2024.

YEAR/MONTH	2019	2020	2021	2022	2023	2024
JANUARY	0.068	0.067	0.064	0.065	0.064	0.067
FEBRUARY	0.071	0.08	0.071	0.068	0.065	0.073
MARCH	0.058	0.067	0.06	0.061	0.053	0.063
APRIL	0.048	0.05	0.05	0.046	0.046	0.047
MAY	0.04	0.044	0.04	0.039	0.04	0.047
JUNE	0.044	0.043	0.043	0.039	0.039	0.046
JULY	0.046	0.044	0.051	0.048	0.044	0.054
AUGUST	0.045	0.049	0.05	0.051	0.05	0.06
SEPTEMBER	0.038	0.044	0.042	0.041	0.039	0.045
OCTOBER	0.037	0.036	0.039	0.034	0.037	0.042
NOVEMBER	0.042	0.051	0.046	0.046	0.046	0.05
DECEMBER	0.056	0.059	0.059	0.058	0.056	0.061
MEAN	0.0504	0.0553	0.0532	0.0505	0.0496	0.0558
STANDARD DEVIATION	0.0002	0.0002	0.0002	0.0003	0.0002	0.0003

Table 4.1.2, which details the monthly CO concentrations from 2019 to 2024, the data show clear seasonal variations. In 2019, the lowest concentration was observed in October (0.037), while the highest occurred in February (0.071). The trend was similar in 2020, with October again recording the lowest value (0.036) and February the highest at 0.080. In 2021, October marked the minimum at 0.039, while February again was highest at 0.071. For 2022, October had the lowest concentration (0.034), and February remained the peak month at 0.068. The 2023 dataset also followed this pattern, with October (0.037) as the minimum and February (0.065) as the highest. In 2024, the lowest value was in October (0.042), and the highest again in February at 0.073. This consistent peak in February across all years may be attributed to seasonal dry conditions and increased combustion activities during the early part of the year, while the low values in October reflect the onset of the rainy season, which typically suppresses airborne pollutants. The yearly means and standard deviations listed in this table reaffirm those in Table 4.1.1, providing a summary of how monthly variations culminate in annual statistics.

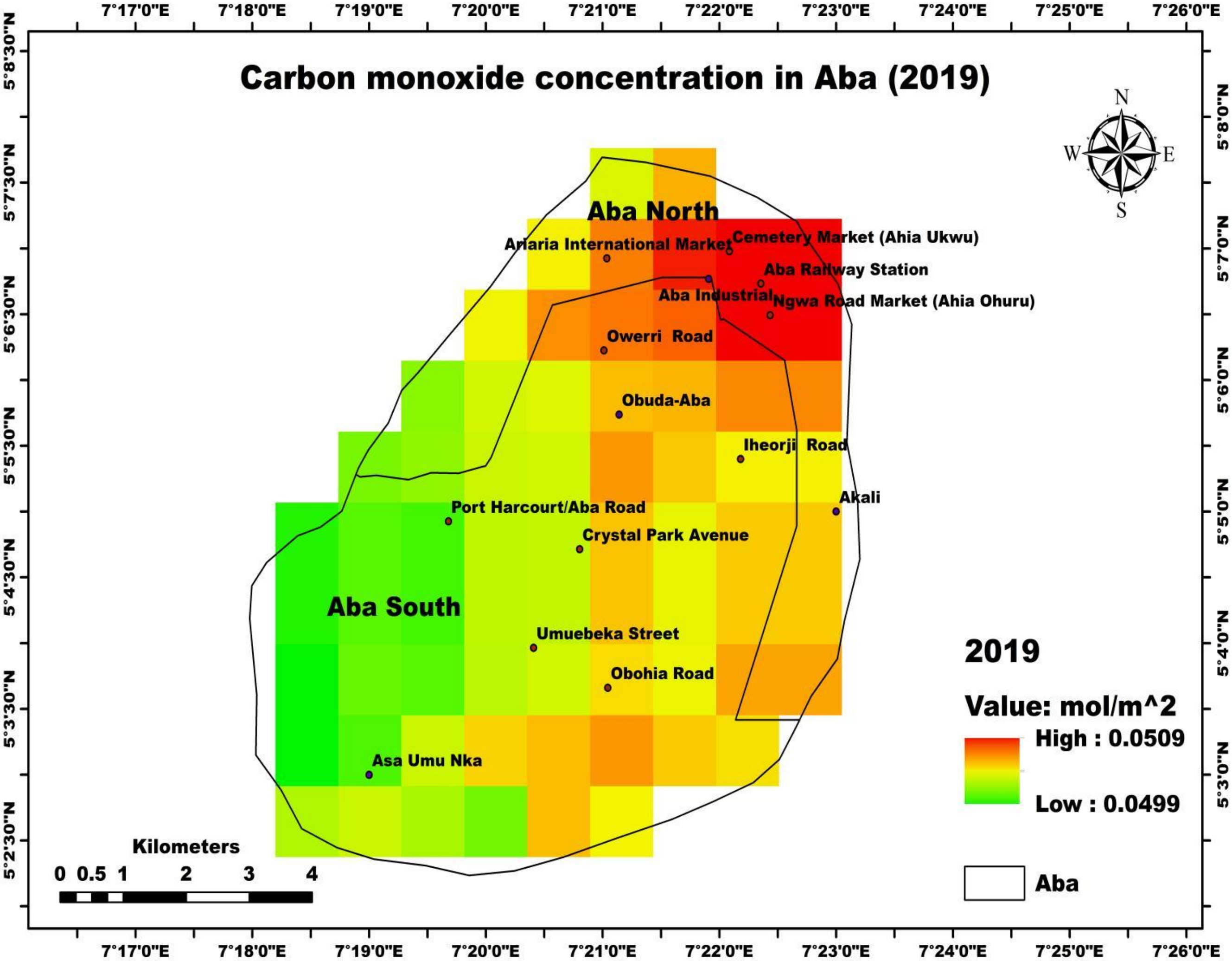

Figure 4.1.1. Map showing Carbon monoxide concentration in Aba for 2019.

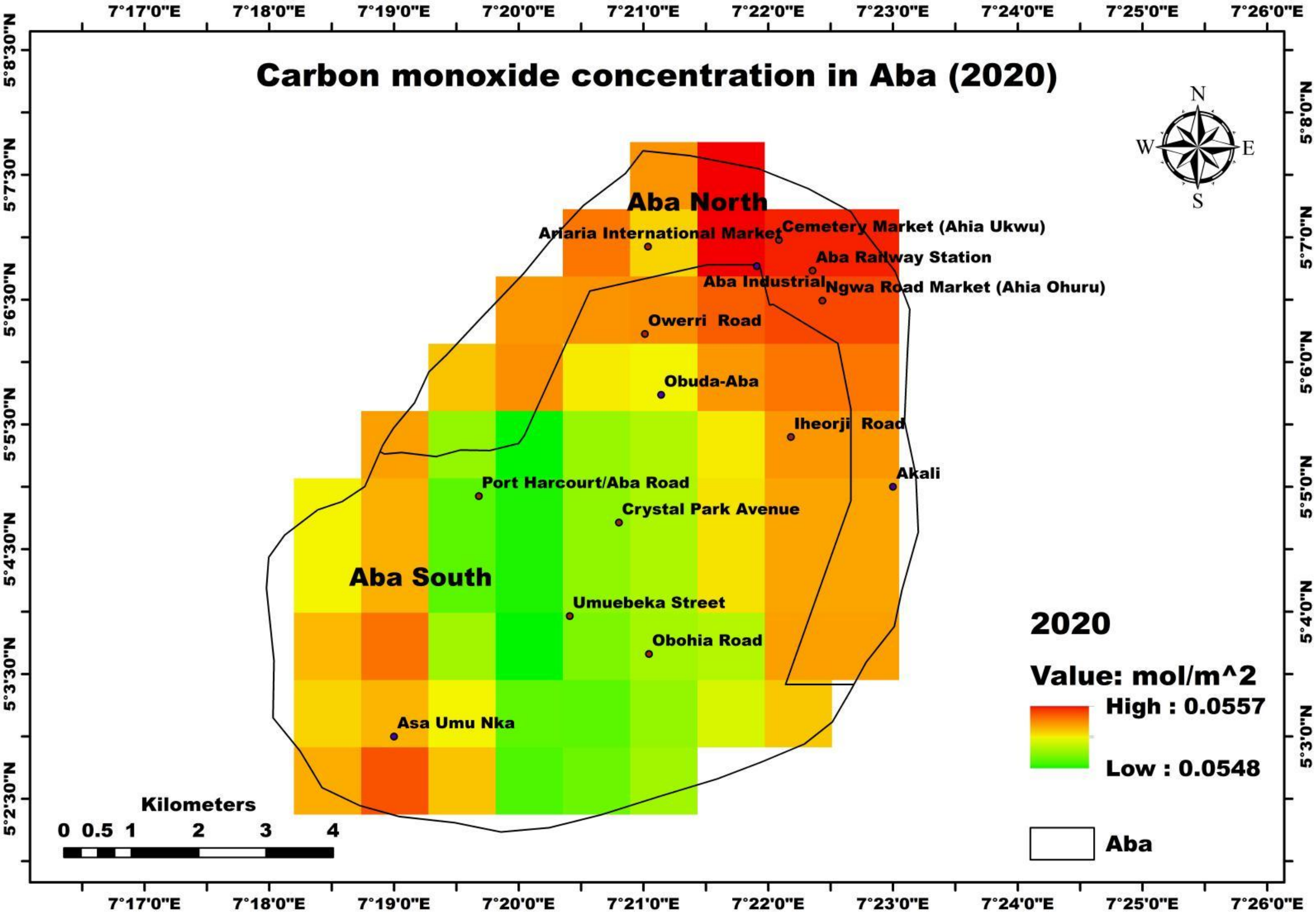

Figure 4.1.2. Map showing Carbon monoxide concentration in Aba for 2020.

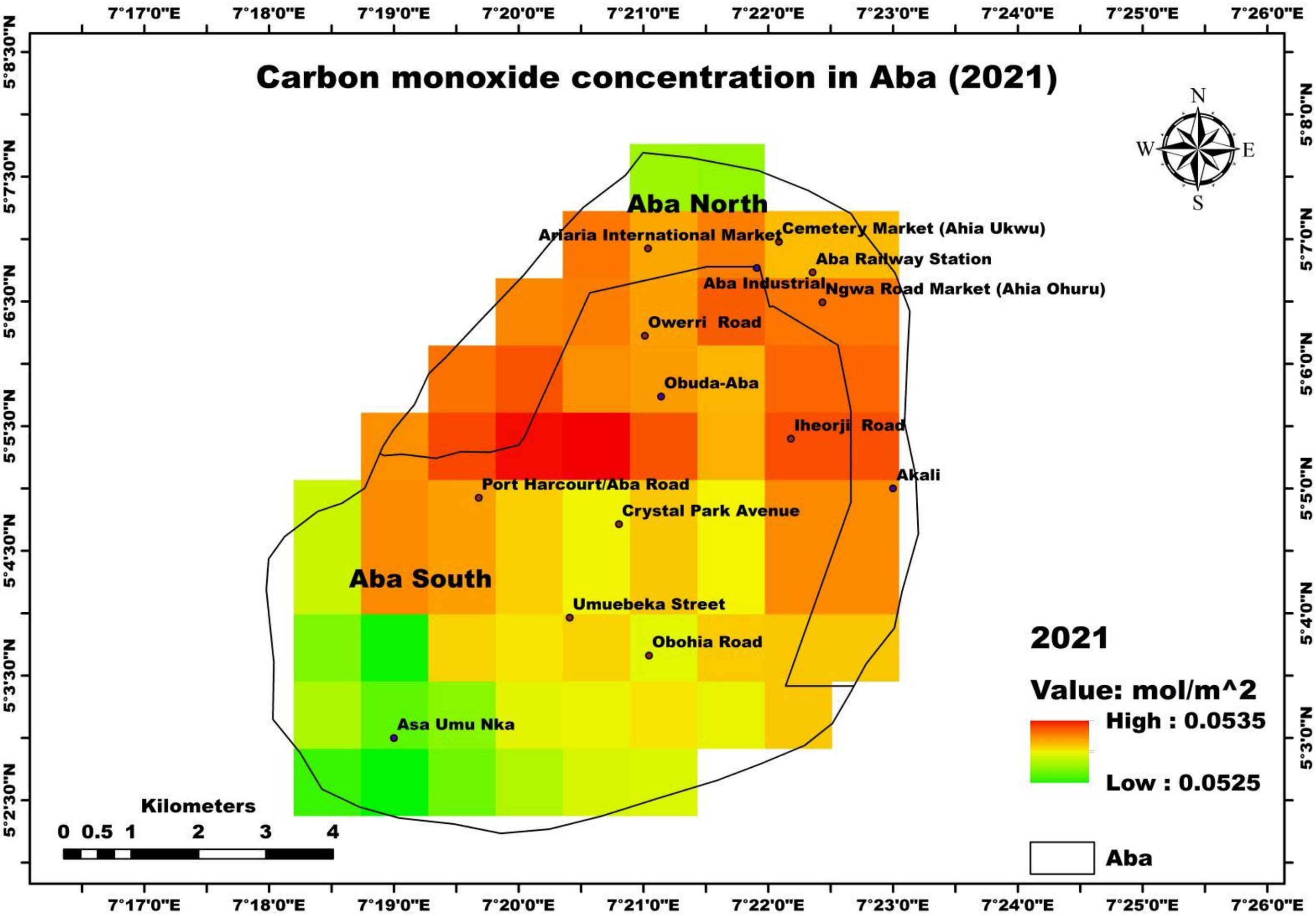

Figure 4.1.3. Map showing Carbon monoxide concentration in Aba for 2021.

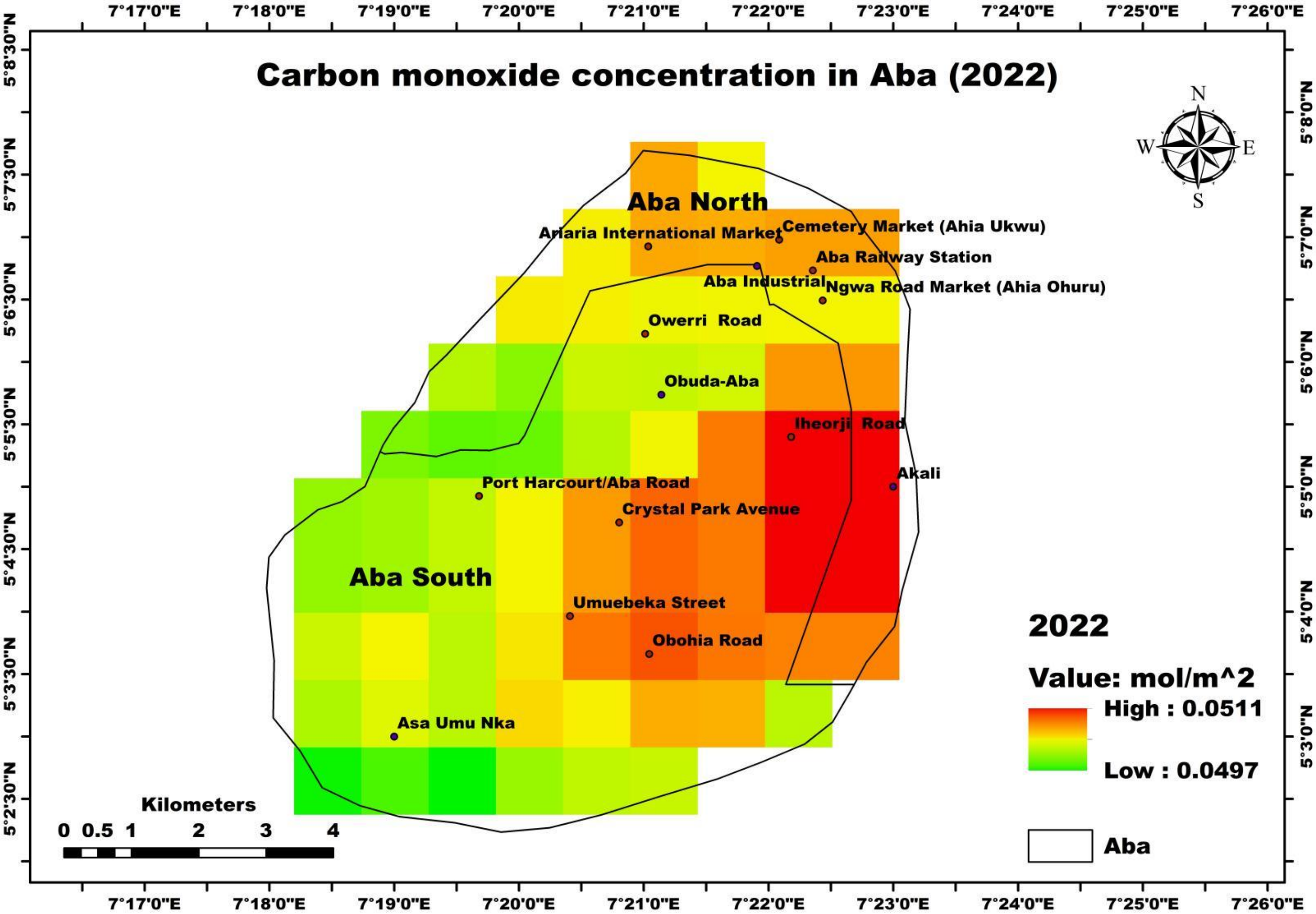

Figure 4.1.4. Map showing Carbon monoxide concentration in Aba for 2022.

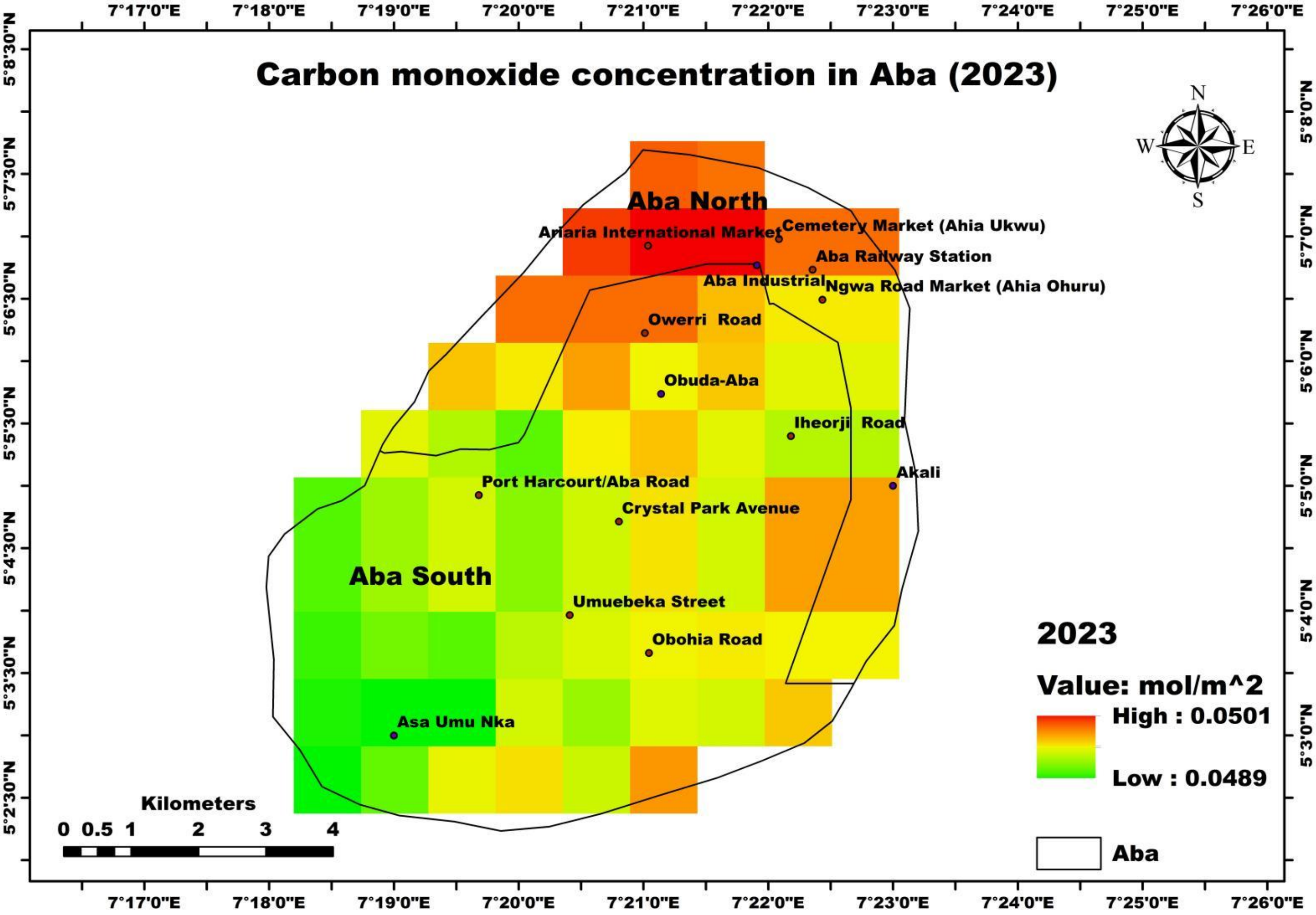

Figure 4.1.5. Map showing Carbon monoxide concentration in Aba for 2023.

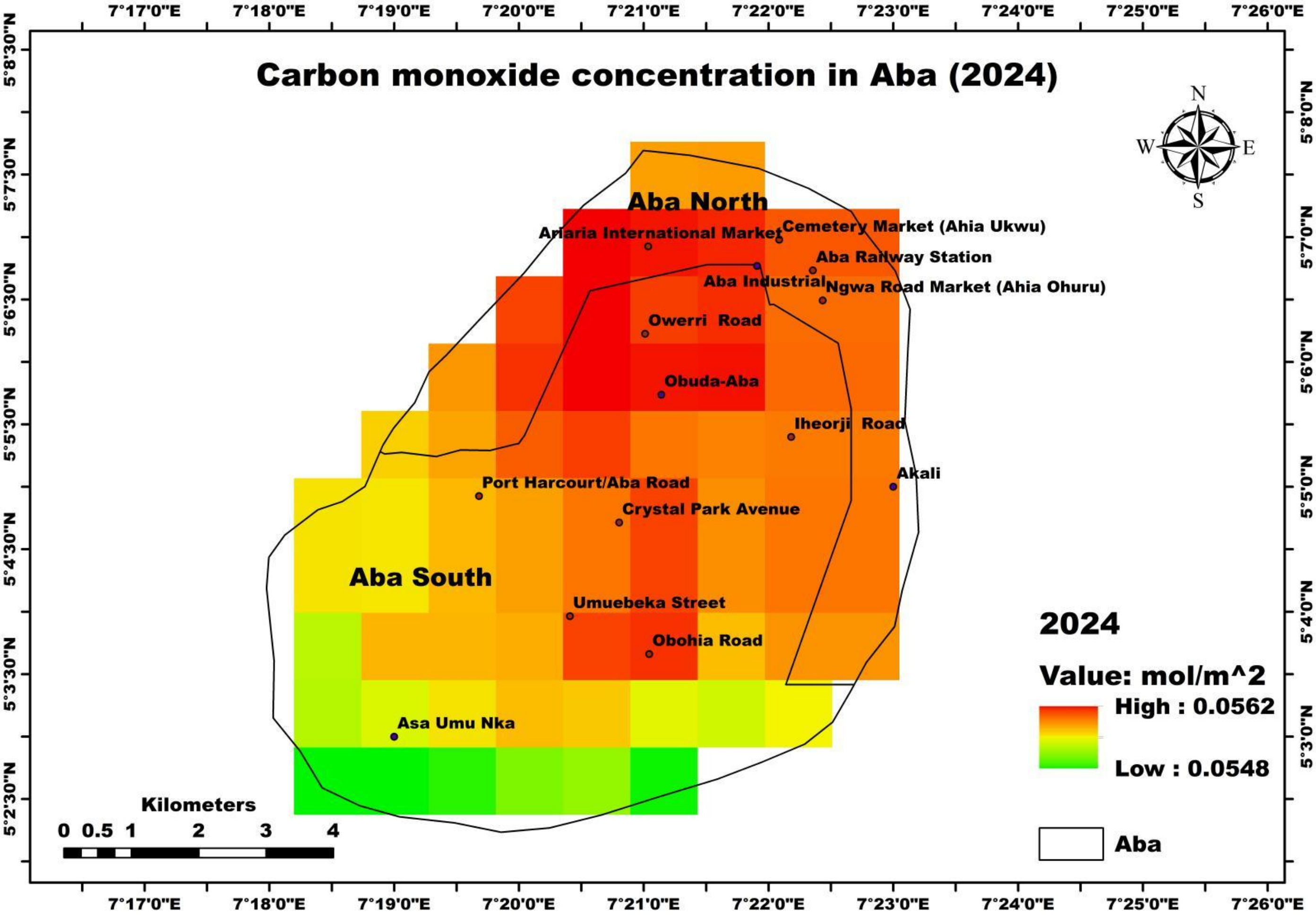

Figure 4.1.6. Map showing Carbon monoxide concentration in Aba for 2024.

The spatial variation of carbon monoxide (CO) concentrations, as presented in Figure 4.1.1, showed that in 2019, areas such as the Aba Industrial area, Ariaria International Market, Aba Railway Station, Cemetery Market (Ahia Ukwu), Ngwa Road Market (Ahia Ohuru), and Owerri Road in Aba North recorded high concentrations, reaching 0.0509 mol/m². Akali in Aba North, Obuda-Aba in central Aba South, and Iheorji Road exhibited moderate concentrations. In contrast, Asa Umu Nka in the southern periphery of Aba South, Port Harcourt/Aba Road, Crystal Park Avenue, Umuebuka Street, and Obohia Road recorded the lowest concentration at 0.0499 mol/m². In 2020 (Figure 4.1.2), the central region of Aba South recorded a low CO concentration of 0.0548 mol/m². However, areas such as Aba Industrial, Akali, Ariaria International Market, Aba Railway Station, Cemetery Market (Ahia Ukwu), Ngwa Road Market (Ahia Ohuru), Owerri Road in Aba North, and Asa Umu Nka experienced high concentrations, each measuring 0.0557 mol/m². By 2021 (Figure 4.1.3), the central region of Aba, including Akali, Obuda-Aba, Aba Industrial area, Ariaria International Market, Aba Railway Station, Cemetery Market (Ahia Ukwu), Ngwa Road Market (Ahia Ohuru), and Owerri Road, fell within the high concentration category at 0.0535 mol/m². Meanwhile, the peripheral areas of Aba South, such as Asa Umu Nka, and parts of Aba North recorded lower concentrations at 0.0525 mol/m². In 2022 (Figure 4.1.4), the highest CO concentration, measured at 0.0511 mol/m², shifted towards the eastern parts of Aba North and Aba South, including Akali, Iheorji Road, Port Harcourt/Aba Road, Crystal Park Avenue, Umuebuka Street, and Obohia Road. The southwestern region of Aba South recorded the lowest concentration at 0.0497 mol/m², while the Aba Industrial area in Aba North fell under the moderate concentration category. In 2023 (Figure 4.1.5), locations such as Aba Industrial, Ariaria International Market, Aba Railway Station, Cemetery Market (Ahia Ukwu), Ngwa Road Market (Ahia Ohuru), and Owerri Road recorded high CO concentrations of 0.0501 mol/m².

Areas including Obuda-Aba, Akali, Port Harcourt/Aba Road, Crystal Park Avenue, Umuebuka Street, Obohia Road, and the central part of Aba South exhibited moderate concentrations. Asa Umu Nka in the southern periphery of Aba South and Iheorji Road experienced the lowest levels at 0.0489 mol/m². Finally, in 2024 (Figure 4.1.6), nearly all regions in Aba North and Aba South recorded high to moderate CO concentrations, reaching 0.0562 mol/m². Only the southern periphery of Aba South remained in the low concentration category, with a value of 0.0548 mol/m².

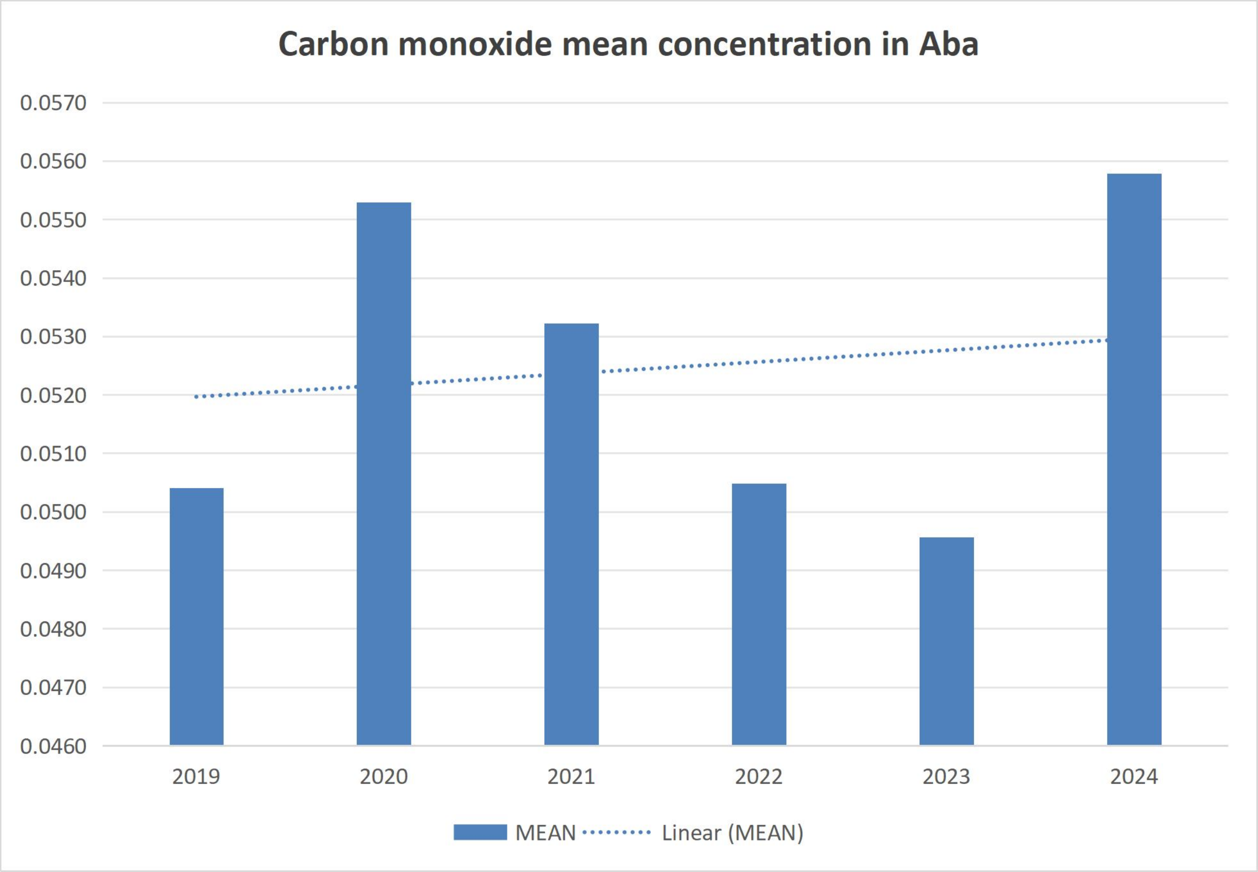

Figure 4.1.7. Trend of annual concentration of CO (2019–2024).

Figure 4.1.7, which illustrates the trend of annual CO concentrations from 2019 to 2024, provides a narrative shaped by environmental policy, economic shifts, and post-pandemic recovery. In 2019, CO levels were relatively low, but in 2020, a significant rise was observed, making it the second-highest year despite the COVID-19 lockdowns. This suggests that localized activities, such as residential generator use and clustered emissions from fewer but active sectors, may have maintained or even increased CO outputs. In 2021, there was a slight decrease, followed by a modest rise in 2022, signaling a partial economic rebound. However, 2023 experienced a notable dip, reflecting the effects of the federal government's fuel subsidy removal, which led to lower fuel usage and consequently reduced CO emissions. By 2024, CO levels rose again as the population and industries adjusted to new energy dynamics, signaling a recovery both in human activity and associated emissions.

4.2. AEROSOL RESULTS PRESENTATION

Table 4.2.1. Annual minimum, maximum, mean and standard deviation of Aerosol concentration from 2019–2024.

AEROSOL	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
MINIMUM	-0.7515	-0.7938	-0.6080	0.0126	-0.0996	0.0011
MAXIMUM	-0.5835	-0.6427	-0.4411	0.1088	0.0533	0.1683
MEAN	-0.6752	-0.7115	-0.5316	0.0637	-0.0335	0.0792
STANDARD DEVIATION	0.0502	0.0421	0.0485	0.0306	0.0439	0.0509

Starting with Table 4.2.1, which shows the annual minimum, maximum, mean, and standard deviation of aerosol concentration, the year 2019 recorded a minimum value of –0.7515 and a maximum of –0.5835, with a mean of –0.6752 and a standard deviation of 0.0502. This indicates a relatively low and consistent aerosol concentration. In 2020, the minimum dropped slightly further to –0.7938, while the maximum stood at –0.6427, and the mean reduced to –0.7115 with a standard deviation of 0.0421, reflecting an even lower and more stable concentration than the previous year, likely influenced by the global slowdown in activities due to COVID-19. By 2021, there was a noticeable increase: the minimum value rose to –0.6080 and the maximum to –0.4411, with the mean at –0.5316 and a slightly higher standard deviation of 0.0485, suggesting more variability. A significant shift occurred in 2022, when the minimum value turned positive (0.0126), and the maximum rose to 0.1088. The mean also became positive at 0.0637, with a lower standard deviation of 0.0306, indicating a recovery period with more consistent higher aerosol concentrations. In 2023, there was a regression, with a minimum of –0.0996, a maximum of 0.0533, and a mean dropping to –0.0335, although the standard deviation increased to 0.0439, implying a more erratic distribution. Finally, in 2024, the values stabilized again: the minimum stood at 0.0011, the maximum peaked at 0.1683—the highest recorded—while the mean rose to 0.0792 and the standard deviation to 0.0509, reflecting both higher and more dispersed aerosol presence.

Table 4.2.2. Monthly concentration of Aerosol from 2019–2024.

YEAR/MONTH	2019	2020	2021	2022	2023	2024
JANUARY	0.214	1.26	-0.235	0.909	1.131	1.26
FEBRUARY	0.33	1.268	0.105	1.434	1.496	1.268
MARCH	-0.143	0.381	-0.458	0.81	-0.132	0.381
APRIL	-0.668	-0.002	-1.105	-0.115	-0.074	-0.002
MAY	-1.029	-0.349	-1.395	-0.386	-0.359	-0.349
JUNE	-0.913	-0.381	-1.398	-0.526	-0.632	-0.381
JULY	-0.971	-0.242	-0.435	-0.517	-0.661	-0.242
AUGUST	-0.916	0.112	-0.588	-0.159	-0.251	0.112
SEPTEMBER	-1.132	-0.606	-0.681	-0.489	-0.58	-0.606
OCTOBER	-1.36	-0.799	-0.759	-0.632	-0.648	-0.799
NOVEMBER	-1.11	-0.323	-0.31	-0.05	-0.498	-0.323
DECEMBER	-0.37	0.663	0.9	0.608	0.794	0.663
MEAN	-0.6752	-0.7115	-0.5316	0.0637	-0.0335	0.0792
STANDARD DEVIATION	0.0502	0.0421	0.0485	0.0306	0.0439	0.0509

Table 4.2.2, which outlines the monthly aerosol concentrations from 2019 to 2024, highlights the months with the lowest and highest values for each year. In 2019, the lowest concentration was recorded in October (–1.360), while the highest occurred in February (0.330). For 2020, October again marked the lowest point (–0.799), whereas February had the peak value at 1.268. In 2021, the month of June experienced the lowest concentration (–1.398), and December had the highest at 0.900. The year 2022 saw May as the month with the lowest aerosol level (–0.386), while February again was highest with a value of 1.434. In 2023, July marked the minimum (–0.661), and February remained the peak month at 1.496. Lastly, in 2024, June had the lowest value (–0.381), while February again stood out with the highest aerosol concentration of 1.268. Across these years, February consistently had the highest concentrations, possibly due to seasonal dryness and increased particulate suspension, while the wet season months like May, June, and October generally showed lower values, likely due to rainfall reducing aerosol content. The annual means and standard deviations listed in this table are identical to those in Table 4.1.1, reaffirming the summary statistics and highlighting how these monthly fluctuations contribute to the overall yearly profiles.

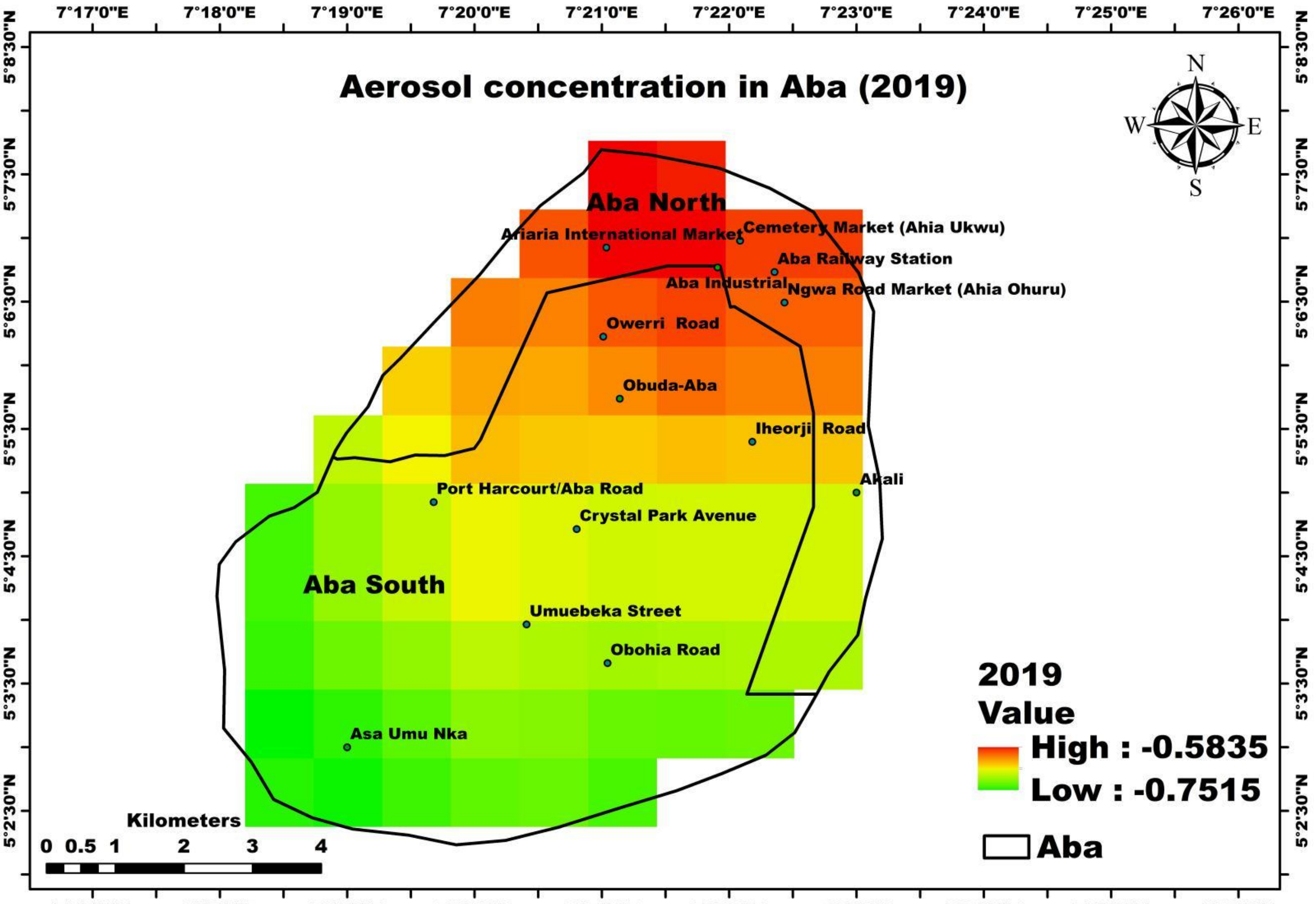

Figure 4.2.1. Map showing Aerosol concentration in Aba for 2019.

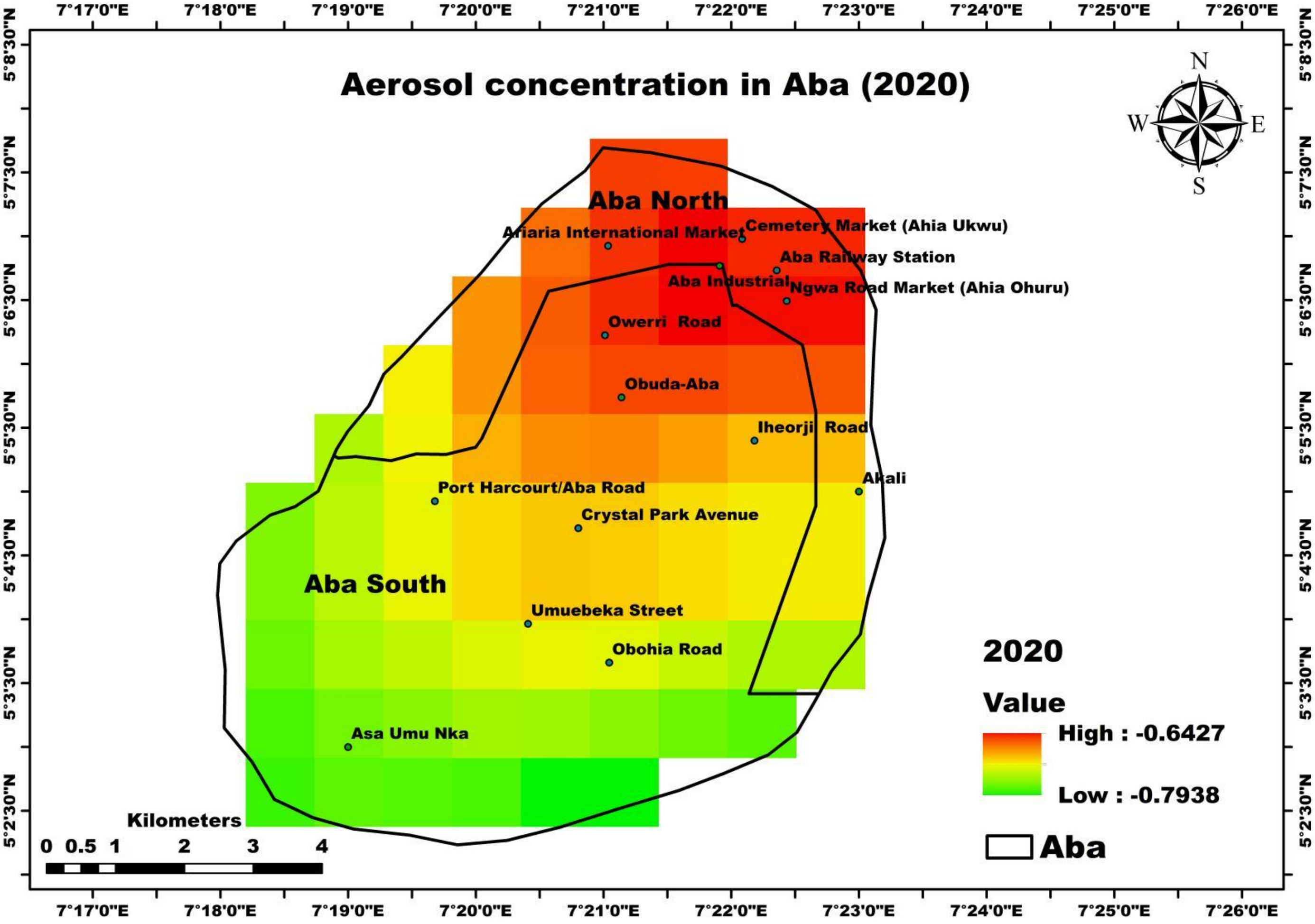

Figure 4.2.2. Map showing Aerosol concentration in Aba for 2020.

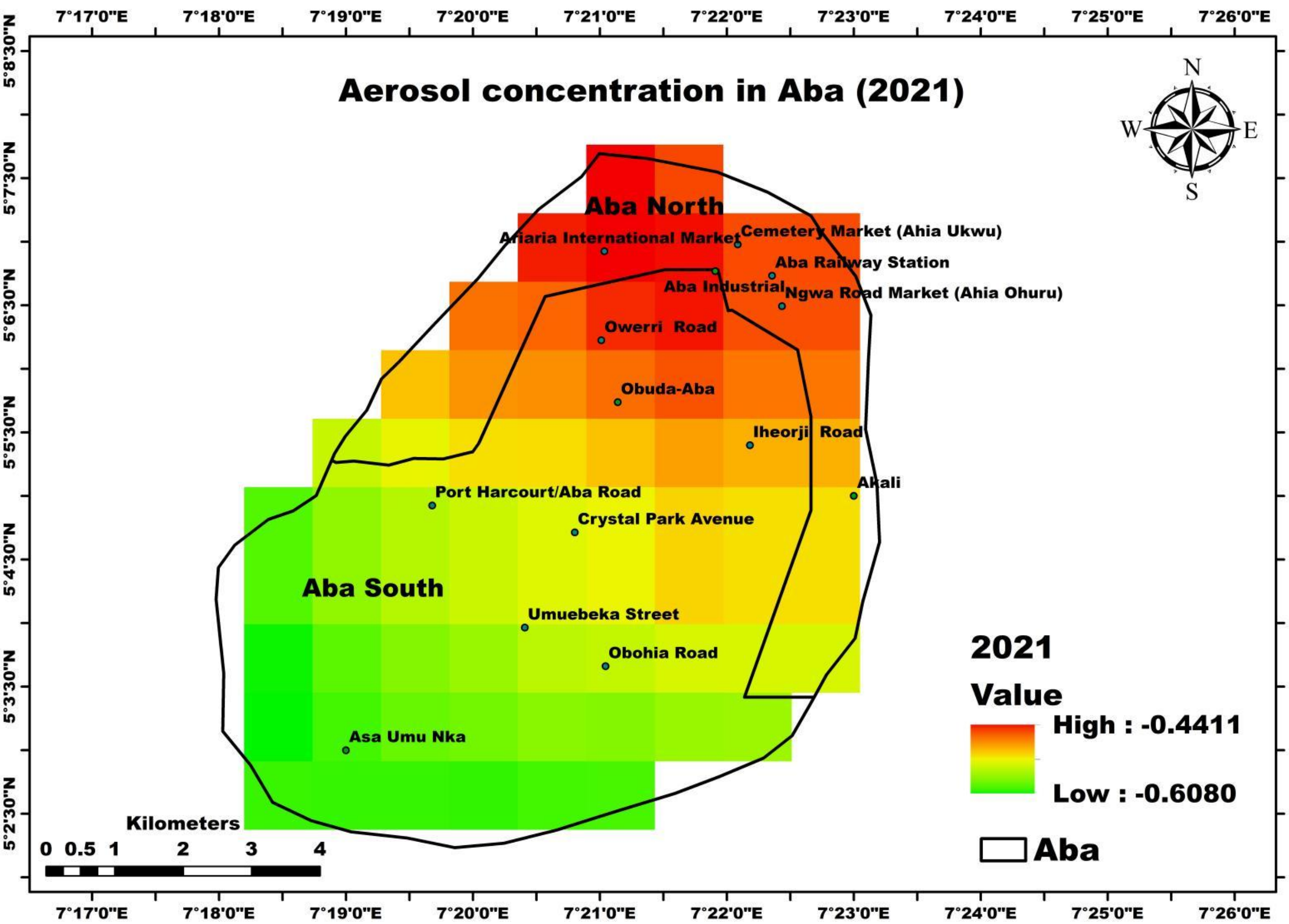

Figure 4.2.3. Map showing Aerosol concentration in Aba for 2021.

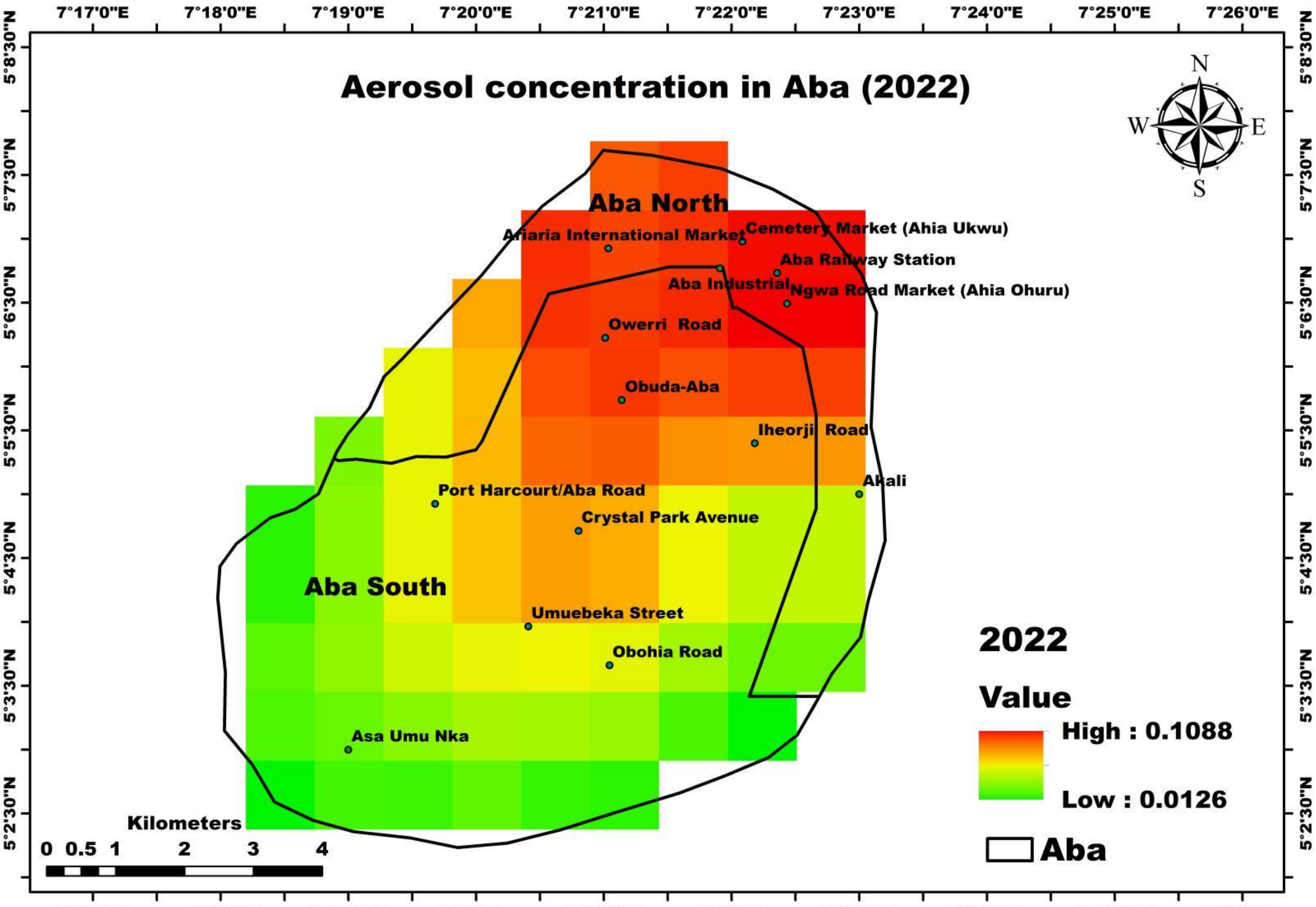

Figure 4.2.4. Map showing Aerosol concentration in Aba for 2022.

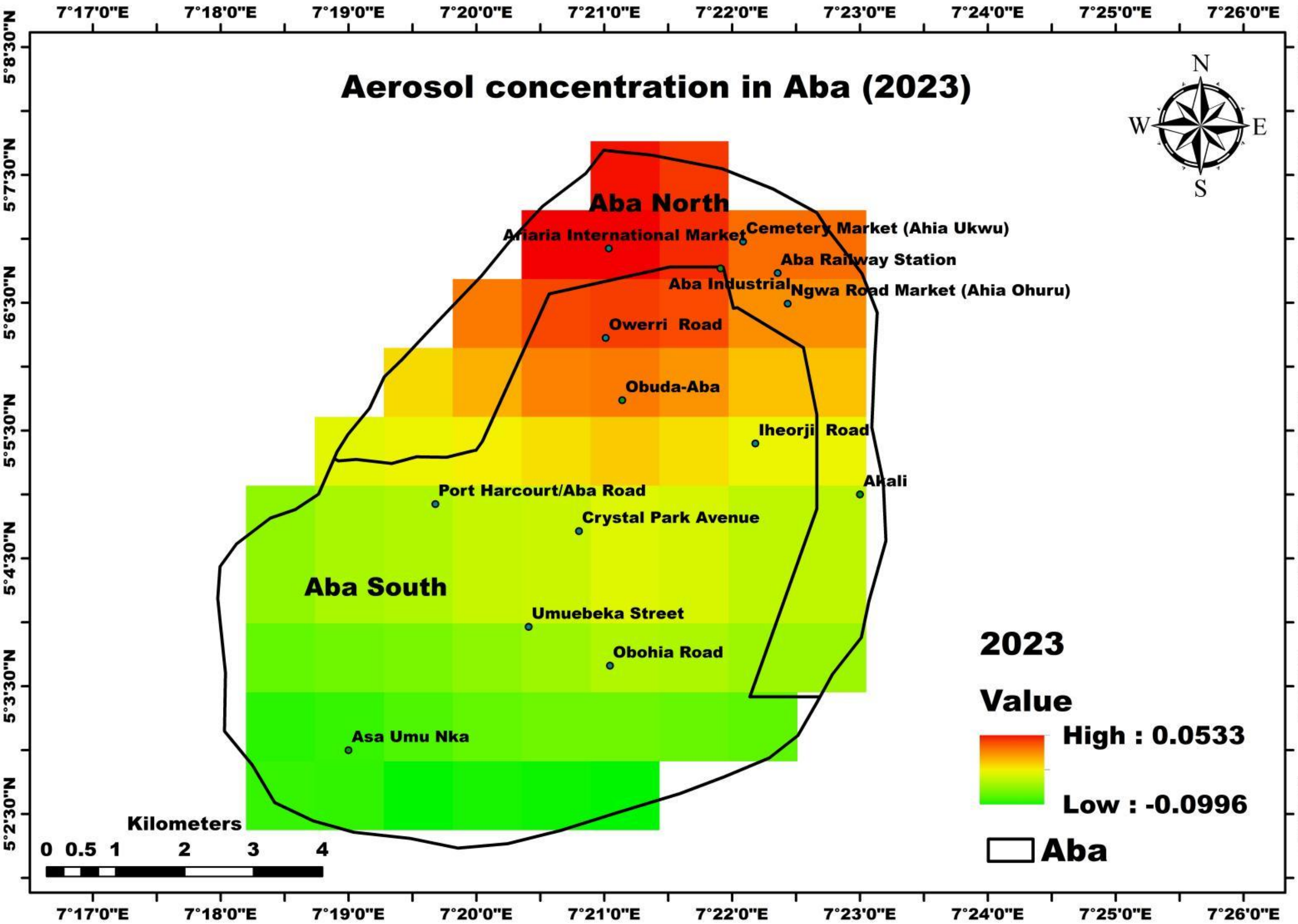

Figure 4.2.5. Map showing Aerosol concentration in Aba for 2023.

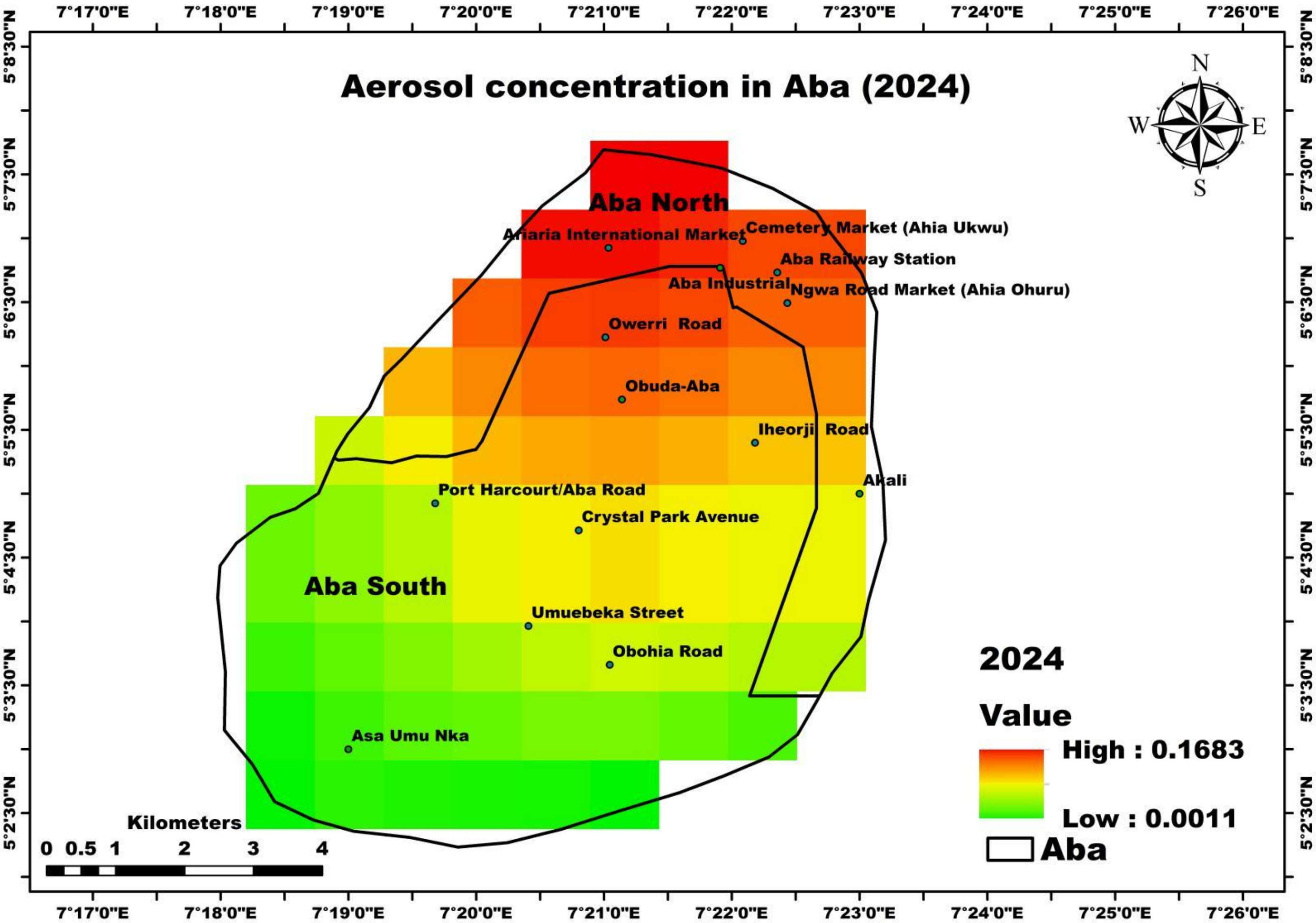

Figure 4.2.6. Map showing Aerosol concentration in Aba for 2024.

The spatial variation of aerosol concentrations, as illustrated in Figure 4.2.1, revealed that in 2019, areas such as the Aba Industrial area, Akali, Ariaria International Market, Aba Railway Station, Cemetery Market (Ahia Ukwu), Ngwa Road Market (Ahia Ohuru), Owerri Road in Aba North, and the central part of Aba South, including Obuda-Aba, recorded high concentrations at -0.5835. In contrast, locations such as Asa Umu Nka in Aba South, Port Harcourt/Aba Road, Crystal Park Avenue, Umuebuka Street, and Obohia Road experienced the lowest concentration at -0.7515. In 2020 (Figure 4.2.2), a similar spatial pattern was observed. Aba Industrial, Akali, Ariaria International Market, Aba Railway Station, Cemetery Market (Ahia Ukwu), Ngwa Road Market (Ahia Ohuru), Owerri Road, and Obuda-Aba recorded high aerosol concentrations at -0.6427, while the southern part of Aba South recorded a low concentration at -0.7938. In 2021 (Figure 4.2.3), the spatial distribution remained consistent with the previous years. The highest concentration was recorded at -0.4411, while the lowest was observed at -0.6080. In 2022 (Figure 4.2.4), the trend continued, with the highest aerosol concentration reaching 0.1088, and the lowest recorded at 0.0126. In 2023 (Figure 4.2.5), areas such as the Aba Metropolis and Obuda-Aba again recorded high concentrations at 0.0533, while Akali and Asa Umu Nka experienced lower concentrations at -0.0996. Finally, in 2024 (Figure 4.2.6), the spatial trend aligned with the pattern observed from 2019 to 2022. The highest concentration was recorded at 0.1683, while the lowest was observed at 0.0011.

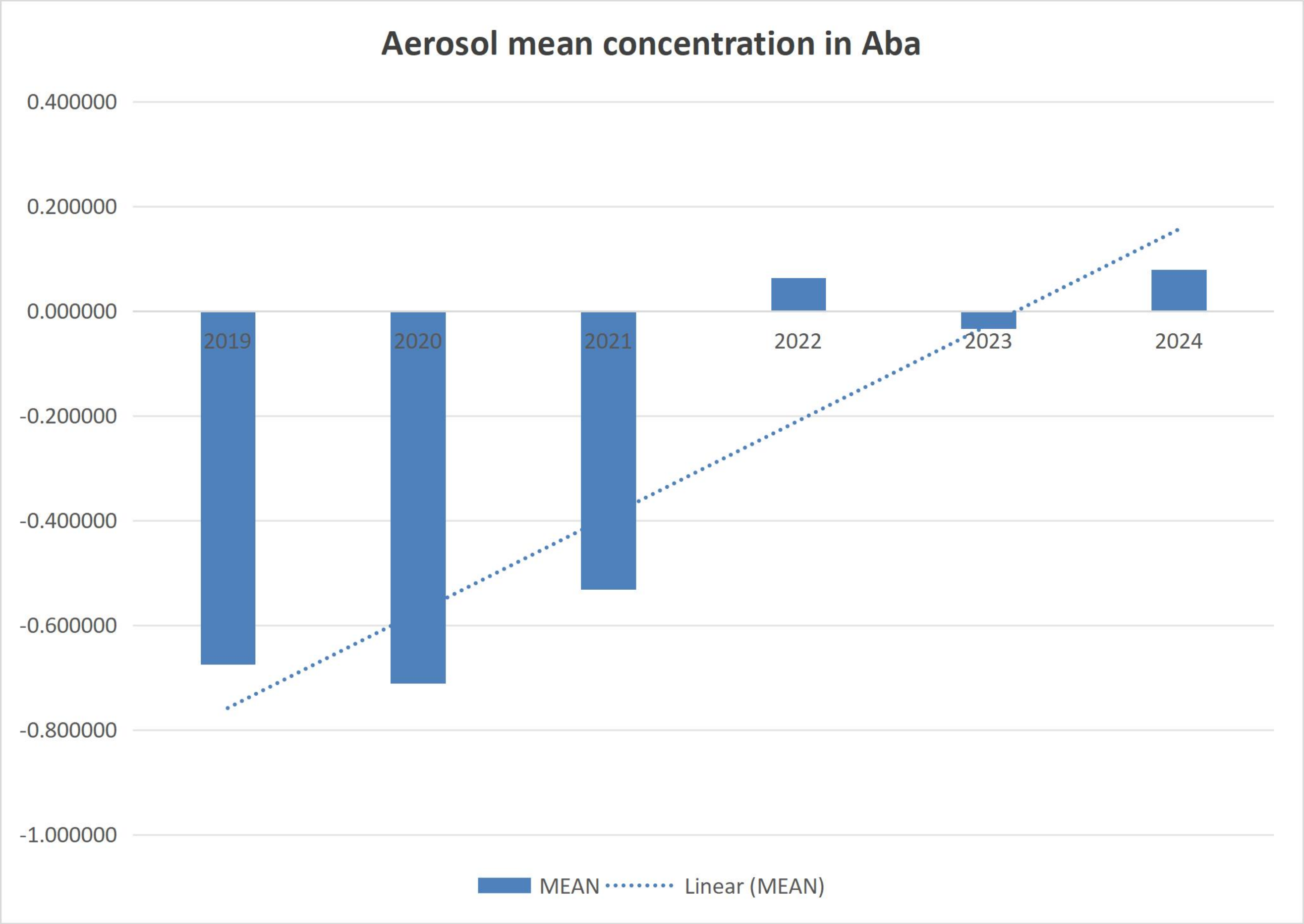

Figure 4.2.7. Trend of annual concentration of Aerosol (2019–2024).

Figure 4.2.7, which illustrates the trend in annual aerosol concentration from 2019 to 2024, reveals a dynamic progression influenced by major events. The year 2020 registered the lowest mean concentration, coinciding with the global COVID-19 lockdowns that significantly curtailed industrial, transport, and commercial activities, thus reducing anthropogenic emissions. In 2022, there was a sharp rebound into positive aerosol values, driven by the resurgence of economic activities and increased oil production following the relaxation of pandemic restrictions. However, in 2023, a decline in aerosol concentration was observed, likely attributable to Nigeria’s fuel subsidy removal policy, which may have led to reduced fuel consumption and changes in public and industrial behavior. By 2024, aerosol levels climbed again as society adjusted to the new economic conditions, suggesting a return to stabilized emission levels and renewed anthropogenic contributions.

4.3. ANALYSIS FOR STATISTICAL SIGNIFICANT DIFFERENCE

Table 4.3.1. Levels of significant difference between years (95% Confidence Interval)

Parameters	Between 2019 and 2020	Between 2020 and 2021	Between 2021 and 2022	Between 2022 and 2023	Between 2023 and 2024	Between 2019 and 2024
CO	$P < 0.05$ (0.016)	$P > 0.05$ (0.238)	$P < 0.05$ (0.027)	$P > 0.05$ (0.105)	$P < 0.01$ (0.001)	$P < 0.01$ (0.001)
Aerosol	$P < 0.01$ (0.001)	$P < 0.05$ (0.004)	$P < 0.01$ (0.003)	$P > 0.05$ (0.257)	$P > 0.05$ (0.117)	$P < 0.01$ (0.002)

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

Table 4.3.1, which shows the statistical differences for carbon monoxide (CO) and aerosols, highlights both year to year variations and long–term trends.

For carbon monoxide (CO), the paired sample t-test showed a significant difference between 2019–2020 (p = 0.016), no significant difference in 2020–2021 (p = 0.238), a significant difference in 2021–2022 (p = 0.027), no significant difference in 2022–2023 (p = 0.105), and a highly significant difference in 2023–2024 (p = 0.001). A direct comparison of 2019 and 2024 also revealed a highly significant difference (p = 0.001).

For aerosols, results indicated a highly significant difference between 2019–2020 (p = 0.001), a highly significant difference in 2020–2021 (p = 0.004), and a highly significant difference in 2021–2022 (p = 0.003). No significant differences were found in 2022–2023 (p = 0.257) or 2023–2024 (p = 0.117). The direct comparison of 2019 and 2024 also showed a highly significant difference (p = 0.002).

CHAPTER FIVE

5.0 DISCUSSION, RECOMMENDATIONS, AND CONCLUSION

5.1 DISCUSSION

This study examined the temporal and spatial distribution of carbon monoxide and aerosol concentrations in Aba between 2019 and 2024. The findings reveal patterns shaped by environmental seasonality, urban activity, national policy decisions, and recovery phases following the COVID-19 pandemic.

Starting with carbon monoxide, the annual data indicate a fluctuating pattern. CO concentrations remained relatively low in 2019 but increased notably in 2020. The rise in CO levels during a period of restricted movement suggests that localised sources such as diesel generator usage, household combustion, and clustered industrial emissions were major contributors, consistent with observations by Okoduwa and Amaechi (2023), Amaechi *et al.* (2025a) and Amaechi *et al.* (2025b) who highlighted how informal energy sources contribute heavily to CO levels in Nigerian cities during the lockdown. The slight drop in 2021 and 2022 followed by a sharper decline in 2023 aligns with the fuel subsidy removal, which likely reduced overall fuel consumption. This supports the argument made by Amaechi *et al.* (2024) who reported similar outcomes, noting that fiscal interventions such as fuel price adjustments can influence environmental outcomes indirectly by reducing fossil fuel demand. The 2024 spike in CO levels, however, reflects the resumption of economic activities and mobility, similar to post-recession rebounds noted in studies of urban Lagos and Port Harcourt (Olowoporoku *et al.*, 2019; Amaechi *et al.*, 2025). This same rebound pattern has been observed globally. In Jakarta, Indonesia, Anugerah, *et al.* (2021) found that CO levels dropped temporarily during COVID-19 lockdowns but surged again as businesses reopened and fuel consumption resumed. In cities like Mexico City and New Delhi, similar post-pandemic surges in CO were documented, attributed to rapid reinstatement of traffic and industrial activities (Vega *et al.*, 2021; Nigam *et al.*, 2022; Mahato and Pal, 2022). However, unlike Nigeria, these cities experienced a slower rebound due to tighter traffic control and public transport policies, which moderated long-term emissions (Vega *et al.*, 2021; Nigam *et al.*, 2022; Mahato and Pal, 2022). This contrast highlights the influence of urban planning and enforcement on how CO trends evolve after major policy or health disruptions.

Monthly trends further support these observations. Across the six-year period, February consistently recorded the highest CO levels. This corresponds with the dry season, when dust particles, biomass burning, and stagnant weather conditions contribute to pollution accumulation. In contrast, October consistently showed the lowest levels. This aligns with the peak of the rainy season in Southern Nigeria, when rainfall and high humidity facilitate the removal of air pollutants through wet deposition. This seasonal cycle has also been reported by Pochanart *et al.* (2003), Sinha *et al.* (2004), Sari *et al.* (2022), Okoduwa and Amaechi (2023) and Onojeghuo *et al.* (2025) who found that wet season rains significantly reduce particulate and gas-phase pollutants in the atmosphere. A similar seasonal CO trend is observed in West African cities like Accra and Abidjan, where dry-season months (December to March) consistently record peak concentrations due to increased combustion, traffic volume, and reduced atmospheric dispersion (Léon *et al.*, 2018; Dajuma *et al.*, 2020). In Southeast Asia, Bangkok and Hanoi experience comparable seasonal CO peaks during dry months, driven by low wind speeds and intensified urban fuel use (Oanh *et al.*, 2023; Doan and Kusaka, 2018). However, in some South American cities like Bogotá and Santiago, peak CO levels occur during winter months (June to August) when thermal inversions trap pollutants near the surface (Oanh *et al.*, 2023; Doan and Kusaka, 2018). These seasonal contrasts show how geography and meteorology interact with human activity to influence pollutant cycles globally.

The spatial distribution of CO concentrations confirms that air pollution is not uniform across the city. Central urban areas such as Aba North and Aba South repeatedly showed higher concentrations than peripheral areas like Asa Umu Nka. This pattern reflects variations in land use, traffic density, commercial activity, and population concentration. Similar findings were reported by Eghomwanre *et al.* (2020) and Mahmud *et al.* (2023) in their study of Onitsha and Benin City, where central business districts recorded higher pollutant concentrations due to denser human activity and more frequent traffic congestion. Globally, similar spatial disparities have been observed. In São Paulo, Brazil, and New Delhi, India, CO levels are significantly higher in densely built-up commercial centers compared to suburban or peri-urban zones (Imam and Banerjee, 2016; Wilson *et al.*, 2015; Dutta *et al.*, 2021). This is largely due to traffic bottlenecks, fuel combustion, and limited green space in urban cores. In Nairobi and Johannesburg, studies have shown that CO hotspots align with major traffic corridors and markets, mirroring what is seen in Aba (Mutono *et al.*, 2022; Khayesi *et al.*, 2010). These international parallels reinforce the conclusion that traffic density and land-use configuration are consistent spatial drivers of CO pollution across both developed and developing regions (Imam and Banerjee, 2016; Wilson *et al.*, 2015; Dutta *et al.*, 2021; Mutono *et al.*, 2022; Khayesi *et al.*, 2010).

On the other hand aerosols, the annual data show a more complex trajectory. Between 2019 and 2021, aerosol levels remained largely negative, which suggests low satellite reflectance values typically associated with cleaner atmospheric conditions. However, from 2022 onwards, there was a shift to positive values aside 2023, with the highest mean recorded in 2024. The sharp increase in 2022 coincides with Nigeria's post-COVID economic reopening, which brought back industrial and transportation activities. This is consistent with global observations of aerosol rebounds after 2020 (Amaechi *et al.*, 2025; Amaechi *et al.*, 2025). The slight dip in aerosol levels in 2023 reflects the influence of fuel subsidy removal. As seen with CO, the policy reduced fuel consumption and associated emissions (Amaechi *et al.*, 2024; Amaechi *et al.*, 2025). However, by 2024, the aerosol concentrations rose again. This indicates renewed combustion activities, increased dust resuspension from urban surfaces, and continued open burning. This pattern is consistent with urban air quality observations from other parts of West Africa (Amaechi *et al.*, 2025; Amaechi *et al.*, 2025). Similar aerosol rebound patterns have been reported in global urban centres. In Southeast Asia, cities such as Bangkok, Jakarta, and Manila saw sharp increases in aerosol optical depth post-2021, largely due to a return to industrial productivity and dry-season biomass burning (Kalita *et al.*, 2020; Gautam *et al.*, 2013; Amnuaylojaroen and Parasin, 2023). In South American cities like Lima and Medellín, studies observed elevated aerosol levels in 2022 and 2023 after relaxed COVID-19 restrictions, driven by construction activity, vehicular congestion, and waste incineration (Martínez Burgos *et al.*, 2023; Mendez-Espinosa *et al.*, 2020; Toro Araya *et al.*, 2021). However, some cities like Santiago and São Paulo recorded only modest increases, attributed to stronger emission control and particulate filtering in transport systems (Toro *et al.*, 2021; Alvim *et al.*, 2023). Compared to these cities, the rise in Aba's aerosol values reflects both intensified human activity and the absence of strict air quality regulations.

Monthly aerosol data also follow a distinct pattern. February emerged as the peak month every year, likely due to dust-laden winds and elevated anthropogenic activity. Conversely, months like May, June, and October consistently recorded the lowest values, further reinforcing the cleansing effect of the rainy season. These seasonal dynamics are widely reported in the literature, particularly in studies focused on West African urban air masses (Ibeneme *et al.*, 2022; Ochei *et al.*, 2023; Saetae *et al.*, 2025). These monthly trends align closely with patterns observed across tropical and subtropical urban centres. In Accra, aerosol concentrations peak between January and March, coinciding with the harmattan season (Fosu-Amankwah *et al.*, 2021). In Bangkok and Hanoi, particulate levels also peak early in the year due to agricultural residue burning and stable atmospheric layers (Phairuang, 2021; Suriyawong *et al.*, 2023; Choochuay *et al.*, 2020). In contrast, cities in the Southern Hemisphere, such as Bogotá and Santiago, experience aerosol peaks during their winter months, typically between June and August, when atmospheric inversions prevent vertical dispersion (Valdés *et al.*, 2013; Cordero *et al.*, 2014). Despite differences in timing, the global evidence confirms that aerosol pollution tends to intensify during dry, stagnant periods, and drop significantly during rainy seasons. Aba fits this trend precisely, with peak aerosol levels in February and minimum levels during the wet months.

Spatially, central Aba consistently recorded the highest aerosol concentrations. These hotspots align with areas of high traffic, frequent waste burning, and industrial emissions. The rise in values in 2024, particularly in densely populated parts of the city, indicates an intensification of these activities. Unlike carbon monoxide, which disperses more readily, aerosols tend to accumulate and persist longer in the atmosphere, especially when not mitigated by rainfall or vegetation cover (Hosannah and Gonzalez, 2014; Pausata *et al.*, 2015; Ulpiani, 2021; Rahman and Meng, 2024). This spatial pattern reinforces the role of land use and human activity in shaping urban air pollution levels (Hosannah and Gonzalez, 2014; Pausata *et al.*, 2015; Ulpiani, 2021; Rahman and Meng, 2024). This spatial pattern is consistent with observations from other major cities in the Global South. In cities such as Delhi, Mumbai, and Lahore, the highest aerosol loads are typically concentrated in dense city cores with intense human activity and limited air flow (Pal *et al.*, 2022; Panicker and Valarmathi, 2025; Sathe *et al.*, 2021; Lodhi *et al.*, 2013; Chauhan *et al.*, 2023; Rani and Kumar, 2022). Similar trends have been found in Latin American cities like São Paulo and Quito, where topography and urban infrastructure create pollutant trapping zones (Vásquez *et al.*, 2019). In Accra and Lagos, aerosol hotspots are aligned with informal markets, motor parks, and slum districts that rely heavily on biomass fuel and open burning (Fosu-Amankwah *et al.*, 2021; Amaechi *et al.*, 2024). Aba's spatial trend follows this same logic, where the concentration of human activity directly translates to higher atmospheric particulate loads. The lack of vegetative cover and poor waste disposal systems further amplify particulate persistence.

Taken together, the trends in carbon monoxide and aerosol concentrations reflect the combined effects of urbanisation, seasonal climate conditions, and national economic policies. Both pollutants showed sensitivity to changes in fuel consumption and economic activity. The fact that CO and aerosols followed similar seasonal and spatial patterns indicates that they share common sources, primarily combustion-related, though their atmospheric behaviour and persistence differ. These findings confirm that Sentinel 5P and Google Earth Engine are reliable tools for monitoring air pollution in developing cities, especially where ground-based monitoring infrastructure is lacking. The results also reinforce the urgent need for targeted air quality interventions in urban centers like Aba. The consistent rise in pollution levels during the dry season and in central business areas points to predictable hotspots and high-risk periods. Without deliberate planning and pollution control measures, the health and environmental risks associated with these pollutants will continue to rise.

5.2 RECOMMENDATIONS

First, local governments in Aba should strengthen enforcement of emission control policies, especially targeting transportation and informal industries. Promoting the use of cleaner fuels and phasing out diesel generators will significantly reduce CO emissions.

Second, the state government should prioritize investment in real-time ground-level air quality monitoring stations to complement satellite data and improve validation.

Third, public awareness campaigns are needed, particularly before the dry season, to discourage waste burning and promote behavior that minimizes particulate emissions.

Fourth, urban planning in Aba must include green buffer zones around industrial areas to reduce pollutant spread into residential neighborhoods.

Lastly, researchers and policymakers should consider integrating air quality management into broader climate adaptation strategies, as seasonal and meteorological factors play a clear role in pollutant dispersion.

5.3 CONCLUSION

This study has demonstrated clear seasonal, annual, and spatial variations in carbon monoxide and aerosol concentrations across Aba between 2019 and 2024. Carbon monoxide levels peaked in 2020 and 2024, reflecting the influence of both post-pandemic recovery and energy use patterns. Aerosols followed a similar trajectory, with notable increases in 2022 and 2024, and strong seasonal peaks in February. Spatially, pollution hotspots were concentrated in central urban zones. These findings not only align with existing literature but also highlight the critical role of human activity, economic policy, and seasonal conditions in shaping air quality. The evidence points to the urgent need for integrated air pollution control strategies that combine urban planning, energy reform, and public engagement.

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