

**MONITORING CONCENTRATION LEVELS OF FORMALDEHYDE AND OZONE IN
LAGOS STATE, SOUTHWESTERN NIGERIA – A CASE STUDY OF 2019–2024**



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BENIN CITY

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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 Formaldehyde and Ozone in Lagos State, SouthWestern Nigeria – a Case Study of 2019–2024 was carried out by Bamidele Emmanuel Godwin 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.

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Date

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(Head of Department)

Date

DECLARATION

I, Bamidele Emmanuel Godwin declare that Monitoring concentration levels of Formaldehyde and Ozone in Lagos State, SouthWestern 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.

Bamidele Emmanuel Godwin

Date

DEDICATION

This work is humbly dedicated to God Almighty, whose boundless wisdom, strength, and grace have carried me through every step of this journey. To my beloved mother, whose unconditional love, sacrifices, and constant prayers have been my greatest motivation. Your unwavering support and guidance have shaped my life and made this accomplishment possible. This achievement belongs to you as much as it does to me

ACKNOWLEDGMENT

I give all glory and honor to God Almighty, whose grace, strength, and guidance sustained me throughout the course of this research. His divine wisdom and presence provided the courage and motivation needed to complete this work.

My profound appreciation goes to my supervisor, Dr. C. F. Amaechi, for his exceptional mentorship, patience, and insightful guidance. Your dedication and thoughtful critiques greatly enriched the quality of this project, and I remain deeply thankful.

I am sincerely grateful to my family, most especially my mother, whose steadfast prayers, support, and endless encouragement have been the foundation of my journey. Your sacrifices and belief in my dreams continue to inspire me.

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ABSTRACT

This study examined the concentration trends and spatial distribution of tropospheric formaldehyde (HCHO) and ozone (O₃) across Lagos State, Southwestern Nigeria, from 2019 to 2024 using Sentinel-5P data processed on the Google Earth Engine (GEE) platform. These pollutants were selected due to their relevance to urban photochemical processes and respiratory health risks in rapidly developing megacities.

Formaldehyde exhibited a marked seasonal cycle, with elevated concentrations during the dry Harmattan season (January–March) and lower values during the rainy months (June–September). High HCHO levels were consistently observed in dense and industrialized local government areas (LGAs) such as Ikeja, Kosofe, Shomolu, Oshodi-Isolo, and Lagos Island. Ozone demonstrated an opposite seasonal pattern, peaking in mid-year months (July–August), particularly across coastal LGAs including Eti-Osa, Ibeju-Lekki, and Epe, due to increased solar radiation and marine airflow dynamics favorable for photochemical ozone formation.

Paired sample t-test results revealed no statistically significant differences in formaldehyde concentrations across all consecutive years ($p > 0.05$), indicating emission stability during the study period. Conversely, ozone concentrations showed a highly significant increase between 2021 and 2022 ($p < 0.01$), suggesting enhanced photochemical activity or intensified precursor emissions during that period. Overall findings highlight the role of anthropogenic emissions, seasonal meteorology, and policy interventions in shaping Lagos air quality. The study recommends strengthened emission controls, improved transportation systems, and continuous satellite-based air-quality monitoring to mitigate pollution impact.

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND OF STUDY

Air pollution is a significant environmental issue affecting urban areas and poses challenges for both developed and developing nations. Its impact on public health is profound, leading to diseases and chronic illnesses. In addition to health risks, air pollution also contributes to changes in climate, which may pose various threats to both local and global communities (Akinola A. *et al* 2014).

Urban air pollution is mainly caused by a wide variety of emission sources, including commercial and residential fuel traffic, manufacturing, and combustion, and consists of a complex mix of gaseous and particulate air pollutants. In the 2019 Health Effects Institute evaluation of global air quality, Nigeria ranked first in Africa and fourth globally for air pollution, with 1,500 air-related fatalities per million population (Health Effects Institute, 2019).

Formaldehyde is a colorless gas at room temperature, characterized by its flammable properties and pungent, irritating odor. Formaldehyde (HCHO) is classified as a volatile organic compound (VOC). VOCs are characterized by their capacity to readily vaporize into the atmosphere, exhibiting high vapor pressures and low boiling points (Carroll and Kirschman, 2022). Formaldehyde (HCHO) is a prominent trace gas in the atmosphere (Freitas and Fornaro, 2022) and serves as a crucial indicator of biogenic, pyrogenic, and anthropogenic hydrocarbon emissions, as it is an intermediate byproduct in the oxidation processes of a substantial quantity of non-methane volatile organic compounds (De Smedt *et al.*, 2010).

Ozone, a form of oxygen known as triplet oxygen (O_3), is created by the interaction between dioxygen (O_2) and singlet oxygen (O , a single oxygen atom) with the help of a third substance capable of absorbing the heat produced during the process. The highly reactive and short-lived singlet oxygen (O) can be produced through the breakdown of nitrogen dioxide (NO_2) or the ionization of O_2 . Ozone is naturally found in both the stratosphere and the troposphere. Stratospheric ozone is mostly found in the tropopause (approximately 8 to 15 km above the surface), an area commonly referred to as the ozone layer. Stratospheric ozone is often referred to as "good" ozone because it plays a crucial role in absorbing harmful ultraviolet (UV-B) radiation that can be damaging to life on Earth. While direct exposure to ozone at ground level can be harmful to living organisms such as humans, animals, and plants, tropospheric or ground-level ozone is termed "bad" ozone due to its potential to cause harm to cells, organs, and various species.(Zhang *et al.*, 2019).

It is obvious that the escalation of anthropogenic activities, particularly the emission of greenhouse gases, is significantly contributing to environmental challenges that have led to loss of human life and damage to property in the region (Olowoporoku *et al.*, 2012).

1.2 STATEMENT OF RESEARCH PROBLEM

In 2018, approximately 11,200 premature deaths were recorded, where children under five are the most affected group, accounting for about 60 percent of total death attributed to air pollution, resulting in an economic burden of US\$2.1 billion, equivalent to 2.1 percent of Lagos State's Gross Domestic Product (GDP). These results alone call for urgent plan of action to improve air quality in the Lagos State. (Lelia C. *et al* 2020).

The primary contributors to this air pollution in Lagos State include road transport, industrial activities, and power generation. (Lelia C. *et al* 2020). These sources are the key drivers in the increase in the level of formaldehyde and ozone concentrations.

Formaldehyde is combustion byproducts and is classified as carcinogenic and plays a role in the formation of ground level ozone, which aggravates respiratory conditions.

Also, elevated concentrations of outdoor ozone can lead to significant health issues. These health risks include breathing difficulties, nausea, eye and throat discomfort, and lung damage. (Menezes *et al.*, 2001) It is essential to evaluate present pollution levels and determine strategies for their mitigation to achieve a healthier environment.

1.3 AIM AND OBJECTIVES

Aim:

The aim of this study is to assess the concentrations levels of tropospheric formaldehyde (HCHO) and Ozone (O₃) in Lagos State.

Objectives:

1. To assess data for the selected air quality parameters in Lagos State for year 2019-2024
2. To determine formaldehyde (HCHO) and Ozone (O₃) emissions for the year under review.
3. To carry out temporal and spatial assessment of the selected air quality parameters formaldehyde (HCHO) and Ozone (O₃)
4. To determine if there is any significant difference over the years.

1.4 JUSTIFICATION

This study directly addresses the critical air pollution challenges faced by the residents of Lagos State, as well as the local government and environmental agencies. Despite these persistent air quality concern, there is a limited or lack of comprehensive data regarding the tropospheric

assessment of formaldehyde and ozone levels concentration across Lagos State, thereby creating gaps in the understanding of these specific pollutants. This study addresses the existing gap by utilizing Sentinel-5P data to analyze temporal variations in formaldehyde and ozone concentrations. By delivering concrete, data-driven insights, the study will help in addressing these gaps which will contribute to the formulation of an effective air quality management strategy, and the findings will provide insights for policy interventions designed to reduce emissions, enhance air quality, and protect public health in Lagos State. Also, by analyzing pollution trends and assessing the impact environmental factors, this study facilitates strategic long-term planning aimed at mitigating the decline of air quality in Lagos State.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 OVERVIEW OF AIR POLLUTION

Air pollution refers to the existence of harmful substances in the air that have negative effects on human health and the environment (WHO, 2024b; Marlier *et al.*, 2016; Mareddy, 2017). These include gases that can enter the respiratory system deeply, such as carbon monoxide (CO), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), volatile organic compounds (VOCs), and particulate matter (PM), including PM_{2.5} and PM₁₀ (WHO, 2024b; Hanigan *et al.*, 2024; Kim *et al.*, 2015). Exposure to particulate matter, especially PM_{2.5}, has consistently been associated with negative health effects such as early mortality, heart conditions, respiratory diseases, and lung cancer (Hanigan *et al.*, 2024; Kim *et al.*, 2015; WHO, 2024b). The World Health Organization stresses that air pollution presents significant dangers to both human health and the environment, highlighting the need for thorough monitoring and prevention strategies (WHO, 2024b; Croitoru *et al.*, 2020; Seinfeld and Pandis, 2016).

The sources of air pollution are categorized into natural and anthropogenic sources. Natural sources are wildfires, volcanic eruptions, etc, releasing large amount of particles and gases into the air. (Marlier *et al.*, 2016; Mareddy, 2017; Seinfeld and Pandis, 2016). Anthropogenic sources, however are the main contributors to persistent air pollution notably in urban areas, where they make up more than 80% of the pollution. (Manisalidis *et al.*, 2020; WHO, 2024b; Croitoru *et al.*, 2020). These sources include industrial discharges, vehicular exhausts, residential heating, agriculture, and improper burning of waste, which significantly modify the air's composition and

leads to adverse health and environmental outcomes. (Manisalidis *et al.*, 2020; Marlier *et al.*, 2016; Seinfeld and Pandis, 2016).

Common gaseous pollutant include sulfur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO), ozone (O₃), and VOCs, while particulate matter (PM) represents a major category of particulate pollutants, but formaldehyde (HCHO) and Ozone (O₃) are of particular interest due to their roles in tropospheric chemistry and their impacts on human health. (Manisalidis *et al.*, 2020; WHO, 2024; Zhang *et al.*, 2021).

Formaldehyde is volatile organic compound (VOC), is extremely reactive with a lifespan in the atmosphere lasting from hours to days before breaking down or degrading through sunlight and interaction with hydroxyl radicals (OH.). (WHO, 2010; Zhang *et al.*, 2021; Manisalidis *et al.*, 2020). It is found relatively low in the atmosphere, typically around 0.01 – 0.1 part per million in urban areas but yet its health effect significant because of its toxicity nature. (Zhang *et al.*, 2021

Formaldehyde or (HCHO, molecular weight 30.03 g/mol) is a colorless gas with a strong, irritating smell with high water solubility (400 g/L at 20°C) and with a boiling point of 19.1°C, making it highly reactive in the air. It breaks down in hours through sunlight or reactions with other molecules often transforming into carbon dioxide or formic acid through photochemical processes. (WHO, 2010; Zhang *et al.*, 2021; Manisalidis *et al.*, 2020). Primary sources include vehicular exhausts, industrial processes, indoors emissions from material like wood while secondary formation forms when VOC oxidation in high-traffic urban areas.

The International Agency for Research on Cancer (IARC) officially classifies it as a human carcinogen. Studies have consistently pointed out that inhalation of formaldehyde can lead to

immediate eye irritation, nose and throat with prolonged exposure linked to face a higher risk of developing nasopharyngeal cancer and leukemia (IARC, 2006).

Environmentally, formaldehyde contributes in the formation of ozone and aerosols (SOA), both of which are impairing air quality and damaging ecosystem by hindering plant photosynthesis.(Palm *et al.*, 2019).These processes are not only degrading air quality but also influence climate dynamics by altering atmospheric radiative forcing. In Los Angeles, United State, formaldehyde originating from traffic and industrial sources have been linked to increase instances of asthma, especially in children heightening the need for strict emission control. (Manisalidis *et al.*, 2020,;WHO, 2024).

Ozone (O₃) is considered to be among the most harmful air pollutants. It plays a significant role in the formation of smog, which is a consequence of chemical reactions involving nitrogen oxides and volatile organic compounds (VOC). (Brimblecombe 2011; Lyu *et al.*, 2019).

Elevated levels of ground-level ozone can be concerning due to the possible impacts on health. Managing ozone present challenges as it is a gas formed in the air and not released directly from sources that can be controlled. Its formation can occur across various times and distances.(Guadel *et al.*, 2018; X *et al.*, 2016).

The good O₃ that absorbs harmful ultraviolet rays is located in the stratosphere, which is a part of the Earth's atmosphere ranging from 10 to 50 km above the surface. In contrast, the bad O₃, present in the lower atmospheric layer closest to the Earth (troposphere: 0-8 km), acts as a damaging secondary pollutant that causes more than a million deaths worldwide each year. (Rabiu *et al.*, 2025).

As a natural process, ozone levels in the stratosphere vary due to solar influences such as solar cycles and solar winds. These variations have significant effects on the environment. They impact stratospheric temperature, UV radiation strength, and atmospheric circulation, which in turn affect the rates of ozone creation and depletion. (Bojinski *et al.*, 2014).

2.2.1. Global Research on Air Pollution

Research on air pollution at a global scale uncovers trends in pollution origins, health consequences, and ways to reduce it, highlighting the pressing need for action in swiftly urbanizing and industrializing areas. Air pollution levels differ across continents due to various factors like industrial operations, city population density, government regulations, and weather conditions. Metropolises such as Delhi, Beijing, and Cairo encounter severe air pollution levels because of their dense populations, industrial operations, and heavy traffic, while cities in developed nations like the United States and Europe generally boast better air quality standards thanks to stringent regulations and advanced monitoring systems (WHO, 2024a).

Studies carried out in heavily polluted cities point out the main sources of urban air pollution, which include:

1. INDUSTRIAL EMISSIONS: According to Xu *et al.*, (2019), manufacturing activities, particularly in industrial centers, play a significant role in emitting sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM). In China, a major global industrial hub, industrial emissions contribute to 40% of PM_{2.5} levels in urban regions.

2. VEHICLE EMISSIONS: Research by Manisidls *et al.*, (2020) indicates that road traffic is a key origin of urban air pollution, as motor vehicles release substantial amounts of NO_x, CO, and PM_{2.5}. In Delhi, India, over 70% of air pollution in the city arises from vehicle exhaust, with diesel engines identified as primary culprits due to their PM_{2.5} and NO_x emissions. Diesel fumes, prevalent in public and heavy transport vehicles, heighten the risks of asthma, chronic bronchitis, and heart conditions. Areas with heavy traffic become pollution hotspots, affecting both pedestrians and commuters. The study recommends stricter emission regulations and investments in cleaner public transportation to alleviate these issues.

3. RESIDENTIAL HEATING AND BIOMASS BURNING: In regions with cold climates or limited access to electricity, burning coal, wood, and biomass for heating and cooking is a common practice. This significantly adds to indoor and outdoor air pollution, especially in low- and middle-income nations (WHO, 2024a). As per WHO statistics, 2.6 billion individuals still depend on traditional biomass, leading to elevated levels of PM_{2.5} and CO in rural and urban environments alike (WHO, 2024b).

2.2.2. Health Impacts in Global Research

Studies focused on health consistently stress the severe effects of air pollution, particularly in urban areas where pollutants are concentrated. The main health issues reported include respiratory infections, heart diseases, and cancer, with specific vulnerable groups like children and the elderly (He *et al.*, 2020; European Environment Agency, 2021; USEPA, 2023).

According to He *et al.*, (2020), cities in Asia such as Beijing, Delhi, and Ulaanbaatar are among the most polluted globally due to rapid industrial growth and population expansion. The high levels of PM_{2.5} in these regions have resulted in an increase in asthma, chronic bronchitis, and

heart diseases. In Beijing, children and the elderly are the most affected, with hospitals observing a rise in respiratory illnesses during periods of high pollution.

European cities have made significant strides in enhancing air quality, mainly because of strict regulations from the EU. Nonetheless, cities like London and Paris still face occasional spikes in pollution, often linked to traffic congestion and industrial operations. The European Environment Agency (EEA) indicates that air pollution leads to more than 400,000 premature deaths annually in Europe, despite improvements in air quality over the last twenty years (European Environment Agency, 2021).

Cities in North America, particularly in the United States, have seen notable progress in air quality following the implementation of the Clean Air Act. However, urban hubs like Los Angeles and Houston continue to grapple with ozone pollution due to high levels of emissions from vehicles and industries (USEPA, 2023). Research suggests that elevated ozone levels in Los Angeles contribute to respiratory problems, with increased rates of asthma among children in low-income neighborhoods (Kunzli *et al.*, 2003; Leifer *et al.*, 2023).

2.2.3. Environmental Impacts Addressed in Global Studies

The environmental consequences of air pollution, especially on agriculture and ecosystems, are extensively researched:

Agricultural Impact: Feng *et al.*, (2019) and Grulke and Heath (2019) discovered that ground-level ozone, formed from NO_x and VOCs reacting in sunlight, hinders crop growth. In countries

like China and India, ozone exposure can reduce wheat and rice yields by up to 15%, posing a significant threat to food security in regions reliant on agriculture (Feng *et al.*, 2019).

Ecosystem Degradation: The European Environment Agency (2021) highlighted that acid rain resulting from SO₂ and NO_x emissions in Europe and North America damages forests and aquatic systems, leading to soil deterioration and loss of biodiversity. Substantial forest areas in central and northern Europe are affected by acidification, impacting the overall health of ecosystems.

2.2.4. Studies on Air Pollution Reduction

Research on mitigation strategies is central in global studies as countries aim to find effective ways to decrease emissions and enhance air quality. Investigations focus on both technological advancements and policy measures:

Policy Measures: Zhang *et al.*, (2021) observed that regulatory frameworks like the U.S. Clean Air Act and the EU's Air Quality Directive have positively impacted air quality by enforcing stringent emission standards. In China, the "war on pollution" initiated in 2013 led to a 35% reduction in PM_{2.5} levels in major cities through the implementation of stricter regulations, industrial relocations, and the promotion of clean energy.

Technological Innovations: The European Environment Agency (2021) stated that technologies such as electrostatic precipitators, scrubbers, and catalytic converters are widely utilized in industry and transportation to reduce emissions. The adoption of renewable energy sources like

solar and wind power has also lessened the dependency on fossil fuels. Countries like Germany and Denmark have significantly decreased SO₂ and NO_x emissions by replacing coal-fired power plants with cleaner energy sources.

2.3 AIR POLLUTION IN AFRICA

Air pollution in Africa is becoming a concern due to the quick growth of cities, industries, and the rise in the number of vehicles being used (Fisher *et al.*, 2021; Bikis, 2023). Numerous African urban areas are witnessing notable rises in the levels of air pollutants, resulting in negative impacts on health and the environment (Herbert *et al.*, 2022; Daramola and Makinde, 2024; Nhomo *et al.*, 2021; Fisher *et al.*, 2021).

2.3.1 Factors Contributing to Air Pollution in Africa

Air pollution in Africa is caused by various factors. Increase in urbanization leads to higher population density, traffic jams, and industrial operations, resulting in increased emissions of pollutants (Fisher *et al.*, 2021; UNEP, 2022). The expansion of industries, often operating under lenient environmental regulations, introduces a considerable amount of pollutants into the air (Fisher *et al.*, 2021). The rise in vehicle usage due to economic growth and improved mobility also contributes to higher emissions of NO_x, CO, and particulate matter (Wu *et al.*, 2023). The burning of biomass for cooking and heating, especially in rural regions, releases substantial quantities of particulate matter and other harmful substances (UNEP, 2023). Furthermore, dust storms in dry regions add to the high levels of particulates in the atmosphere (Fisher *et al.*, 2021).

Nigeria, as the most populous country in Africa undergoing rapid economic expansion, encounters significant air pollution issues. The nation's heavy dependence on fossil fuels for energy production, in addition to the increasing industrial operations and traffic congestion, has

led to heightened levels of air pollutants in major urban centers (Ukpere *et al.*, 2018; Aigbe *et al.*, 2023; Amaechi *et al.*, 2024).

2.4 AIR POLLUTION IN LAGOS STATE

The continuous growth, rise in population, and evolution of Lagos city, a highly industrialized city globally, have led to its current polluted states. It is evident that the escalating human actions, particularly the release of greenhouse gases, are creating significant environmental challenges that have caused fatalities and damage to properties in the state. The overall impact of air contamination on the residents and surroundings of Lagos is hindering the progress of its sustainability initiatives.(Akinola *et al.*, 2014).

2.4.1 Sources of air pollution in Lagos State

Gas emissions in Lagos originate from waste sites, open burners, and power generators. Other significant sources of air pollution include vehicle exhaust from the growing number of cars, industrial and commercial buses, the use of chemicals, waste, and the burning of fossil fuels by industries.(Akinola *et al.*, 2014).

2.5 METHODS FOR MONITORING AIR QUALITY.

Monitoring air quality is crucial to evaluate pollution levels, pinpoint pollution origins, and develop efficient policies. Precise and prompt air quality information allows policymakers, researchers, and the general public to grasp pollution patterns, evaluate health hazards, and monitor the impact of actions taken. There are three main approaches to monitor air quality: portable devices, stationary monitoring stations, and remote sensing. Each method has its

advantages and limitations, and frequently, a blend of these techniques is employed to acquire thorough air quality data.

3.0 METHODOLOGY

3.1 Map of the Study Area

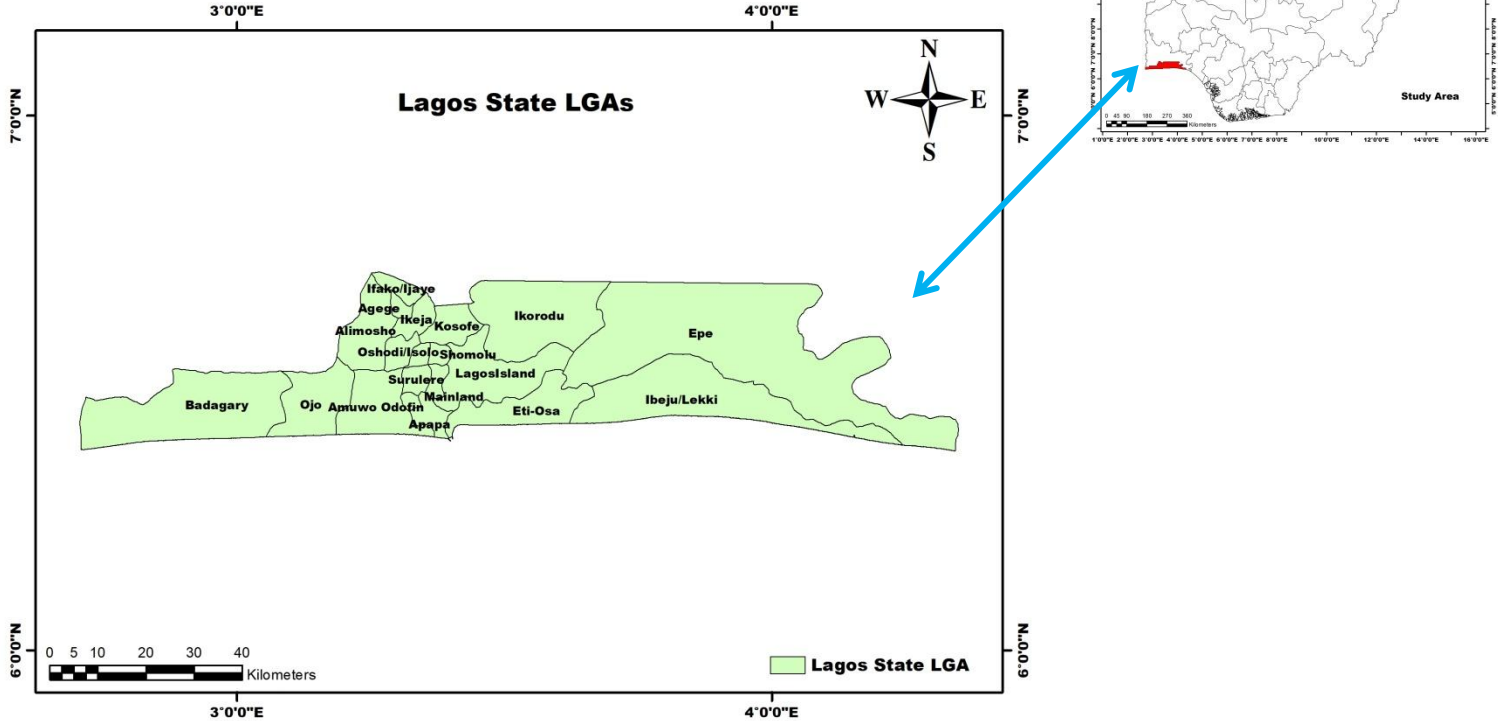


Fig 3.1: Map of Lagos State South Western Nigeria

Lagos State is the smallest state by land area, with a total area of 3,577.28 square kilometers. It is situated between latitudes 6°22' N and 6°52' N and longitudes 2°42' E and 3°42' E. It is one of the most populous cities in Nigeria, having an estimated population ranging from 24.5 million in 2015 to 29 million by 2025 (Okimiji *et al* 2021). It is also one of the world's fastest-growing megacities, expected to become the largest city by the year 2100 (Hoornweg and Pope 2016). It generated 25 percent of the country's Gross Domestic Product (GDP) in 2015 and 70 percent of the country's industrial and commercial activities. (PwC, 2015).

It consists of 20 local government areas (LGA), which include Agege, Alimosho, Apapa, Ifako-Ijaye, Ikeja, Kosofe, Mushin, Oshodi-Isolo, Somolu, Eti-Osa, Lagos Island, Lagos Mainland,

Surulere, Ojo, Ajeromi-Ifelodun, Amuwo-Odofin, Badagry, Ikorodu, Ibeju-Lekki, Epe, and Ikeja, which is the state capital. Lagos State is a unique urban setting with a high population density and rapid urbanization (Auwalu *et al.*, 2023), making it suitable for this study. High vehicle density (227 vehicles/km/day) and old cars (over 15 years old) are the primary contributors to air pollution in Lagos State. The abundance of outdated vehicles in Lagos, along with the city's limited transportation alternatives and traffic congestion, has resulted in a decline in air quality that poses a significant threat to public health (Amaechi, C.F *et al.*, 2023).

3.2 RESEARCH DESIGN

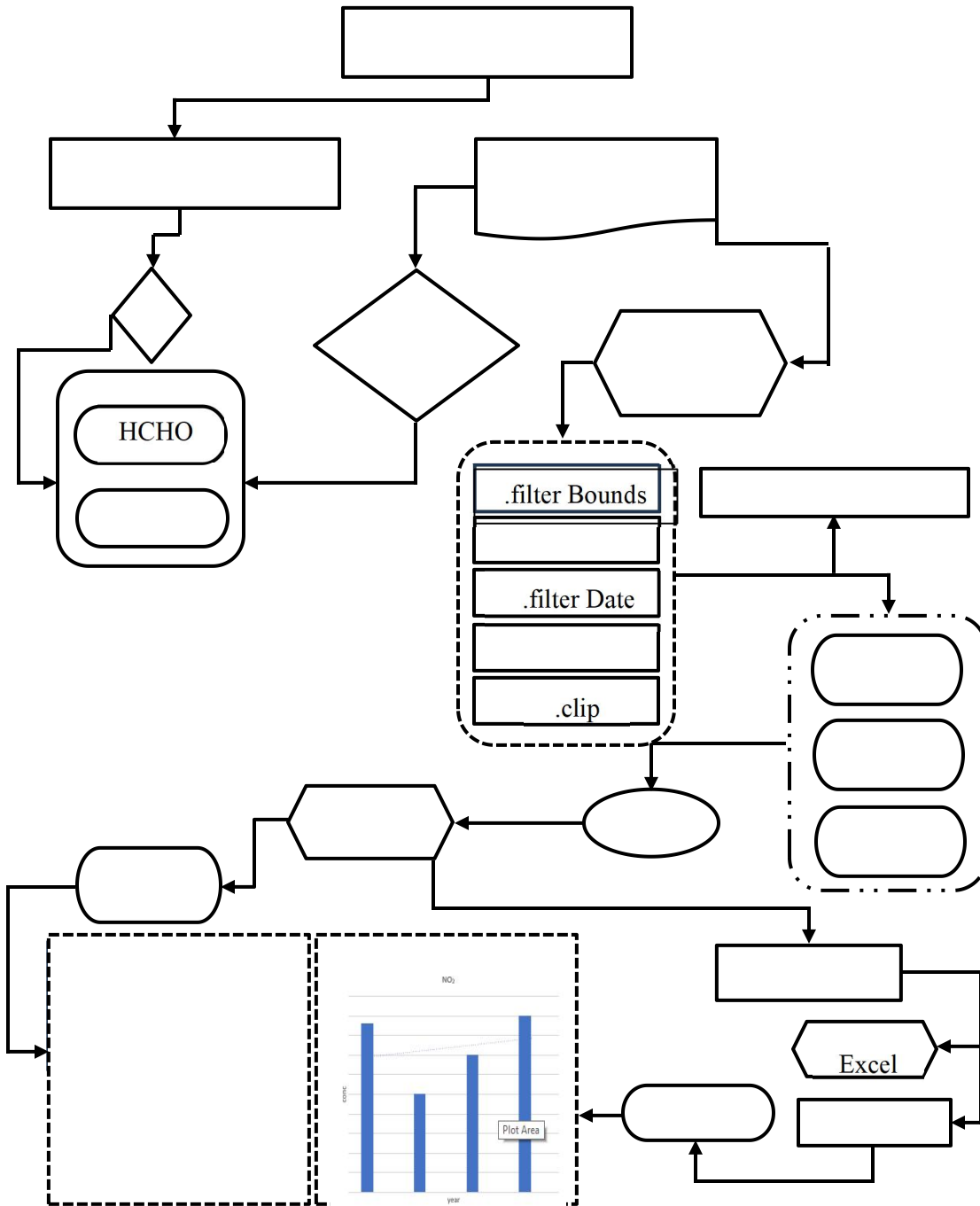


Figure 3.2: Flowchart of the research design

3.3 Data Type and Source

This study relies on secondary satellite data to examine concentrations and temporal patterns of formaldehyde (HCHO) and ozone (O₃) across Lagos State from 2019 to 2024. Specifically, it utilizes measurements from the Sentinel-5 Precursor (Sentinel-5P) satellite mission, which is equipped with the TROPOspheric Monitoring Instrument (TROPOMI). This sensor is designed to deliver detailed, high-resolution observations of atmospheric trace gases, including key pollutants like HCHO and ozone (O₃). Sentinel-5P provides near-daily global coverage with ground pixel sizes around 7×5.5 km², making it well-suited for capturing both local and regional pollution trends (Copernicus, 2020). The instrument's retrieval algorithms, which have been validated against ground-based FTIR and in situ observations. (De Smedt *et al.*, 2018; Veeffkind *et al.*, 2012). These levels of precision allow for reliable detection of both seasonal cycles and longer-term shifts in urban atmospheric composition.

To process and analyze these datasets, this study employed the Google Earth Engine (GEE) cloud platform. GEE is particularly advantageous for environmental studies of this nature because it integrates powerful server-side computational capabilities with a vast repository of satellite imagery and geospatial datasets (Gorelick *et al.*, 2017; Amani *et al.*, 2020; Kumar & Mutanga, 2018). Spatial averaging was then conducted to derive annual mean concentrations over each Local Government Area (LGA) within Lagos State, thereby enabling a clear assessment of spatial distribution and temporal evolution of these pollutants across the study timeframe.

3.4 Method of Data Analysis

The Sentinel- 5 Precursor (Sentinel 5P) launched by the European Space Agency (ESA) in October 2017, is a component of global atmospheric monitoring. Equipped with TROPospheric Monitoring Instrument (TROPOMI), enable the measurement of key atmospheric pollutants, including Formaldehyde (HCHO) and ozone (O₃), which are essential for the understanding of air quality and climate patterns. The Sentinel- 5P satellite provide high resolution data for these gases offering spatial resolution of 5.5km x 3.5km for formaldehyde and 5.5km x 7km for ozone (O₃) and supplies global coverage on daily basis for detailed and frequent monitoring of atmospheric conditions. (Vigouroux *et al.*, 2020; Sha *et al.*, 2021).

The accuracy of the Sentinel-5P of formaldehyde and ozone (O₃) measurement has been thoroughly validated and compared to extensive ground –based networks. There have been assessment of formaldehyde data against the measurement from 25 ground-based Fourier-Transform infrared (FTIR) stations within the Network for the Detection of Atmospheric Composition Change (NDACC). These stations cover various environments, from remote clean areas to heightened HCHO levels due to human activities or natural emissions. (Vigouroux *et al.*, 2020).

Google Earth Engine (GEE) is the most powerful platform for analyzing and processing geospatial data particularly satellite image from Sentinel-5P (Velasategui-Montoya *et al.*, 2023; Tamiminia *et al.*, 2020).Google Earth Engine enables researchers to handle large amount of satellite data through cloud based technology, making environmental analysis easier through features like data visualization, analysis, and exports functions (Velasategui-Montoya *et al.*, 2023).

This platform make complex task of environmental analysis simple by providing tools for data visualization, analysis and export of data. By using Sentinel 5P data into Google Earth Engine, researchers can generate maps, time-series graphs, and spatial models of atmospheric pollutants. Several studies has showed that using both Sentinel-5P and GEE can enhance air quality monitoring (Okoduwa and Amaechi, 2023; Kazemi Garajeh *et al.*, 2023; Amaechi *et al.*, 2024).

Using Google Earth Engine and Sentinel 5-P have increase the global air monitoring capabilities. Google Earth Engine allows efficient visualization and processing of data while Sentinel 5-P offers high resolution atmospheric data which is crucial for the understanding of the pollutant patterns. These platforms together have shown to be efficient in advance air quality research as demonstrated by their application in Ezcomycjiaku *et al.*, (2021), Okoduwa and Amaechi (2023), Amaechi *et al.* (2024).

3.6 Method of Data Collection

The data analysis in this research was conducted using ArcMap version 10.7.1, Google Earth Engine (GEE), and Microsoft Excel to assess the air quality in Lagos State. GEE was used to obtain Sentinel-5P satellite images, which provided data on formaldehyde and ozone (O₃) concentration levels. These images were then imported into ArcMap, where Lagos State-specific shapefiles were applied to filter out unnecessary data, ensuring accuracy in spatial representation. The refined raster data were converted into maps to display the distribution of formaldehyde and ozone (O₃) in Lagos State from 2019 to 2024. A color-coded system was introduced, with green indicating low levels, yellow showing moderate concentrations, and red representing high levels of pollutants, effectively demonstrating the intensity of pollution during the study period.

Microsoft Excel was utilized to analyze the trends in formaldehyde and ozone (O₃) concentrations over time, with results presented graphically to illustrate changes in air quality. This method facilitated a clear and accessible presentation of pollution patterns, aiding in a comprehensive understanding of air quality trends in Lagos State.

Data collection began on January 1, 2019, to coincide with the availability of consistent Sentinel-5P datasets for formaldehyde and ozone (O₃) as documented in the Earth Engine Data Catalog. While data for these pollutants were accessible from mid-2018, starting the analysis in 2019 ensured a complete and consistent annual dataset, enhancing the reliability of temporal comparisons. Formaldehyde and ozone (O₃) were chosen as significant pollutants due to their association with primary emission sources in Lagos State, such as vehicle emissions, industrial activities, and biomass burning. These pollutants are key indicators of air quality, with well-established links to health and environmental impacts in urban areas, aligning with global air quality monitoring standards.

A paired sample t-test was employed to examine year-to-year variations in formaldehyde and ozone (O₃) concentrations. This statistical method was deemed suitable for the study as it considers the relationship between data from consecutive years, accounting for factors like emission patterns, regulations, and weather conditions that create inter-year correlations. By comparing paired data points, the t-test determines if the mean differences in pollutant concentrations between years are statistically significant, reducing the impact of external factors and focusing on changes attributable to actual shifts in pollution levels. This approach ensures dependable insights into the temporal dynamics of air quality in Lagos State.

Table 1 HCHO and O₃ dataset obtained from Sentinel-5P

Band Name	Dataset	Unit	Min	Max	Description
HCHO_column_number_density	OFFL/L3_HCHO	mol/m ²	-0.0172	0.0174	Tropospheric HCHO column number density.
O3_column_number_density	OFFL/L3_O3	mol/m ²	0.025	0.3048	Total atmospheric column of O ₃ between the surface and the top of atmosphere, calculated with the GODfit algorithm.

CHAPTER FOUR

4.0 RESULTS

4.1 FORMALDEHYDE (HCHO) RESULTS PRESENTATION

Table 4.1.1: Annual minimum, maximum, mean and standard deviation of HCHO concentrations from 2019-2024.

HCHO	2019	2020	2021	2022	2023	2024
MIN	0.000143	0.000155	0.000166	0.000178	0.000174	0.000178
MAX	0.000250	0.000270	0.000313	0.000295	0.000294	0.000290
MEAN	0.000204	0.000217	0.000227	0.000227	0.000223	0.000226
STD	0.000021	0.000020	0.000025	0.000021	0.000023	0.000019

Annual HCHO emission concentration from Table 4.1.1 shows that in 2019, the minimum formaldehyde concentration was 0.000143 mol/m², while the maximum was 0.000250 mol/m². The mean concentration was 0.000204 mol/m², with standard deviation of 0.000021

For 2020, the lowest concentration was 0.000155 mol/m², while the highest concentration was 0.000270 mol/m². The mean concentration was 0.000204 mol/m², with slightly lower standard deviation of 0.000020.

For 2021, the minimum concentration was 0.000166 mol/m², while the maximum concentration was 0.000227 mol/m², which is the highest throughout the years. The mean concentration was 0.000227 mol/m², with an increase in standard deviation of 0.000025.

In 2022, the minimum and the maximum concentrations were 0.000178 mol/m² and 0.000295 mol/m² respectively. The mean concentration was 0.000227 mol/m², same as the previous year but there is reduction in standard deviation with the value of 0.000021 mol/m².

For 2023, there is slight decline in both the minimum and maximum concentrations, recorded at 0.000174 mol/m², and 0.000294 mol/m². The mean concentration dropped to 0.0000223 mol/m², with a standard deviation of 0.000023.

In 2024, the minimum concentration increase to 0.0000178 mol/m², while the maximum concentration decline to 0.000290 mol/m². The mean value was 0.000226 mol/m², with lowest standard deviation across the years at 0.00019 mol/m².

Overall, there have been consistent upward trend in formaldehyde from 2019 to 2021, followed by relative stabilization from 2022 to 2024. In 2021, the highest standard deviation was observed, while 2024 recorded the lowest.

4.1.2 Monthly Formaldehyde distribution for the year 2019-2024

In 2019, the peak formaldehyde (HCHO) level was recorded in January at 0.000279mol/m², while the lowest was in July at 0.000110mol/m². The mean concentration was 0.000190 mol/m², with a standard deviation of 0.000065.

The year 2020 shows a similar pattern, with highest level of HCHO was observed in January at 0.000304 mol/m², and the lowest value was in September at 0.000192 mol/m². The mean concentration slightly increase to 0.000192 mol/m², as well as the standard deviation value at 0.000070 mol/m². Though the

average mean was similar to 2019, but there was a noticeable drop during the lockdown month (e.g March-May) which point out decrease in human-made emission from transportation and industries.

For 2021, February recorded the highest concentration of 0.000310mol/m^2 , while August and September recorded the lowest concentration which they both exhibited the same HCHO levels at 0.000117mol/m^2 . The mean concentration was 0.000202 mol/m^2 , with a standard deviation of 0.000070 . This trend is consistent with the previous year, with HCHO level spiking during the dry season and reducing in rainy months. However, the variability was less compared to 2020, which indicate consistent emissions, likely due to the resumption of businesses and vehicular activities following the COVID-19 lockdown.

In 2022, the highest concentration occurred in January at 0.000312mol/m^2 , making it the overall peak across the entire dataset, while the lowest concentration was recorded in July at 0.000111mol/m^2 . The annual mean concentration level reached 0.0000202mol/m^2 , with a standard deviation of 0.000073 . This year saw an increase in mean concentration, in comparison to the other mean concentration before COVID-19 pandemic, potentially suggesting a recovery in economic operation.

The year 2023 followed a similar trend, showing the highest concentration HCHO level in January at 0.000301mol/m^2 , and the lowest in August at 0.000118mol/m^2 . The mean concentration decrease slightly to 0.000200mol/m^2 , with a standard deviation of 0.000066 , This reduction in HCHO concentration level indicate an improved air quality conditions, potentially linked to the removal of fuel (Premium Motor MS) subsidy policy, which led to the reduction in vehicular emissions due to higher fuel prices (Amaechi *et al.*, 2024).

Finally in 2024, January again have the highest concentration at 0.000310mol/m^2 , while August had the lowest at 0.000104mol/m^2 . The mean was 0.000199mol/m^2 , but the standard deviation rose to 0.000075 .

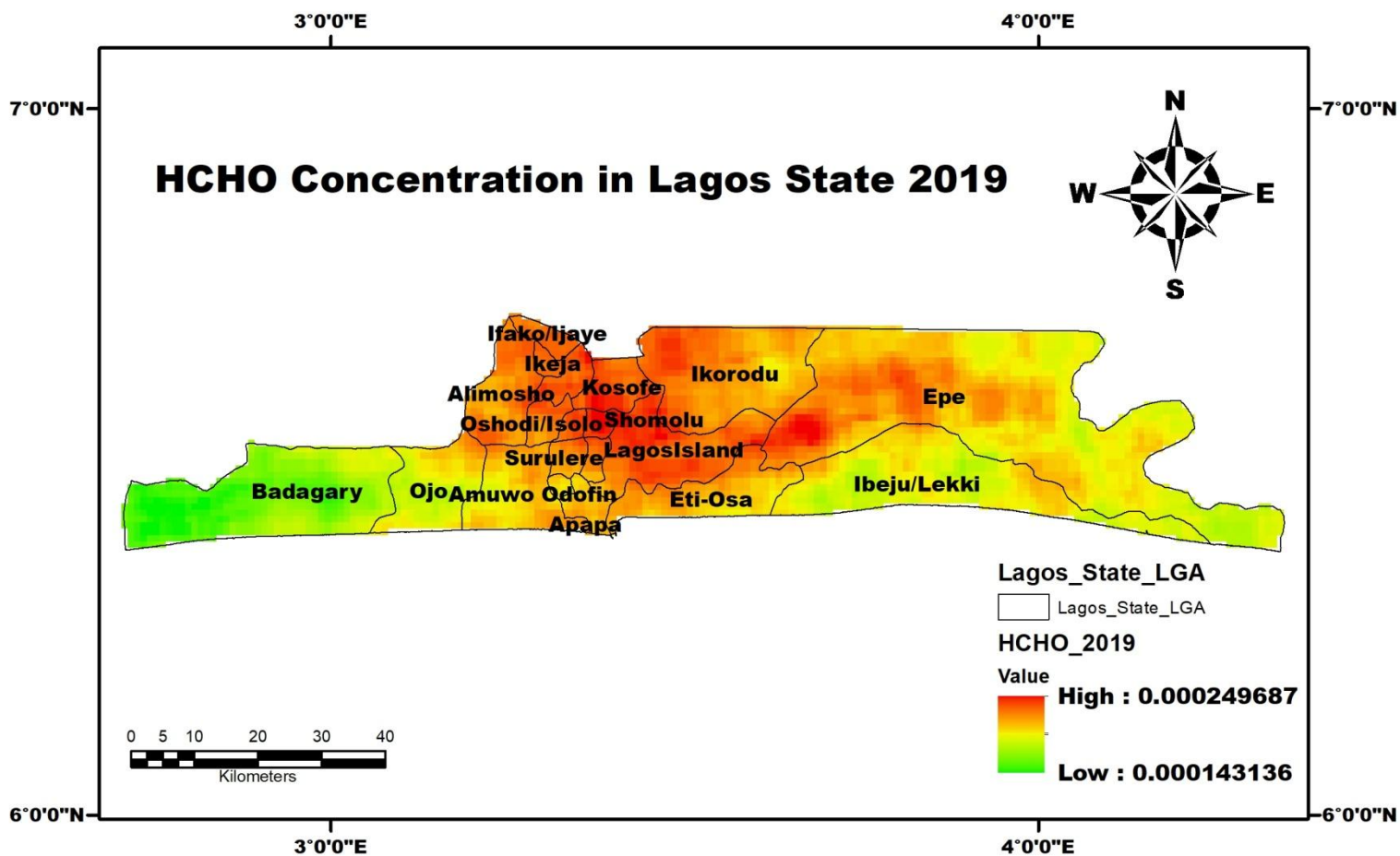


Figure 4.1.1: Map showing Formaldehyde Concentration in Lagos State for 2019

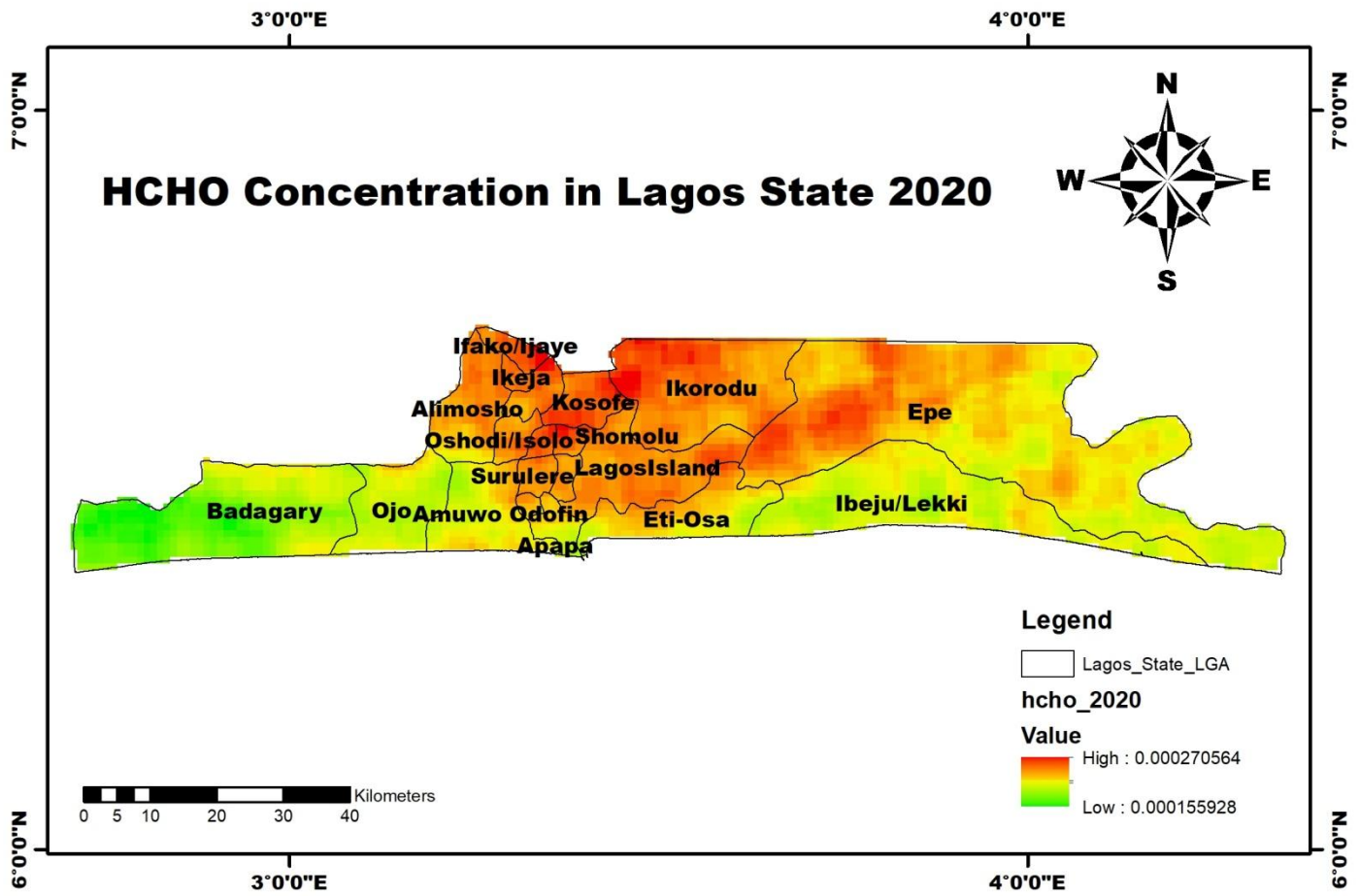


Figure 4.1.2: Map showing Formaldehyde Concentration in Lagos State for 2020

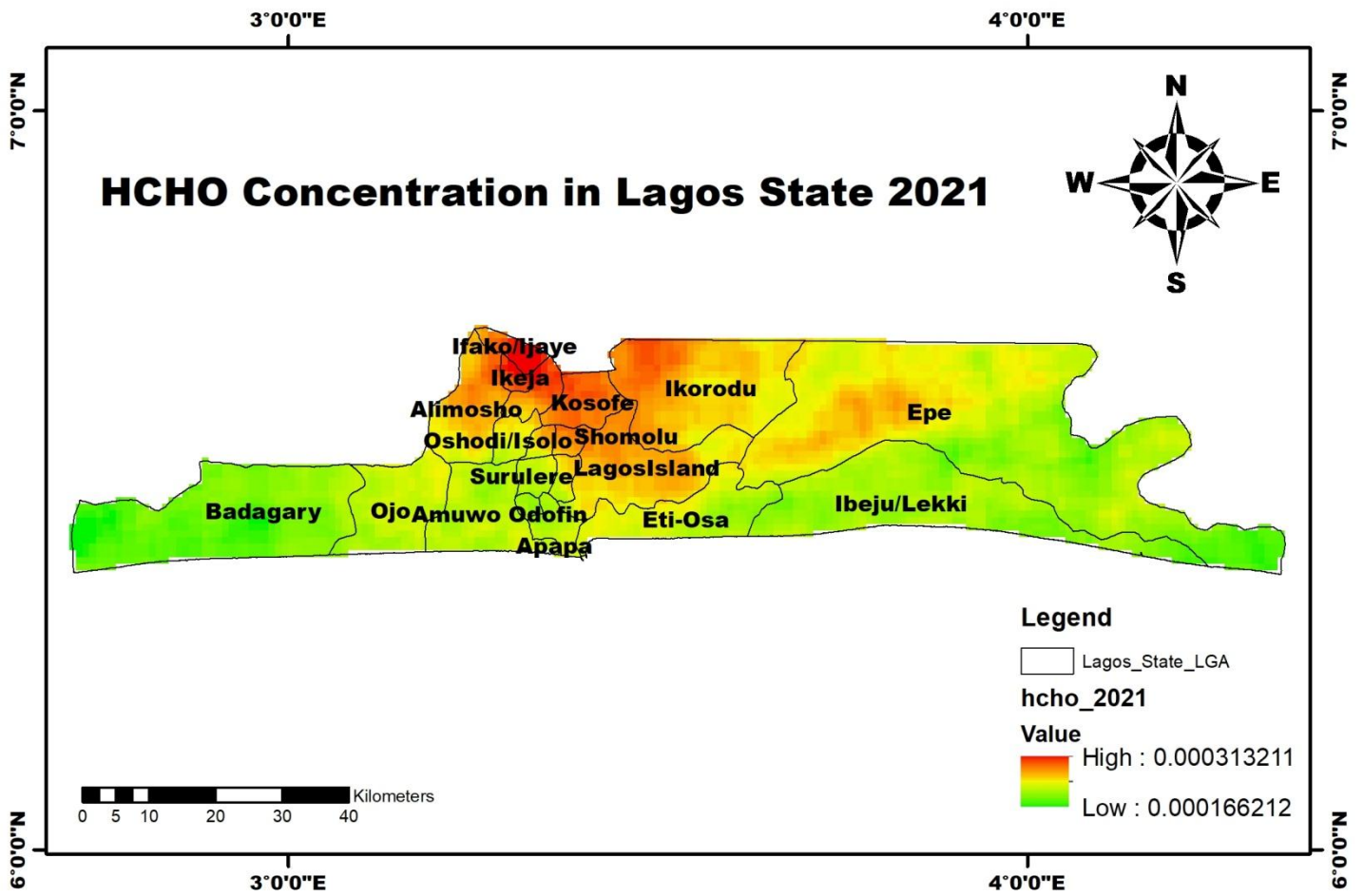


Figure 4.1.3: Map showing Formaldehyde Concentration in Lagos State for 2021

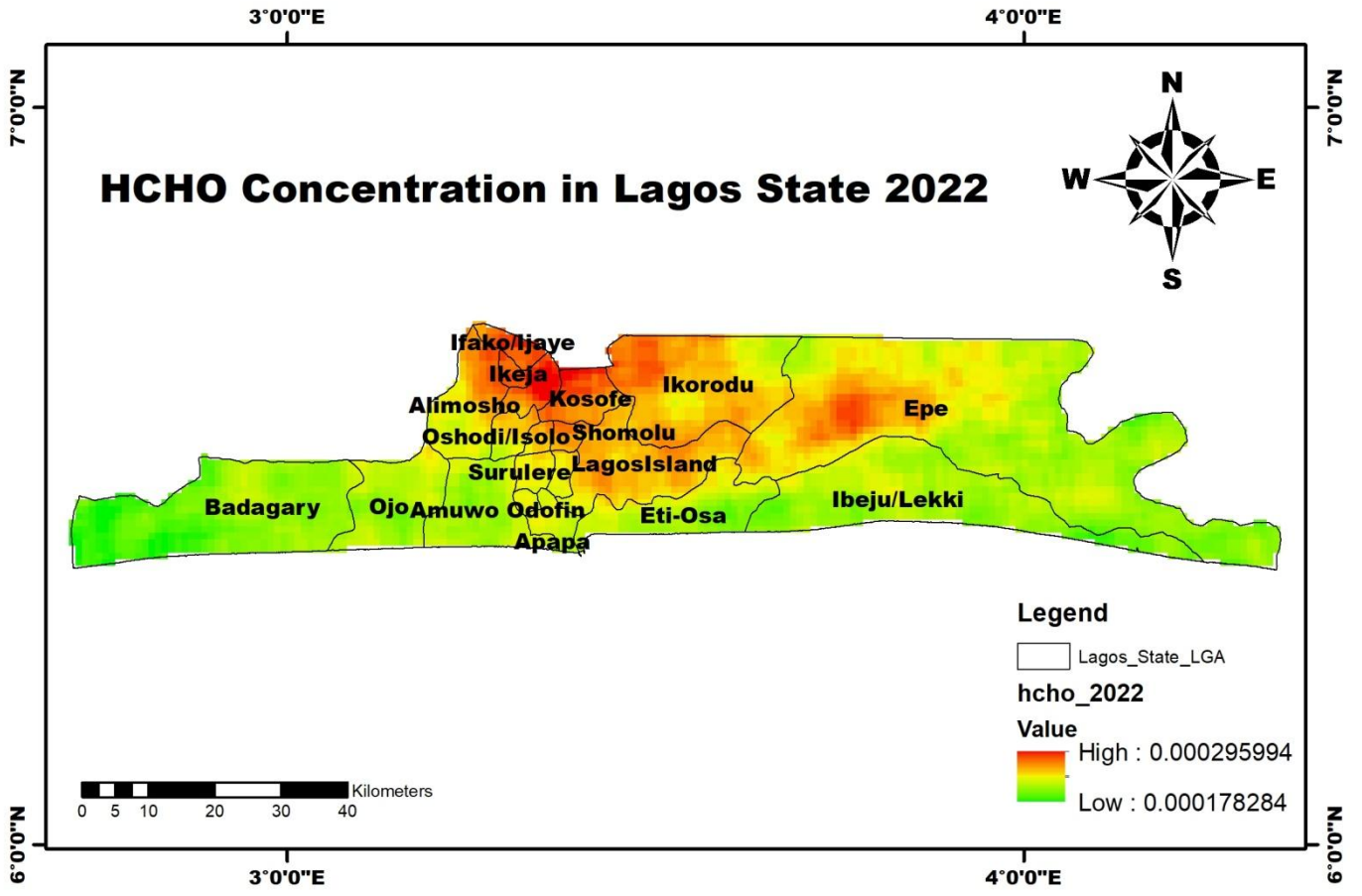


Figure 4.1.4: Map showing Formaldehyde Concentration in Lagos State for 2022

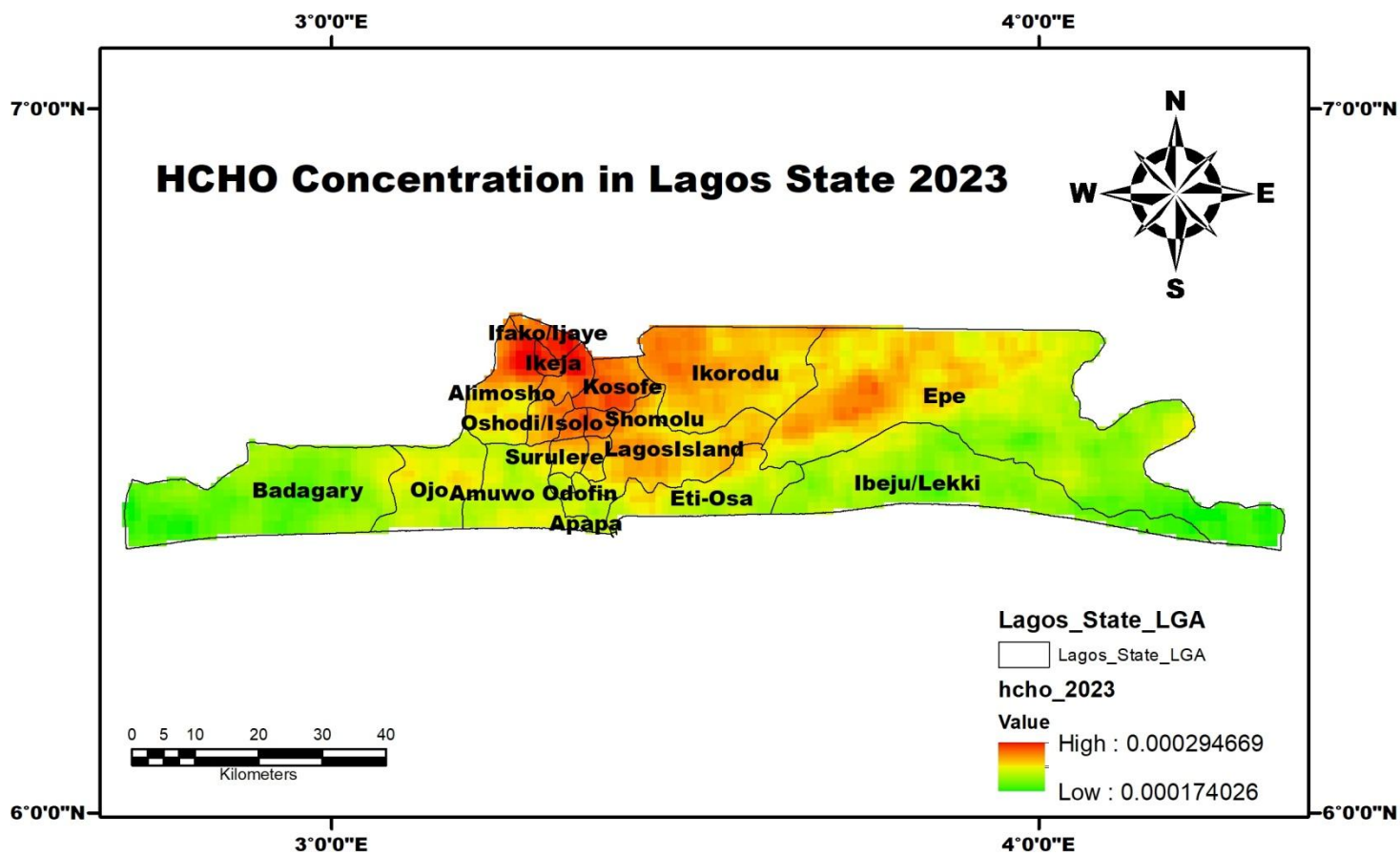


Figure 4.1.5: Map showing Formaldehyde Concentration in Lagos State for 2023

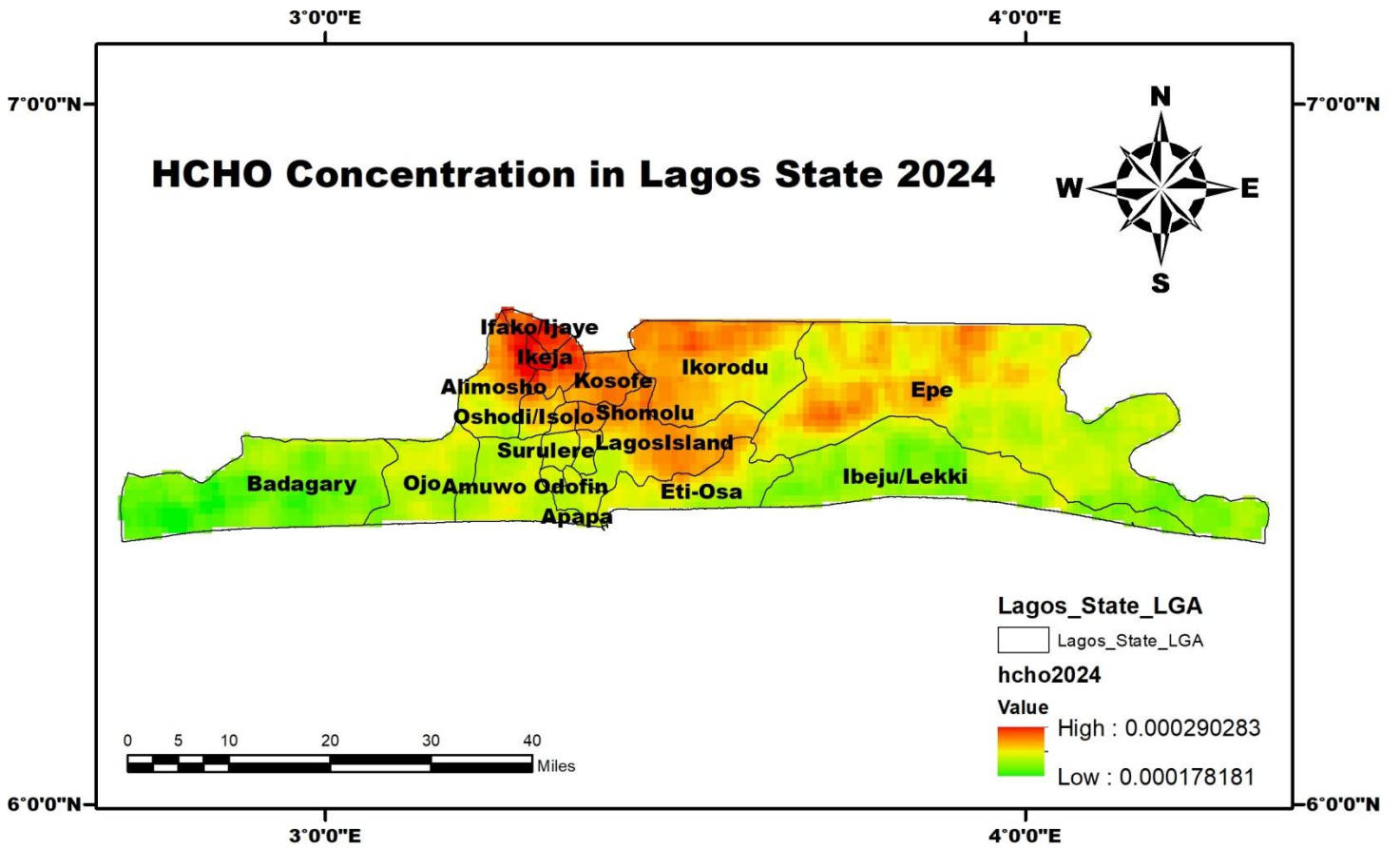


Figure 4.1.6: Map showing Formaldehyde Concentration in Lagos State for 2024

4.1.3 SPATIAL VARIATION OF FORMALDEHYDE CONCENTRATION ACROSS THE STUDY YEARS (2019-2024)

The Spatial variation for HCHO concentrations, as shown in Figure 4.1.3, indicate that in 2019, Local Government Areas like Kosofe, Shomolu, Lagos Island, Oshodi Isolo, Ifako/Ijaye, Alimosho, and Epe in the Northwestern part of Lagos State fall into the high category with concentration of 0.000250 mol/m^2 , and moderate concentration are evenly distributed across Ibeju/Lekki, Eti-Osa, Ojo, Surulere, and Amuwo Odofin, while the lowest concentration of 0.000143 mol/m^2 is only found in Badagry Local Government Area in Lagos State.

For 2020, in the figure 4.1.2 shown, Local Government Areas such as Ifako/Ijaye, Ikeja, Kosofe, Ikorodu, Oshodi/Isolo, Shomolu, Lagos Island, Surulere and Epe located at the Northwestern part of Lagos State fall into the high category with a concentration of 0.000270 mol/m^2 , Local Government Areas such as Apapa, Eti-Osa and Amuwo Odofin located at the Southern part of Lagos State fall under the moderate concentration category, while the lowest concentration of 0.000156 mol/m^2 is recorded in Ibeju Lekki and Badagry Local Government Areas of Lagos State.

According to Figure 4.1.3 in 2021, Local Government Area like Ifako/Ijaye, Ikeja, Kosofe, Ikorodu, Shomolu and Lagos Island of the Northern area of Lagos state fall into the high category with a concentration of 0.000313 mol/m^2 , the central part such as Surulere, Ojo, and Apapa fall under the moderate concentration category. The lowest concentration of 0.000166 mol/m^2 is found in Local Government Areas like Badagry, Amuwo Odofin, Ibeju Lekki, Eti-Osa and outskirts region of Epe LGA.

According to the Figure 4.1.4 in 2022, the northeastern region of the Local Government Area of Lagos fall under the high category with concentration of 0.000296 mol/m^2 , Locations such as

Surulere, Amuwo Odofin, Apapa, and Ojo in the Local Government Area of Lagos state fall under the moderate concentration category. The lowest concentration of 0.000178 mol/m² is recorded in LGAs such as Badagry, Eti-Osa, and Ibeju/Lekki.

For 2023, Figure 4.1.5 indicated that the Northern LGAs of Lagos State fall under the high category with a concentration of 0.000295 mol/m², while the majority of the LGAs in the central part of Lagos State are under the moderate concentration category. The lowest concentration of 0.000174 mol/m² is observed in LGAs such as Badagry, Ibeju/Lekki, and outskirts region of Epe LGA.

Finally, Figure 4.1.6 revealed that in 2024, Ifako/Ijaye, Ikeja, Kosofe, Shomolu, Ikorodu, Lagos Island and Epe fall under the high category with concentration of 0.000290 mol/m². The central LGAs such as Surulere, Amuwo Odogun, Apapa and Ojo fall under the moderate concentration category. The lowest concentration of 0.000178 mol/m² is observed in Badagry and Ibeju/Lekki LGAs of Lagos State.

Formaldehyde Annual Mean Trend

Figure 4 shows an overall stable trend with slight fluctuations in the annual mean concentration of HCHO from 2019-2024. HCHO concentrations slightly decreased nationally from 2019 to 2020, followed by a slight rise in HCHO concentration levels from 2020 to 2021, reaching the highest peak. A slight decline in mean concentration was observed from 2021 through 2023, after which there was a slight increase in 2024. In 2020, the concentration levels of HCHO decreased nationally from 2019 potentially due to reduced anthropogenic activities during COVID-19 lockdowns, though regional increases were noted from continued biomass burning (Omokpariola *et al.*, 2024; Aliyu and Botai 2020; Emuneku *et al.*, 2025). In 2023, the decline in

HCHO concentration may be attributed to the removal of fuel (PMS) subsidy policy, which reduced vehicular and emission-related activities (Agboola *et al.*, 2024).

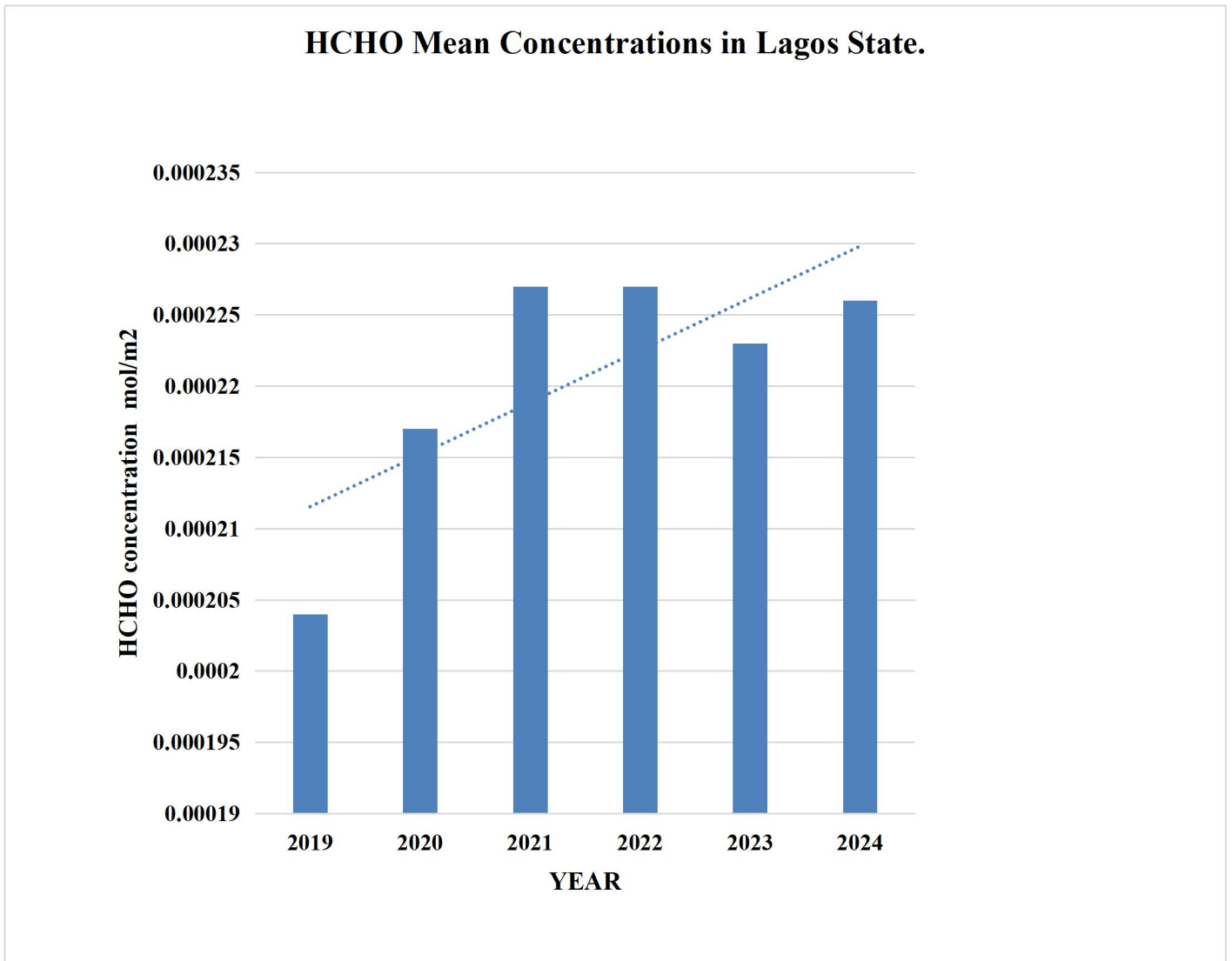


Figure 4.1.7 Formaldehyde Annual Mean Trend from 2019 -2024

4.2 OZONE RESULTS PRESENTATION

Table 4.1.1: Annual minimum, maximum, mean and standard deviation of O₃ concentrations from 2019-2024.

O ₃	2019	2020	2021	2022	2023	2024
MIN	0.120	0.120	0.121	0.123	0.122	0.122
MAX	0.121	0.121	0.122	0.124	0.122	0.123
MEAN	0.121	0.121	0.121	0.124	0.122	0.122
STD	0.000174	0.000148	0.000140	0.000136	0.000109	0.000111

For 2019, the minimum O₃ concentration was 0.120 mol/m², while the maximum O₃ concentration was 0.120 mol/m². The mean value 0.121 mol/m², with a standard deviation of 0.000174 .

In 2020, both minimum and the maximum values remained identical to 2019, at 0.120 mol/m², and 0.121 mol/m², respectively. The mean value still remain constant at 0.121 mol/m², however the standard deviation decreased to 0.000148.

For 2021, the minimum concentration increased to 0.121 mol/m², as well as the maximum concentration to 0.122 mol/m². The mean concentration remained consistent at 0.121 mol/m², while the standard deviation decline to 0.000140.

The year 2022 saw another incremental rise, the minimum rose to 0.123 mol/m², and the maximum concentrations reached 0.124 mol/m², the highest maximum concentration across all years.

In 2023, the minimum concentration value was 0.122 mol/m², and the maximum dropped to 0.122 mol/m². The mean concentration also slightly reduce to 0.122 mol/m², and the standard deviation reached its lowest value at 0.000109

Finally, 2024 minimum concentration levels remain at 0.122 mol/m², while the maximum concentration slightly increases to 0.123 mol/m². The mean value remain at 0.122 mol/m², with the standard deviation of 0.000111, just a little higher than 2023.

4.2.1 Monthly Ozone (O₃) distribution for the year 2019-2024

Appendix 2 show that in 2019, the highest ozone concentration level was in July at 0.127 mol/m², reflecting enhanced photochemical production during wetter months when solar radiation peaks. The lowest was recorded in January with a concentration of 0.116 mol/m², where cooler harmattan winds limit precursor reactivity. The mean concentration for the year was 0.121 mol/m², with standard deviation of 0.00385.

During 2020, the highest concentration value observed was in August with a peak concentration of 0.126 mol/m², while the lowest concentration value was recorded at 0.112 mol/m², in January. The mean concentration remained at 0.121 mol/m², which match to 2019, but with a slight higher deviation of 0.00398 mol/m², which could be linked to the effect of the COVID-19 lockdown.

In 2021, the maximum concentration was recorded in July with a value of 0.127 mol/m², while the minimum concentration was 0.114 mol/m² in January. The mean concentration stayed at 0.121 mol/m², with a standard deviation of 0.00416.

By 2022, the maximum concentration reached 0.129 mol/m², in both August and September, while the minimum concentration was still in January with a value of 0.115 mol/m². The annual mean concentration increased to 0.124 mol/m², with a high standard deviation of 0.0004712.

The year 2023 have a highest concentration of 0.127 mol/m² in July and August, with lowest concentration at 0.115 mol/m² in December. The mean concentration was 0.122 mol/m², with standard deviation of 0.00349.

Lastly, the year 2024 maximum concentration level was 0.129 mol/m², which occurred also in both July and September, while the minimum concentration at 0.112 mol/m² was recorded in February.

The mean concentration rose to 0.123 mol/m^2 , same as the standard deviation, which increase to 0.00623 , the highest recorded the in the study period.

From the six years study period, Ozone concentrations generally peaks in July and August, likely due to enhance photochemical production hinder higher solar radiation and temperature, and drop in the early months, mostly January and February which could be also likely due to meteorological factors like harmattan conditions which can limit precursor reactivity.

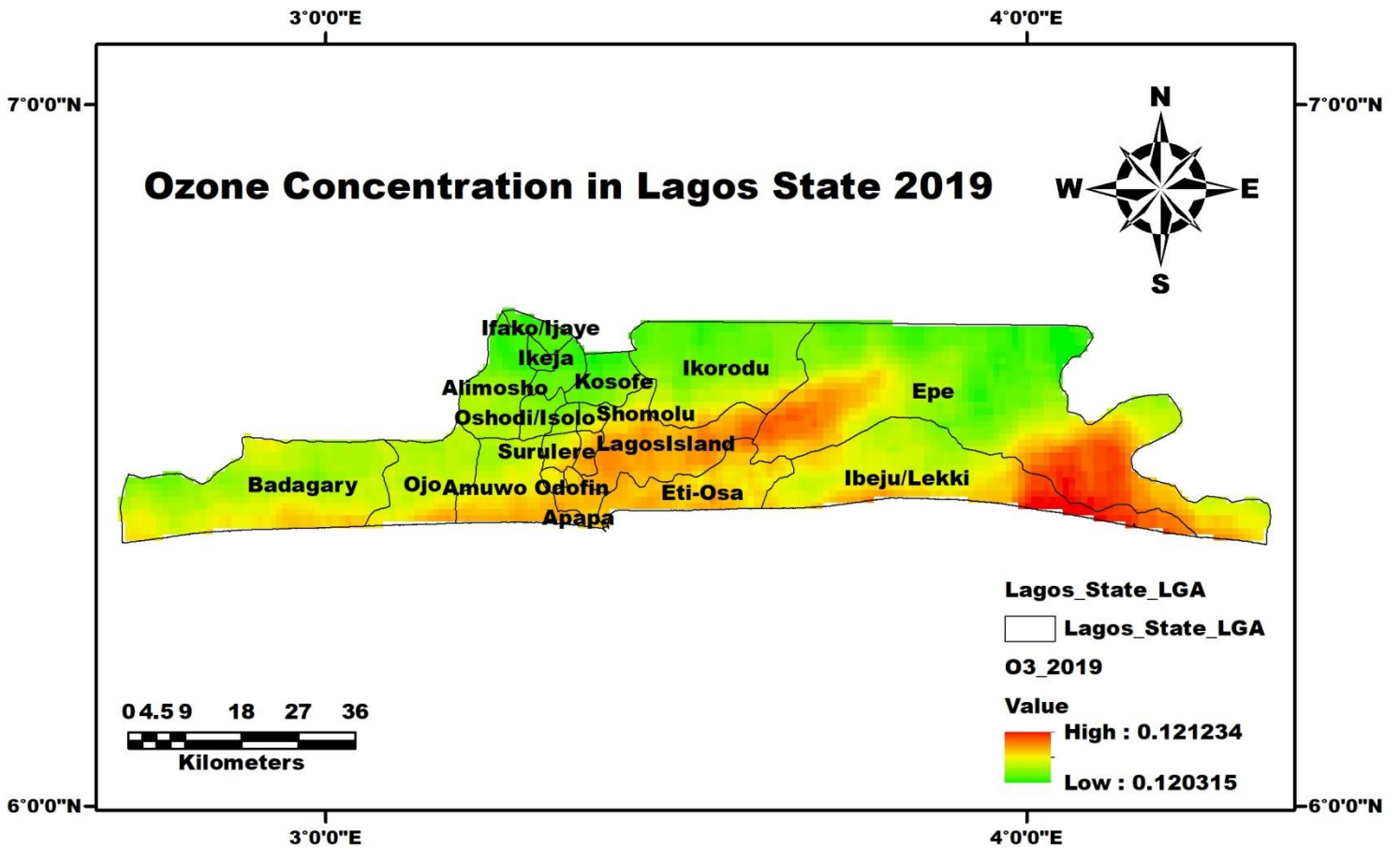


Figure 4.2.1: Map showing Ozone Concentrations in Lagos State for 2019

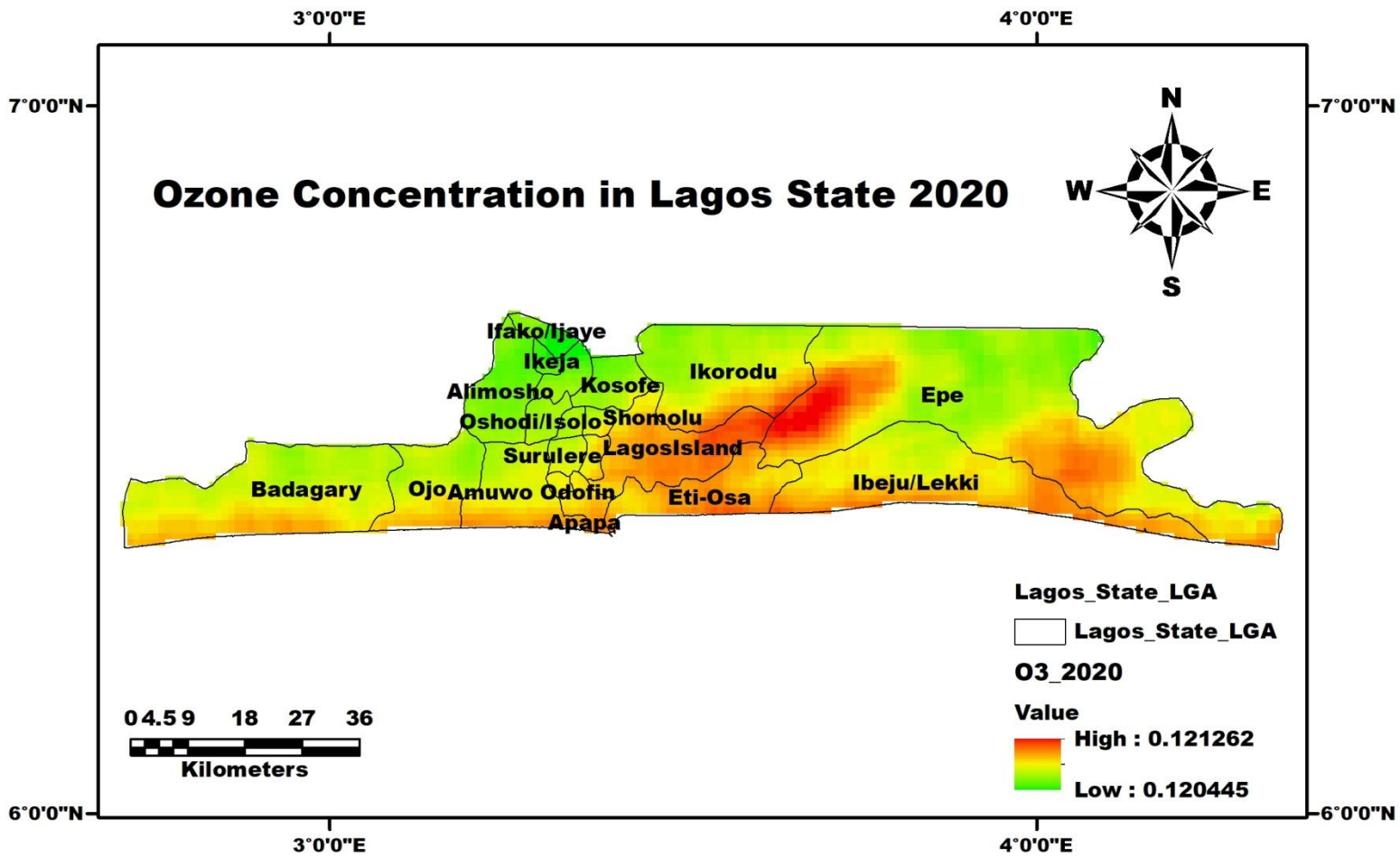


Figure 4.2.2: Map showing Ozone Concentrations in Lagos State for 2020

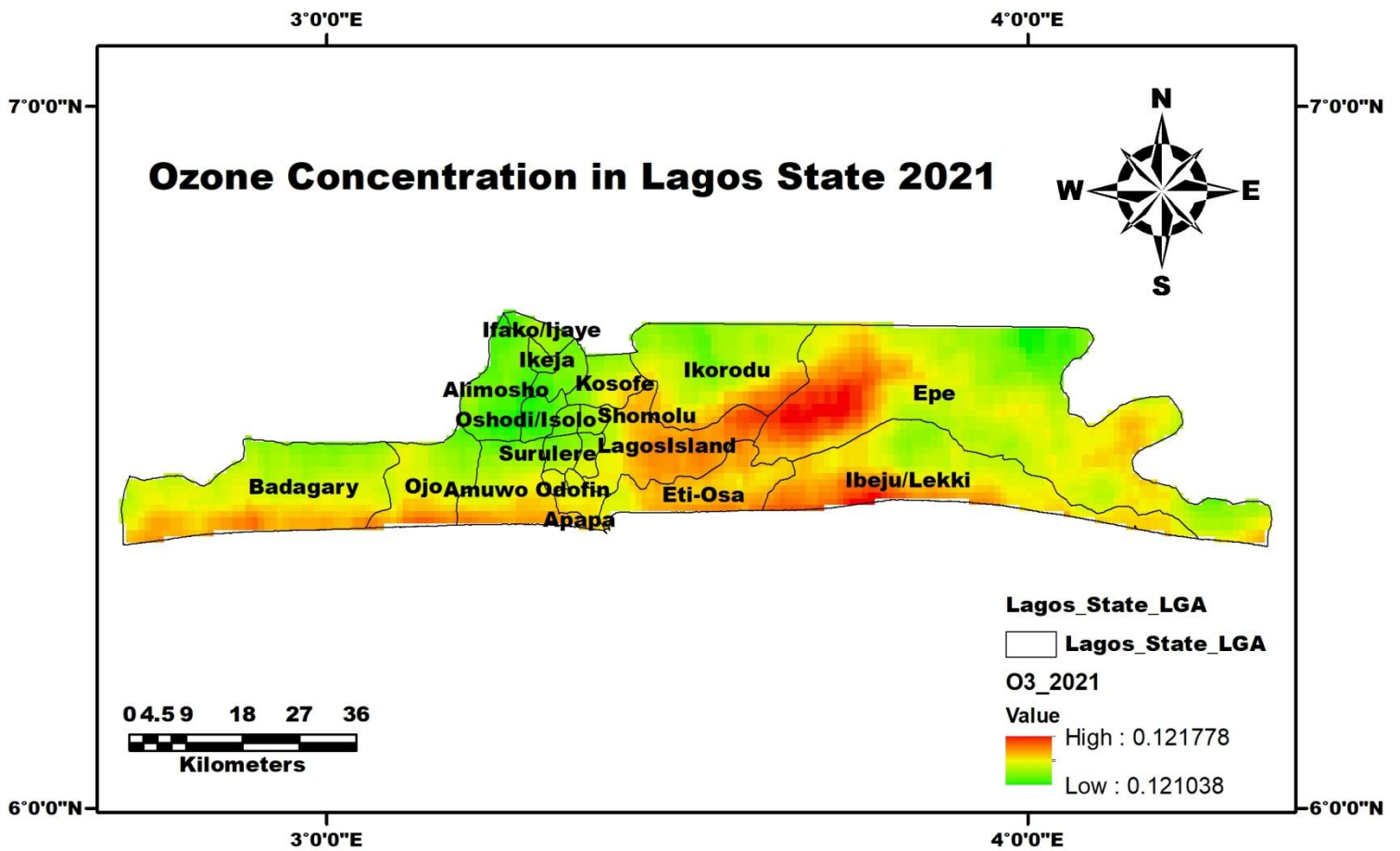


Figure 4.2.3: Map showing Ozone Concentrations in Lagos State for 2021

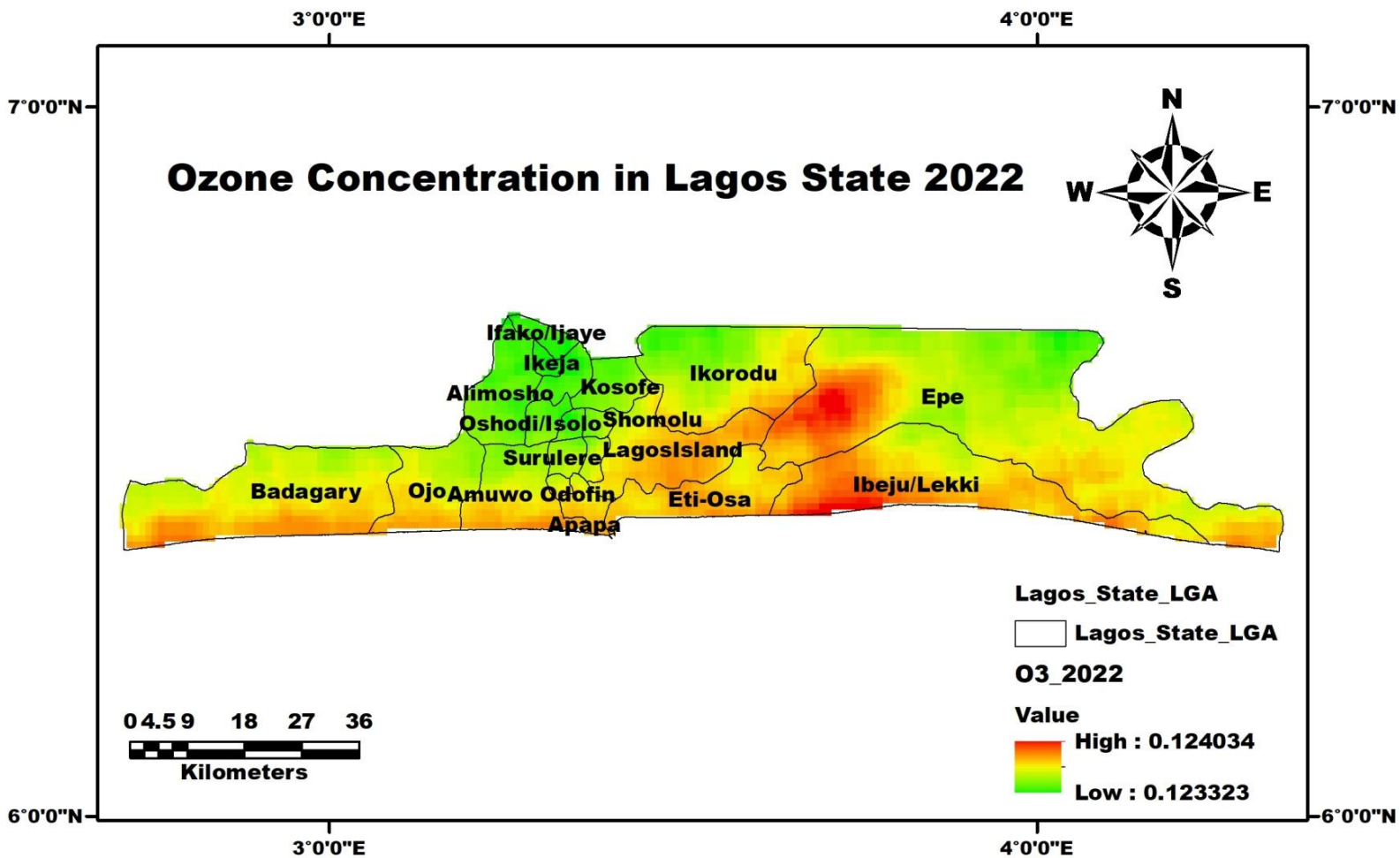


Figure 4.2.4: Map showing Ozone Concentrations in Lagos State for 2022

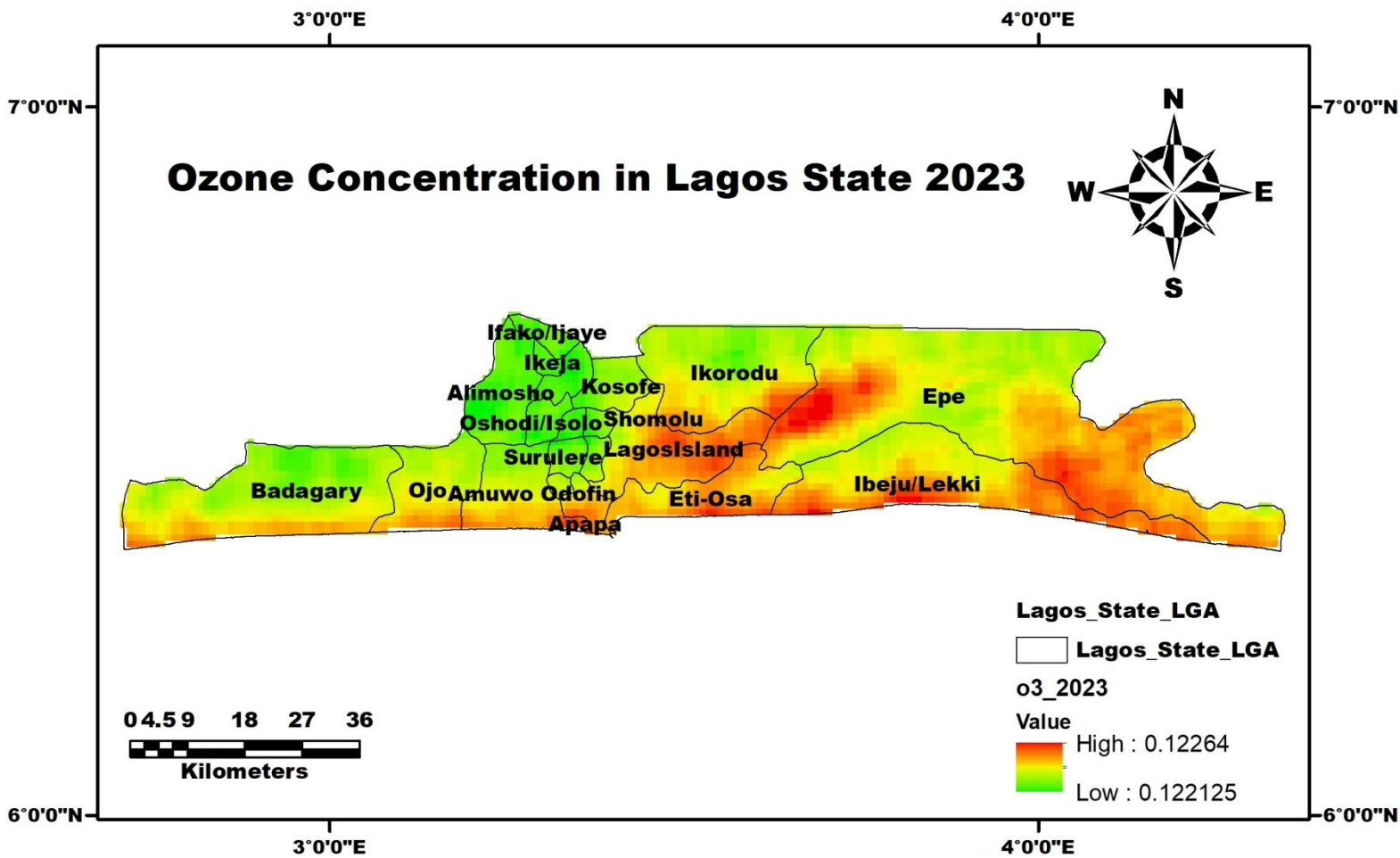


Figure 4.2.5: Map showing Ozone Concentrations in Lagos State for 2023

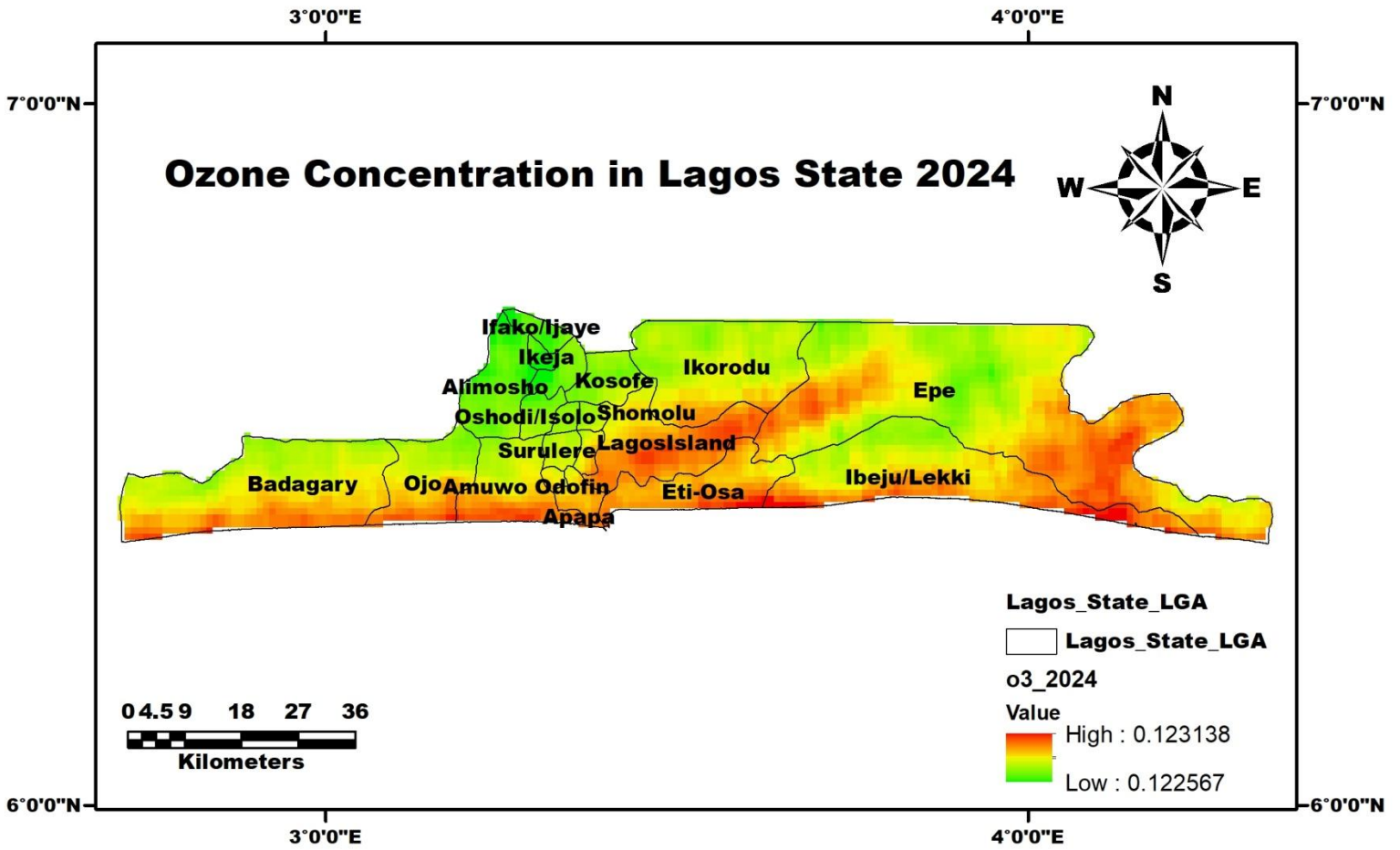


Figure 4.2.6: Map showing Ozone Concentrations in Lagos State for 2024

4.2.3 SPATIAL VARIATION OF OZONE CONCENTRATION ACROSS THE STUDY YEARS (2019-2024)

The spatial variation of ozone concentration, as depicted in Figure 4.2.1 shows that in the year 2019, LGAs like Lagos Island, and outskirts of Epe and Ibeju/Lekki are under the high category with a concentration of 0.121 mol/m^2 , moderate concentrations are evenly distributed across the southern LGAs such as Badagry, Ojo, Amuwo Odofin, Apapa, Eti-Osa, Surulere and Shomolu, while the lowest concentration of 0.120 mol/m^2 are found in the Northern LGAs such as Ifako/Ijaye, Ikeja, Alimosho, Kosofe and Oshodi-Isolo.

In 2020, as shown in Figure 4.2.2, revealed that LGAs such as Lagos Island, Eti-Osa, Epe, Ibeju/Lekki, fall into the high category with a concentration of 0.121 mol/m^2 . Locations such as Badagry, Ojo, Amuwo Odofin, Apapa, Surulere fall under the moderate concentration category. The lowest concentration of 0.120 mol/m^2 is recorded in the northern LGAs of Lagos State.

For 2021, as revealed in Figure 4.2.3 shows that Lagos Island, Eti-Osa and some part of Ibeju/Lekki and Epe fall into the high category with a concentration of 0.121 mol/m^2 , while Southwestern LGAs such as Badagry, Ojo, Amuwo Odofin and Apapa are in moderate category. The lowest concentration of 0.121 mol/m^2 is found again in the Northern LGAs of Lagos State.

According to Figure 4.2.4 in 2022, LGAs such as Epe, Eti-Osa, Lagos Island and Ibeju-Lekki fall into the high category with a concentration of 0.123 mol/m^2 , while the southern LGAs such as Amuwo Odofin, Apapa, Ojo and some part of Badagry fall under the moderate category. The lowest concentration of 0.123 mol/m^2 encompasses the Northern LGAs such as Ifako/Ijaye, Ikeja, Alimosho, Oshodi/Isolo and Kosofe.

Figure 4.2.5 illustrates that in 2023, the Southeastern LGAs such as Eti-Osa, Lagos Island, Ibeju/Lekki and Epe fall into the high category with a concentration of 0.1226 mol/m². The Local Government Areas like Ojo, Amuwo Odofin, and Shomolu are in the moderate concentration, while with the lowest concentration of 0.1221 mol/m², is observed at the Northern LGAs of Lagos State.

Finally in 2024, Figure 4.2.6 revealed that Lagos Island, Eti-Osa, Apapa, Amuwo Odofin, Ibeju/Lekki and some part of Epe fall into the high category, with a concentration of 0.123 mol/m². LGAs like Ikorodu, Surulere, Ojo are fall into the moderate category. The lowest concentration of 0.122 mol/m² is observed in LGAs such as Ifako/Ijaye, Ikeja, Alimosho, and Kosofe.

4.3.1 Ozone Annual Mean Trend

Figure 4.2.7 shows an overall stable trend with a sharp increase in 2022 in the annual mean concentration of ozone from 2019-2024. Ozone concentrations slightly decreased from 2019 to 2020, followed by a rise from 2020 to 2021, and a sharp increase in ozone concentration levels from 2021 to 2022, reaching the highest peak. A slight decline in mean concentration was observed from 2022 through 2023, after which there was stabilization in 2024. In 2020, the concentration levels of ozone decreased from 2019 due to seasonal meteorological factors like increased rainfall and humidity during the wet season, which suppressed photochemical formation despite limited COVID-19 lockdown impacts (Aliyu and Botai 2020). The sharp increase in 2022 may be attributed to post-pandemic economic recovery boosting NO_x and VOC emissions from traffic and industry, compounded by anomalous high temperatures (+1.2°C above average) and low rainfall enhancing photochemical reactions in southern regions (Enuneku *et al.*, 2025; Agboola *et al.*, 2024). In 2023, the decline in ozone concentration may be

attributed to the removal of fuel (PMS) subsidy policy, which reduced vehicular and generator emissions of precursors by 30-40% (Amaechi *et al.*, 2023).

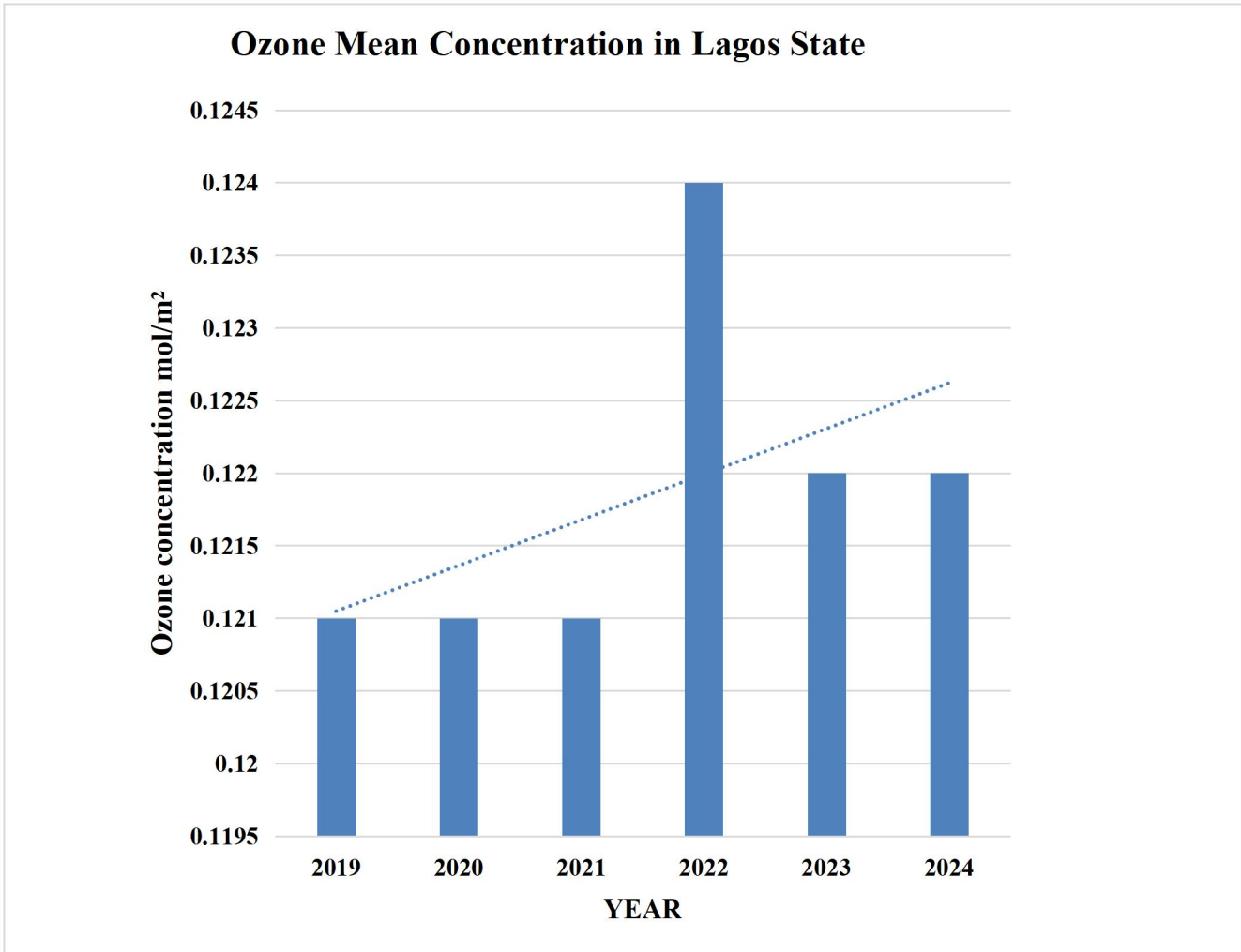


Figure 4.2.7 Ozone Annual Mean Trend from 2019 -2024

Table: 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
Formaldehyde	0.717	0.124	0.977	0.639	0.789
Ozone	0.921	0.239	0.008	0.222	0.737

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

Analysis for Statistically significance difference

For Formaldehyde, the paired sample t-test indicated no statistically significant difference across all consecutive study years — 2019 to 2020 ($p = 0.717$), 2020 to 2021 ($p = 0.124$), 2021 to 2022 ($p = 0.977$), 2022 to 2023 ($p = 0.639$), and 2023 to 2024 ($p = 0.789$). Since all p-values are greater than 0.05, the result implies that variations in formaldehyde concentrations between the years were not significant, suggesting relatively consistent emission trends throughout the five-year period.

For Ozone, there was also no statistically significant difference between 2019 to 2020 ($p = 0.921$), 2020 to 2021 ($p = 0.239$), 2022 to 2023 ($p = 0.222$), and 2023 to 2024 ($p = 0.737$). However, a highly statistically significant difference was observed between 2021 to 2022 ($p = 0.008$), indicating a notable shift in ozone levels within that period. This significant change could be attributed to environmental or anthropogenic factors such as increased industrial activity, vehicular emissions, or seasonal variations that affected ozone formation or depletion in the atmosphere.

Overall, the results suggest that formaldehyde levels remained stable during the study period, while ozone exhibited one notable year of fluctuation (2021–2022). This aligns with typical patterns observed in urban air quality monitoring, where ozone concentrations can fluctuate sharply due to short-term meteorological or emission changes (Okoduwa and Amaechi, 2023).

5.0 CHAPTER FIVE

5.1 DISCUSSION

This study analyzed the levels of Formaldehyde (HCHO), and Ozone concentrations in Lagos State Nigeria, using Sentinel-5P images in Google Earth Engine (GEE), during the period from 2019 to 2024.

5.1.1 FORMALDEHYDE DISTRIBUTION IN LAGOS STATE ACROSS THE STUDY YEARS

Formaldehyde (HCHO) concentration in Lagos State from 2019 to 2024 showed a clear, seasonal, spatial and annual trend. Formaldehyde concentration levels are typically at their highest during the dry season (Harmattan) season and their lowest during the rainy season. For example, in 2019 formaldehyde (HCHO) concentration peaked in January 0.000279 mol/m^2 , and decreased to a minimum in July at about 0.000110 mol/m^2 . The same high concentration levels were observed from 2020 to 2024 at around 0.000030 mol/m^2 , with low concentration in mid-year. This dry season accumulation is probably due to the reduction in wet deposition and still air during Harmattan season, along with the burning of biomass and emissions from vehicles that release volatile organic compounds, while the wet season (June to September), bring rains and dispersion that reduce formaldehyde levels (Freitas and Fornaro 2022). In 2020, from the result, the formaldehyde concentration was only slightly impacted by COVID-19 lockdown, which aligns with finding indicating that incomplete lockdown measures and ineffective movement restriction led to continued emissions (Amaechi *et al.*, 2024; Suhardono *et al.*, 2023). The highest mean formaldehyde concentration occurred in 2021 and 2022 at 0.000202 mol/m^2 , with the lowest in 2019 (0.000190 mol/m^2). Notably after 2022, there is decline in mean concentration

in formaldehyde level. For instance, in 2023, the mean concentration dropped to 0.000200mol/m^2 with reduced fluctuations. Furthermore, the statistical significance test revealed no significant differences in formaldehyde concentrations across all observed years ($p > 0.05$), reinforcing the observed trend of relatively stable annual HCHO levels despite seasonal fluctuations and policy-related changes in fuel consumption patterns. This trend reflects the enhancement in air quality observed following the elimination of fuel subsidies in Nigeria in May 2023, which drove higher fuel prices and reduced vehicle usage. Amaechi *et al.*, 2024, also discovered notable declines in CO and aerosols (and minor reduction in NO₂) subsequent to the subsidy policy, leading to lower levels of pollution in Lagos State.

High formaldehyde concentrations were consistently recorded in high-traffic congestion, commercial, and industrial LGAs in Lagos State. Each year, the Northern and central LGAs like Ifako/Ijaye, Ikeja, Kosofe, Oshodi/Isolo, Shomolu, Lagos Island and Ikorodu consistently fall into the “high” category ranging approximately $0.00025\text{-}0.00031\text{ mol/m}^2$. Conversely, Southern and coastal LGAs like Badagry, Eti-Osa and Outskirt of Ibeju/Lekki consistently exhibited the lowest formaldehyde levels. This suggest that dense traffic, industry and generators in central Lagos emit more hydrocarbons, which then oxidize into formaldehyde HCHO while coastal regions like Badagry experience lower levels of accumulation.

5.1.2 OZONE (O₃) DISTRIBUTION IN LAGOS STATE ACROSS THE STUDY YEARS

In contrary to formaldehyde, the seasonal pattern of tropospheric ozone in Lagos is different, tropospheric ozone concentration peaked in mid-year (July-August), with the lowest during the Harmattan months, in January and February. Between the year 2019 to 2024, the ozone value

have consistently occur higher during warm rainy season, when intense sunlight and convection maximize photochemical production process (Brimblecombe 2011). The six years data of ozone concentration confirms the findings by Omokpariola *et al.*, (2024), who observe peaks in Ozone during warmer months (June-September), and low concentration level during the cooler months. In 2022, the highest mean of ozone value across all the years was observed, peaking around 0.124 mol/m², possibly may reflect intense sunlight that year. After observing a high mean concentration in 2022, there is notably lower ozone variability in 2023, which could be as a result of reduced emission after the removal of fuel subsidies in 2023, and rose again in 2024 as economic activity resumed.

High levels of ozone concentrations were observed in the Local Government Areas situated along the coast and lagoons of Lagos State. Annually, regions such as Eti-Osa, Ibeju/Lekki, Lagos Island, and Epe , which are found in this region fall into the “high” category approximately 0.121-0.124 mol/m². While inland commercial, and industrial LGAs such as Ifako/Ijaye, Ikeja, Alimosho, Kosofe, Oshodi consistently have the lowest ozone concentration approximately 0.120-0.122 mol/m². This indicate that ozone precursors; NO_x and Volatile Organic Compounds (VOCs) emitted in the urban centers are often titrated out locally, while region along the coastal areas with cleaner background air support photochemical ozone build-up (Lelieveld *et al.*, 2020). Also sea breeze and increased moisture near coastal region can also enhance ozone formation and hinder its dispersion.). While most year-to-year ozone changes were statistically insignificant ($p > 0.05$), a marked and significant increase was observed between 2021 and 2022 ($p = 0.008$), supporting the evidence of heightened photochemical activity during that period and highlighting ozone’s sensitivity to short-term atmospheric and emission dynamics.

In essence, Lagos State air contains high levels of formaldehyde during dry, cool months when dispersion is limited, and increases levels of ozone in warm, rainy months when photochemistry is active. Human activities strongly influence these patterns. In urban areas, release of formaldehyde is representative for VOCs, mainly from sources such as congested road traffic, generators, and certain industries while ozone formation is driven by sunlight interacting with these urban emissions and the overall chemical composition of the environment (Freitas and Fornaro 2022). Also, socioeconomic interventions have influenced these patterns; the temporary reduction in 2023 implies that increased fuel costs caused a drop in emissions, yet the rise in 2024 shows a rebound to pollution levels before the subsidy. Various research studies, like those conducted by Zambrano-Monserrate *et al.*, (2020), Saha *et al.*, (2022), Kumari and Toshniwal (2020), Amaechi *et al.*, (2024), and Pal *et al.*, (2022) suggested that 2020 lockdown only resulted in minimal impacts. Lastly, findings mirror other research conducted in Lagos, Amaechi *et al.*, 2024 highlights the roles of weather conditions such as harmattan, dust, precipitation etc., and policy in shaping air quality in Lagos State.

5.2 RECOMMENDATIONS

Based on the findings, Lagos State should enforce stricter vehicle emission regulation in high traffic zones like Ifako/Ijaye, Ikeja, Kosofe, Oshodi/Isolo, Shomolu, Lagos Island and Ikorodu as there are research that indicate that traffic is a major source of Volatile Organic Compounds (VOCs) and NO_x, precursors of both Formaldehyde and Ozone (Manisalidis *et al.*, 2020). To support this, urban air quality monitoring stations should be established across Lagos State, especially in high commercial and industrial areas, to offer real time data for policy actions and monitor changes in pollution levels throughout the year. Also identifying these pollution

hotspots will help in directing specific effort to reduce pollution, including stricter regulations on biomass and open waste burning, to reduce the precursors of Formaldehyde and Ozone.

Aside from the regulation of the emissions, expanding the Bus Rapid Transit (BRT) system, finishing the Lagos State light rail initiatives, and incorporating electric buses can reduce the reliance on private cars. Beyond expanding public transportation, encouraging non-motorized modes of travel like cycling paths and footpaths could also reduce short-distance car trips. This will lower both formaldehyde and ozone precursor in line with the finding that traffic reduction improve air quality (Omokpariola *et al.*, 2024).

Additionally, behavioral changes are important in reducing pollution from domestic sources such as biomass burning and waste incineration. Public awareness campaigns highlighting the health risks of pollutants especially cardiovascular and respiratory disease should be combined with strict enforcement of anti-burning regulations. This public awareness programs should target vulnerable peri-urban areas where waste burning is most common.

5.3 CONCLUSION

Air pollution in Lagos State remains a serious environmental and public health concern. This study reveals that formaldehyde reaches its highest concentration during the dry season particularly in heavily populated urban local government area (LGAs), while ozone peaks during rainy season, with high concentration observed in coastal regions. The spatial and seasonal trends are influenced by anthropogenic emissions, weather patterns, and recent socio-economic measures. Remote sensing provided a cost-effective and reliable means of monitoring air quality trends. Urgent intervention through stricter emission control, urban planning improvement, public awareness and continuous air quality monitoring is needed to mitigate the health and

environmental impact of air pollution in Lagos state. By implementing these strategies, Lagos State can make improvement in air quality, lessen the health impact and serve a model for megacities across Africa.

REFERENCE LIST

- Aigbe, H.P., Omoregie, E.S. and Ebewele, R.O. (2023) Air quality modeling and health risk assessment of volatile organic compounds in Benin City, Nigeria. *Environmental Monitoring and Assessment*, 195(3), 1–15.
- Akinola, A.K., Komolafe, A.A., Adegboyega, S.A., Anifowose, Y.B., Akinluyi, F.O. and Awoniran, D.R. (2014) Air pollution and climate change in Lagos, Nigeria: Needs for proactive approaches to risk management and adaptation. *American Journal of Environmental Sciences*, 10(4), 412–423.
- Aliyu, Y.A. and Botai, J.O. (2020) An algorithm for the retrieval of aerosol optical depth over land from Sentinel-5P/TROPOMI. *Atmospheric Measurement Techniques*, 13(6), 3147–3163.
- Amaechi, C.F., Nzeagwu, O.F. and Okoduwa, A.K. (2023) Effect of fuel subsidy removal on air quality in Lagos State, South Western Nigeria. *Ethiopian Journal of Environmental Studies & Management*, 16(6), 816–829.
- Auwalu, A., Abdullah, K., Mansor, S.B., Shariff, A.R.M. and Mahmud, A.R. (2023) Air quality monitoring using Sentinel-5P TROPOMI data: A case study in Kuala Lumpur. *Environmental Monitoring and Assessment*, 195(2), 280.
- Bikis, A. (2023) Urban air pollution and greenness in relation to public health. *Journal of Environmental and Public Health*, 2023, Article 8516622.
- Bojinski, S., Verstraete, M., Peterson, T.C., Richter, C., Simmons, A. and Zemp, M. (2014) The concept of essential climate variables in support of climate research, applications, and policy. *Bulletin of the American Meteorological Society*, 95(9), 1431–1443.
- Brimblecombe, P. (2011) Air pollution episodes. *Encyclopedia of Environmental Health*, 39–45.

- Carroll, G.T. and Kirschman, D.L. (2022) A peripherally located air recirculation device containing an activated carbon filter reduces VOC levels in a simulated operating room. *PubMed*, 7(50), 46640–46645.
- Copernicus (2020) Copernicus Climate Change Service (C3S) Climate Data Store. Available at: <https://cds.climate.copernicus.eu/> (Accessed: 15 January 2025).
- Croitoru, L., Chang, J.C., Akpokodje, J. and Onuoha, E. (2020) The health cost of ambient air pollution in Lagos. *Journal of Environmental Protection*, 11(8), 753–765.
- Daramola, S.G. and Makinde, E.O. (2024) Modeling air pollution around major dumpsites in Lagos State using geospatial methods. *SSRN Electronic Journal*. Available at: <https://ssrn.com/abstract=4745591>.
- De Smedt, I., Van Roozendael, M., Stavrakou, T. et al. (2010) Trend detection in satellite observations of formaldehyde tropospheric columns. *Geophysical Research Letters*, 37(18).
- De Smedt, I., Theys, N., Yu, H. et al. (2018) Sentinel-5P/TROPOMI tropospheric NO₂ retrieval: The version 2 algorithm. *Atmospheric Measurement Techniques*, 11(1), 409–425.
- European Environment Agency (2021) *Air quality in Europe 2021*. EEA Report No. 15/2021.
- Feng, Z., De Marco, A., Anav, A. et al. (2019) Economic losses due to ozone surface pollution in China. *Environmental Pollution*, 253, 899–908.
- Fisher, S., Bellinger, D.C., Cropper, M.L. et al. (2021) Air pollution and development in Africa. *The Lancet Planetary Health*, 5(10), e681–e688.
- Freitas, A.D. and Fornaro, A. (2022) Atmospheric formaldehyde monitored by TROPOMI throughout 2020 over São Paulo State, Brazil. *Remote Sensing*, 14(13), 17.
- Gaudel, A., Cooper, O.R., Ancellet, G. et al. (2018) Tropospheric Ozone Assessment Report. *Elementa: Science of the Anthropocene*, 6, 39.

- Gorelick, N., Hancher, M., Dixon, M. et al. (2017) Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202, 18–27.
- Health Effects Institute (2019) *State of Global Air 2019*.
- He, G., Liu, T., Zhou, L. et al. (2020) Impact of COVID-19 pandemic on air quality in China. *Resources, Conservation & Recycling*, 159, 104834.
- Kazemi Garajeh, M., Haji, H.R., Karami, F. et al. (2023) Spatial modeling of air pollution using machine learning. *Atmospheric Pollution Research*, 14(1), 101–112.
- Kim, K.H., Kabir, E. and Kabir, S. (2015) Human health impact of airborne particulate matter. *Environment International*, 74, 136–143.
- Kumar, L. and Mutanga, O. (2018) Google Earth Engine applications since 2014. *Remote Sensing*, 10(9), 1500.
- Kumari, P. and Toshniwal, D. (2020) Impact of lockdown on air quality worldwide. *Urban Climate*, 34, 100719.
- Leifer, I., Melton, C., Manish, N. et al. (2023) Validation of TROPOMI NO₂ column data. *Atmospheric Measurement Techniques*, 16(4), 1023–1041.
- Lelieveld, J., Pozzer, A., Pöschl, U. et al. (2020) Loss of life expectancy from air pollution. *Cardiovascular Research*, 116(11), 1910–1917.
- Lyu, X., Wang, N., Guo, H. et al. (2019) Causes of summertime O₃ pollution in Jinan. *Atmospheric Chemistry and Physics*, 19(5), 3025–3042.
- Manisalidis, I., Stavropoulou, E., Stavropoulos, A. and Bezirtzoglou, E. (2020) Environmental and health impacts of air pollution. *Frontiers in Public Health*, 8, 14.
- Mareddy, A.R. (2017) *Environmental Impact Assessment: Theory and Practice*. Oxford: Butterworth-Heinemann.

- Marlier, M.E., Jina, A.S., Kinney, P.L. and DeFries, R.S. (2016) Extreme air pollution in global megacities. *Current Climate Change Reports*, 2(1), 15–27.
- Menezes, K.A. and Shively, T.S. (2001) Estimating long-term ozone trends. *Environmental Science & Technology*, 35(13), 2554–2561.
- Omokpariola, D.O., Nduka, J.N. and Omokpariola, P.L. (2024) Short-term trends of air quality in Nigeria. *SN Applied Sciences*, 6, 856–868.
- Olowoporoku, A., Longhurst, J. and Barnes, J. (2012) Framing air pollution as a major health risk in Lagos. In: *Air Pollution XX*, 479–486.
- Pal, S.C., Chowdhuri, I., Saha, A. et al. (2022) COVID-19 lockdown impact on urban air quality. *Geoscience Frontiers*, 13(6), 101368.
- Rabiu, A.B., Ogunjo, S.T., Akerele, A. and Adebisi, O.A. (2025) Long-term variability of total column ozone in Nigeria. *Discover Geoscience*, 3, 75.
- Saha, L., Kumar, A., Kumar, S. et al. (2022) Impact of COVID-19 lockdown on global air quality. *Environmental Sustainability*, 5(1), 5–23.
- Seinfeld, J.H. and Pandis, S.N. (2016) *Atmospheric Chemistry and Physics*. 3rd edn. Wiley.
- Sha, Z., Bai, Y., Li, R. et al. (2021) Multi-source data fusion for precipitation. *Remote Sensing*, 13(20), 4089.
- Suhardono, A., Nugroho, A., Pramono, A. et al. (2023) Air pollution monitoring in Jakarta. *Journal of Physics: Conference Series*, 2406, 012034.
- Tamiminia, H., Salehi, B., Mahdianpari, M. et al. (2020) Google Earth Engine for geo-big data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 164, 152–170.
- United Nations Environment Programme (2022) *Integrated assessment of air pollution and climate change for sustainable development in Africa*.

- United Nations Environment Programme (2023) *Towards a pollution-free planet: Background report*.
- U.S. Environmental Protection Agency (2023) *Our Nation's Air: Status and Trends Through 2022*.
- Veenkind, J.P., Aben, I., McMullan, K. et al. (2012) TROPOMI on Sentinel-5P. *Remote Sensing of Environment*, 120, 70–83.
- Velastegui-Montoya, A., Montalván-Burbano, N., Peña, V. et al. (2023) Google Earth Engine: Global analysis and future trends. *Remote Sensing*, 15(14), 3675.
- World Health Organization (2010) *WHO guidelines for indoor air quality: Formaldehyde*.
- World Health Organization (2024a) *WHO global air quality guidelines*.
- World Health Organization (2024b) *Ambient air quality database*.
- Wu, Y., Xu, J., Liu, Z. et al. (2023) Population-weighted exposure to air pollutants. *Toxics*, 12(2), 197.
- Xu, Y., Duan, J., Wang, Z. et al. (2019) Industrial emissions and PM_{2.5} in China. *Atmospheric Environment*, 211, 1–10.
- Zambrano-Monserrate, M.A., Ruano, M.A. and Sanchez-Alcalde, L. (2020) Indirect effects of COVID-19 on the environment. *Science of The Total Environment*, 728, 138813.
- Zhang, Y., Li, X., Song, Y. and Wang, Y. (2021) Policy measures for air pollution reduction. *Environmental Pollution*, 14, 100–110.

Monthly Concentration of HCHO from 2019-2024

HCHO	2019	2020	2021	2022	2023	2024
January	0.000279	0.000304	0.000288	0.000312	0.000301	0.000310
February	0.000275	0.000294	0.000310	0.000298	0.000300	0.000300
March	0.000224	0.000217	0.000258	0.000239	0.000228	0.000240
April	0.000198	0.000188	0.000231	0.000201	0.000200	0.000205
May	0.000189	0.000165	0.000188	0.000169	0.000173	0.000187
June	0.000131	0.000154	0.000153	0.000151	0.000140	0.000130
July	0.000110	0.000109	0.000124	0.000111	0.000130	0.000117
August	0.000111	0.000113	0.000117	0.000120	0.000118	0.000104
September	0.000131	0.000099	0.000117	0.000118	0.000143	0.000112
October	0.000140	0.000169	0.000153	0.000173	0.000171	0.000163
November	0.000208	0.000234	0.000210	0.000242	0.000212	0.000240
December	0.000278	0.000256	0.000278	0.000291	0.000285	0.000278
Mean	0.000190	0.000192	0.000202	0.000202	0.000200	0.000199
Standard Dev	0.0000650	0.000070	0.0000070	0.000073	0.000066	0.000075

Monthly Concentration of Ozone (O₃) from 2019-2024

O₃	2019	2020	2021	2022	2023	2024
January	0.116	0.112	0.114	0.115	0.120	0.113
February	0.117	0.116	0.116	0.118	0.120	0.112
March	0.121	0.120	0.121	0.119	0.121	0.116
April	0.122	0.120	0.122	0.121	0.123	0.120
May	0.122	0.120	0.122	0.123	0.124	0.125
June	0.124	0.123	0.124	0.127	0.124	0.128
July	0.127	0.124	0.127	0.128	0.127	0.129
August	0.125	0.126	0.126	0.129	0.127	0.128
September	0.122	0.124	0.125	0.129	0.125	0.129
October	0.120	0.124	0.123	0.128	0.122	0.127
November	0.118	0.122	0.120	0.125	0.119	0.125
December	0.114	0.118	0.116	0.123	0.115	0.121
Mean	0.121	0.121	0.121	0.124	0.122	0.123
Standard Dev	0.00385	0.00398	0.00416	0.004712	0.00349	0.00623