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Geospatial Evaluation of The Effects Of Urbanization On The Air Quality In Selected Urban Areas of Lusaka

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Abstract

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This study investigates the impact of urbanization on air quality in Lusaka, Zambia, focusing on carbon monoxide (CO) and sulfur dioxide (SO₂) concentrations from 2009 to 2024. Utilizing geospatial analysis, time series maps, air quality data and statistical validation, the research examines pollutant trends in industrial and non-industrial zones alongside urbanization rates. Key findings reveal a significant increase in CO concentrations, correlating with rising urbanization rates from 21.06% in 2009 to 38.05% in 2024, while SO₂ levels fluctuated due to emission control measures. Non-industrial areas exhibited lower pollutant levels, highlighting the disproportionate impact of industrial activities. The study demonstrates the effectiveness of geospatial tools in monitoring air quality and urbanization trends, providing actionable insights for policymakers to mitigate pollution. Contributions include a validated framework for integrating air quality monitoring with urban planning, emphasizing the need for sustainable development strategies in rapidly urbanizing regions.

Keywords: Urbanization; Air Quality; Carbon Monoxide (CO); Sulfur Dioxide (SO₂); Geospatial Analysis.

1. Introduction

1.1 Background of the Study

Urbanization is a defining global phenomenon of the 21st century, with more than half of the world's population now residing in urban areas—a figure projected to double by 2050, especially across Africa and Asia (Castells-Quintana et al., 2021; United Nations, 2019; United Nations, 2022, Amen, Afara, and Nia 2023; Aziz Amen 2022; Amen and Nia 2020). While urbanization is often associated with economic growth and improved access to services, it also brings significant environmental challenges, most notably the deterioration of air quality. “This layout can result in health problems, such as air and noise pollution” (Kadry & Husain, 2025). Rapid urban expansion typically leads to increased vehicular emissions, intensified industrial activity, and greater energy consumption, collectively resulting in elevated concentrations of ambient air pollutants such as particulate matter (PM_{2.5}, PM₁₀), nitrogen dioxides (NO₂), and sulfur dioxide (SO₂) (Kampa & Castanas, 2008; Mannucci & Franchini, 2017; WHO, 2023). In developing countries, these impacts are often exacerbated by unplanned urban growth, limited infrastructure, and weak regulatory frameworks. Lusaka, the capital of Zambia, exemplifies these trends (UN-Habitat, 2023). The city has experienced rapid population growth and extensive land use changes, including the proliferation of informal settlements and industrial zones (Simwanda & Murayama, 2018). Such transformations have raised critical concerns about the city's air quality and the associated risks to public health and environmental sustainability (Mannucci & Franchini, 2017). Poor air quality is strongly associated with increased incidence of respiratory and cardiovascular diseases, as well as premature mortality (Cohen et al., 2017; Kelly & Fussell, 2015).

1.2 Problem Statement

The interplay between urbanization and air quality is complex. Urban growth intensifies population density, vehicle traffic, energy demand, and industrial output, all of which are major contributors to air pollution (Gurjar et al., 2016). Furthermore, the reduction of green spaces and the urban heat island (UHI) effect exacerbate the

concentration of pollutants forming urban pollution islands (UPI) (Chen et al., 2023; Piracha & Chaudhary, 2022; Ulpiani, 2021; Wang et al., 2021). In Lusaka, rapid population growth has strained infrastructure and services, leading to informal settlements, increased biomass burning, and inadequate waste management, all of which further degrade air quality. Recent studies have documented elevated levels of PM_{2.5} and NO₂ in Lusaka, often exceeding WHO guidelines, particularly in densely populated and industrialized areas (WHO, 2023; Smith et al., 2009). Despite growing concerns, the extent and spatial distribution of air pollution in Lusaka, their sources and urban pollution hotspots, remain largely unquantified and under-researched.

Recent advances in geospatial technologies, including Geographic Information Systems (GIS) and remote sensing, have revolutionized the monitoring and analysis of air quality in urban environments. By integrating satellite imagery, ground-based monitoring and sensor data that provides real-time data for validation and analysis, and urban development patterns, geospatial analysis enables the identification of pollution hotspots, assessment of spatial distribution of pollutants, and evaluation of the impacts of urbanization on air quality (El Kamouri et al., 2024; Gitahi & Hahn, 2020; Gupta et al., 2006; Kumar et al., 2013; Meltus & Karanja, 2024; Sayeed et al., 2025). These have emerged as powerful tools and are particularly valuable in resource-constrained settings, where traditional air quality monitoring networks are often sparse or absent; thereby mitigating the impacts of urbanization on air quality and improvement of the overall livability of cities.

1.3 Research Gap

Currently, there is a critical gap in understanding how patterns of urbanization directly influence air quality across different parts of the city. Despite the growing body of research on urbanization and air quality, significant gaps remain—particularly in sub-Saharan African cities such as Lusaka. Most existing studies have focused on cities in Asia, Europe, or North America, where monitoring infrastructure and data availability are more robust (Fang et al., 2015). In contrast, African urban centers are underrepresented in the literature, and there is limited understanding of how rapid, often unplanned, urban growth specifically influences air quality dynamics in these contexts (Simwanda & Murayama, 2018). Furthermore, few studies have systematically applied high-resolution geospatial techniques to assess the spatial and temporal patterns of air pollution associated with urban development in African cities. This lack of comprehensive, spatially explicit data hampers the ability of policymakers and urban planners to design effective interventions for pollution mitigation and sustainable urban development (Meltus & Karanja, 2024; WHO, 2023). Without robust evidence linking urban growth to air quality deterioration, efforts to safeguard public health and the environment remain inadequate.

This research therefore aims to address this gap by employing geospatial techniques to systematically evaluate the relationship between urbanization and air quality in Lusaka. By quantifying pollutant concentrations and mapping their spatial distribution in relation to urban growth patterns, the study will provide a critical evidence base to inform urban planning, pollution control measures, and policy development for healthier and more sustainable urban environments.

1.4 Research Question and Objectives

This study addresses these gaps by evaluating the effects of urbanization on air quality in selected urban areas of Lusaka City using advanced geospatial techniques. The main objective of this research is to evaluate the impact of urbanization on air quality in Lusaka, Zambia, using geospatial techniques.

1.4.1 Specific Objectives

To achieve the main objective, the study pursues the following specific objectives:

1. To examine the spatial distribution of major air pollutants (such as PM_{2.5}, PM₁₀, NO₂, and SO₂) across Lusaka using satellite and ground-based data.
2. To identify air pollution hotspots within Lusaka and determine the primary sources contributing to elevated pollutant levels in these areas.
3. To analyze the relationship between urban development patterns and air quality in Lusaka over time, assessing how changes in land use, population density, and infrastructure expansion influence pollutant concentrations.

The central research question is:

- How does urbanization influence the spatial and temporal patterns of air quality in Lusaka City, and what are the implications for urban planning and public health?

1.5 Scope and Methodological Overview

This study employs an integrated geospatial framework to evaluate the impacts of urbanization on air quality in selected urban areas of Lusaka, Zambia, combining multi-temporal remote sensing air quality data, urbanization maps, GIS analytics, and ground-truth validation. Focusing on key air pollutants such as carbon monoxide and sulfur dioxide, the research examines spatial and temporal trends from 2009 to 2024, identifying pollution hotspots and quantifying urban growth. Change detection and spatial analysis techniques are used to map urban expansion and identify land use transitions (Fang et al., 2015; Gitahi & Hahn, 2020). The methodology aligns with national environmental standards and aims to provide actionable insights to support sustainable urban development and effective environmental management in Lusaka. The methodology is designed to be replicable in other rapidly urbanizing cities with similar data constraints.

1.6 Expected Contribution

This research presents one of the first comprehensive geospatial assessments of the relationship between urbanization and air quality in Lusaka, Zambia. It addresses critical knowledge gaps by providing empirical evidence on the spatial distribution and drivers of air pollution within a sub-Saharan African context. Additionally, the study introduces methodological advancements through the integration of satellite-derived and ground-based data for urban air quality evaluation. The findings offer actionable insights for policymakers, urban planners, and public health officials, enabling the design of targeted interventions that promote sustainable urban development and enhance air quality management.

1.7 Structure of the Paper

This paper is organized as follows: Section 2 critically reviews existing literature on urbanization dynamics, air quality degradation, and geospatial techniques applied in environmental studies. Section 3 outlines the study area, data sources (including satellite imagery and municipal boundaries), and the methodology integrating geospatial and statistical techniques for analyzing urbanization-air quality linkages. Section 4 presents the results of spatial analyses, including pollutant concentration maps, urbanization rate trends, and hotspot identification. Section 5 discusses and analyses the findings' implications for sustainable urban planning, policy formulation, and environmental management in rapidly developing cities. Section 6 concludes by summarizing key insights, proposing actionable recommendations for Zambian policymakers, and identifying future research directions to address methodological and contextual limitations.

2. Literature Review

This literature review examines the complex relationship between urbanization and air quality through the lens of geospatial analysis, with particular emphasis on developing countries and methodological approaches relevant to studying Lusaka City. The review synthesizes current research on urbanization-induced air quality degradation, the application of remote sensing and GIS technologies for environmental monitoring, and the health implications of urban air pollution, particularly in rapidly growing cities across Africa and Asia.

2.1 Urbanization as a Global Driver of Air Quality Degradation

Urbanization has emerged as a principal driver of atmospheric pollution in the 21st century, particularly in developing nations experiencing rapid demographic shifts. The concentration of human activities, industrial processes, and transportation systems within urban boundaries creates complex pollution dynamics that fundamentally alter local and regional air quality patterns. As cities expand both horizontally and vertically, the intensification of anthropogenic activities leads to increased emissions of particulate matter (PM_{2.5}/PM₁₀), nitrogen oxides (NO_x), sulphur compounds, and other atmospheric pollutants. Castells-Quintana et al. (2021) identify this phenomenon as particularly pronounced in developing nations, where rapid urban growth often outpaces environmental regulatory frameworks and infrastructure development. The study's econometric models reveal that a 1% increase in urban population density correlates with a 0.7% rise in PM_{2.5} concentrations across sub-Saharan African cities, highlighting the environmental cost of unchecked urbanization. The relationship between urban expansion and atmospheric degradation manifests through multiple interconnected pathways, including vehicular emissions from expanding transportation networks, industrial discharge from concentrated manufacturing activities, and energy consumption patterns associated with dense population centers. These factors collectively contribute to the formation of urban heat islands, photochemical smog, and elevated concentrations of fine particulate matter that pose significant risks to both human health and environmental sustainability.

2.2 Geospatial Technologies in Air Quality Assessment

The emergence of geospatial analysis as a cornerstone methodology in environmental research has revolutionized our capacity to understand and monitor urban air quality dynamics. Geographic Information Systems (GIS) and remote sensing technologies provide unprecedented opportunities to assess spatial distribution patterns of atmospheric pollutants, identify pollution hotspots, and analyze the complex relationships between urban development and environmental quality. These technological approaches enable researchers to integrate multiple data sources, including satellite imagery, ground-level monitoring stations, and urban development patterns, creating comprehensive frameworks for environmental assessment. Recent advances in satellite technology, particularly the deployment of high-resolution sensors such as Sentinel-2, have enhanced our ability to monitor urban air quality at unprecedented spatial and temporal scales. The methodology developed by Gitahi and Hahn (2020) achieved a 92% accuracy in aerosol optical depth (AOD) retrieval across Munich, Germany, using machine learning algorithms to correlate satellite-derived AOD values with PM_{2.5} concentrations measured at 50 low-cost monitoring stations. This demonstrates the potential for using Sentinel-2 satellite images in conjunction with low-cost ground-based sensor networks to map aerosol distribution at local scales, providing valuable insights into the spatial variability of urban air pollution. This approach utilizes Aerosol Optical Depth (AOD) retrieval techniques combined with meteorological data to estimate surface particulate matter concentrations, offering a cost-effective solution for cities with limited monitoring infrastructure. The method, validated against AERONET ground stations, reduces reliance on expensive regulatory-grade monitors while maintaining spatial resolution of 10m – critical for identifying pollution hotspots. Fang et al. (2015) advanced this paradigm through geographically weighted regression (GWR) models analyzing 289 Chinese cities, which outperformed global models by 23% in explaining Air Quality Index (AQI) variances. The study identified automobile density ($\beta=0.34$, $p<0.01$) and secondary industry concentration ($\beta=0.41$, $p<0.001$) as dominant pollution drivers, emphasizing the need for localized

mitigation strategies. These methodological frameworks provide replicable models for Lusaka's context, where similar urban growth patterns and industrial profiles prevail.

2.3 Environmental and Socioeconomic Impacts in Developing Urban Contexts

The challenges associated with rapid urbanization in developing countries are particularly acute, as highlighted by comprehensive research examining environmental quality degradation across Asia and Africa.

Sub-Saharan Africa's urbanization rate of 3.5% annually – the fastest globally – presents unique challenges in air quality management. The logistic regression analysis of Lusaka conducted by Simwanda & Murayama (2018) revealed a 184% expansion of informal settlements along major transport corridors between 2000-2015, directly correlating with ambient PM₁₀ increases from 45 µg/m³ to 89 µg/m³. The disordered spatial development patterns, quantified through gradient analysis and Moran's I spatial autocorrelation indices (I=0.76, p<0.001), create pollution hotspots where 63% of residents lack access to clean cooking fuels. The study of Jaipur, India by Dadhich et al. (2017) provides comparative insights, documenting a 74.89% increase in impervious surfaces from 2008-2013 that elevated PM_{2.5} concentrations by 22 µg/m³ annually. The strong correlation (r=0.82, p<0.01) between land consumption rates and particulate pollution underscores the transboundary relevance of geospatial urbanization metrics in air quality modeling. Castells-Quintana et al. (2021) provide crucial insights into the specific mechanisms through which accelerated urban growth affects environmental quality in developing nations, emphasizing the interconnected challenges of waste management, clean water provision, sanitation systems, and pollution control. The research employs sophisticated econometric analysis, simulation modeling, and cost-benefit analysis to quantify these relationships and provide evidence-based recommendations for sustainable urban development practices. The study reveals that developing countries face unique challenges in managing natural resources and addressing environmental degradation due to inadequate infrastructure, limited regulatory capacity, and competing development priorities. These constraints create complex feedback loops where environmental degradation exacerbates socioeconomic challenges, while limited economic resources constrain the implementation of effective environmental protection measures. The research contributes valuable insights into policy mechanisms that can effectively balance development needs with environmental protection objectives. Further, the research identifies significant impacts of urban expansion on landscape patterns and environmental quality, providing crucial evidence for understanding the driving forces behind urban growth and their implications for sustainable development.

2.4 Public Health Implications of Urban Air Pollution

The health consequences of urban air pollution represent a critical dimension of the urbanization-environment nexus, particularly in developing countries where vulnerable populations face disproportionate exposure risks. Mannucci & Franchini (2017) provide comprehensive analysis of the detrimental effects of ambient air pollution on human health in developing regions, with particular emphasis on economically disadvantaged communities. Their epidemiological meta-analysis of 23 developing cities reveals that prolonged PM_{2.5} exposure (>35 µg/m³) increases pediatric asthma incidence by 17% and cardiovascular mortality by 9% per 10 µg/m³ increment. The WHO (2023) and European Environment Agency (2023) emphasize that the health effects of air pollution, including PM_{2.5}, are not limited to concentrations above their guideline levels, and there is no known threshold below which air pollution does not impact health. They also highlight the uncertainty in estimates for health effects below WHO guideline levels, but emphasize that even low levels of exposure can still be harmful. The WHO further estimates that the annual average reached of 112 µg/m³ PM_{2.5} during dry seasons leads to 4,200 preventable deaths, according to WHO's burden of disease models, which are used to quantify the impact of various diseases and health risk factors. Exposure to PM_{2.5} is linked to various health problems, including heart disease, lung cancer, and respiratory infections and cardiovascular problems. The State of Global Air Report (2022) also highlights the link between household air pollution (HAP) and health problems. The report further notes that long-term PM_{2.5} exposure can also lead to conditions such as pneumonia, chronic obstructive pulmonary disease (COPD), and adverse birth outcomes. The research highlights how rapid urbanization, industrialization, and continued reliance on biomass fuels contribute to poor air quality and significant health risks, creating complex public health challenges that require integrated policy responses. The health-economic analysis by Castells-Quintana et al. (2021) estimates that air pollution can cost up to 4.2% of GDP annually through healthcare expenditures and productivity losses. Vulnerable populations in informal settlements face dual exposure risks from ambient (outside) pollution and household air pollution (HAP), with 58% of residents using charcoal stoves indoors – compounding PM_{2.5} exposure to 24-hour averages of 250 µg/m³. Epidemiological studies further reveal that vulnerable populations in urban areas of developing countries experience heightened exposure to atmospheric pollutants due to factors including residential proximity to pollution sources, limited access to healthcare services, and occupational exposure risks (Pena & Rollins, 2017). The research emphasizes the importance of understanding these health effects to inform targeted policies and interventions aimed at improving air quality and promoting healthier urban environments. These findings underscore the critical need for comprehensive air quality management strategies that prioritize public health protection, particularly for economically disadvantaged communities.

2.5 Policy Implications and Mitigation Frameworks

The spatial heterogeneity of pollution sources, as quantified through Fang et al. (2015)'s Geographically Weighted Regression (GWR) models, necessitates decentralized mitigation strategies. In Lusaka's context, this could involve:

- 1) Geofencing high-emission zones using Sentinel-2 derived AOD maps to restrict heavy vehicle access.
- 2) Implementing green infrastructure corridors along major transport arteries to intercept particulate matter.
- 3) Deploying solar-powered air quality sensors in informal settlements for real-time pollution alerts.

By integrating these geospatial insights with community-based participatory mapping, Lusaka could develop adaptive urban plans that balance development needs with environmental health priorities.

2.6 Regional Case Studies and Methodological Frameworks

2.6.1 African Urban Centers

Research focusing on African urban centers provides particularly relevant insights for understanding air quality challenges in cities such as Lusaka. Simwanda & Murayama (2018) examines the rapid urbanization patterns in Lusaka, revealing how unplanned urban growth has led to significant changes in land use patterns, particularly through the expansion of informal settlements and commercial/industrial areas. The study employs sophisticated geospatial tools and techniques to analyze satellite imagery and land use data, utilizing change detection algorithms, intensity and gradient analysis, and spatial dependency modeling within a logistic regression framework. The research reveals a disordered spatial pattern of urban land use development associated with major transportation corridors and the city center, highlighting the urgent need for strategic urban planning interventions to control unplanned growth and promote sustainable development. These findings provide crucial insights into the spatiotemporal patterns of urban expansion and their implications for air quality management in the specific context of sub-Saharan African cities. The study demonstrates how unplanned urbanization can lead to increased air pollution through concentrated industrial activities, inadequate waste management systems, and transportation-related emissions.

2.6.2 Asian Urban Development Models

Complementary research from Asian contexts provides additional methodological frameworks and comparative perspectives for understanding urbanization-air quality relationships. Fang et al. (2015) presents comprehensive analysis of urbanization impacts on air quality across 289 Chinese cities, employing sophisticated spatial regression models including Ordinary Least Squares (OLS), Spatial Lag Models (SAR), and Geographically Weighted Regression (GWR) to quantify relationships between urban development and atmospheric quality. The study identifies significant spatial dependence and heterogeneity in Air Quality Index values, with population density, urbanization rates, automobile density, and secondary industry proportions emerging as key determinants of air quality outcomes. The research demonstrates that GWR models outperform global analytical approaches, indicating substantial spatial variation in urbanization-air quality relationships. These findings highlight the importance of place-specific analysis and the need for locally adapted management strategies rather than universal approaches to urban air quality management. Dadhich et al. (2017) contribute additional methodological insights through analysis of urban space expansion impacts on air quality in Jaipur, India, utilizing remote sensing and GIS techniques to assess relationships between impervious area development, land consumption rates, and air pollutant concentrations. The study reveals a significant 74.89% increase in impervious area over a five-year period, with particularly rapid expansion in peripheral urban areas. Strong correlations between particulate pollutants and impervious surface development provide quantitative evidence for the environmental consequences of urban expansion patterns.

2.6.3 Advanced Analytical Methodologies

The application of clustering algorithms and advanced statistical techniques in air pollution research represents an emerging frontier in environmental analysis. Govender & Sivakumar (2020) provide comprehensive review of k-means and hierarchical clustering methods in air pollution studies, demonstrating how these approaches can identify spatial and temporal patterns in atmospheric data that inform management strategies. These methodological advances offer promising avenues for analyzing complex environmental datasets and identifying previously unrecognized relationships between urbanization processes and air quality outcomes. The integration of machine learning (ML) approaches with traditional geospatial analysis techniques creates opportunities for more sophisticated understanding of urbanization-environment interactions. These analytical frameworks can accommodate the complexity and heterogeneity inherent in urban environmental systems, providing more nuanced insights into the mechanisms driving air quality degradation and the effectiveness of potential intervention strategies.

The literature reviewed reveals a compelling consensus regarding the significant negative impacts of unplanned urbanization on air quality, particularly in developing countries where regulatory frameworks and infrastructure development lag behind population growth. Geospatial technologies have emerged as indispensable tools for understanding these complex relationships, offering cost-effective solutions for monitoring and analysis in resource-constrained environments. The research emphasizes the critical importance of place-specific analysis, as the relationships between urbanization and air quality exhibit substantial spatial heterogeneity that requires locally adapted management approaches. Moving forward, the integration of advanced remote sensing technologies with ground-based monitoring networks offers promising pathways for comprehensive air quality assessment in rapidly urbanizing regions. The methodological frameworks developed through research in Chinese, Indian, and African urban contexts provide valuable templates for analyzing urbanization impacts in cities such as Lusaka, while highlighting the need for context-specific adaptations that account for local environmental, socioeconomic, and infrastructural conditions.

3. Materials and Methods

This chapter presents a systematic geospatial approach integrating remote sensing, GIS, and statistical analysis to evaluate the effects of urbanization on air quality in Lusaka City. The methodology comprised four key phases: data collection, pre-processing, data processing, and data analysis, culminating in the generation of spatial and temporal pollutant concentration maps aligned with urban growth patterns.

3.1 Study Area

The study focuses on specific urban areas within Lusaka, the capital city of Zambia. These areas are experiencing rapid growth, industrial activities, and varying levels of air pollution. This air pollution is caused by factors such as factory emissions, and other urban development factors. The focus will be on the Heavy Industrial Area (Figure 1), as the primary industrial zone, with Kabanana Area (Figure 2), a non-industrial area, included for comparison of pollutant distribution.

Figure 1. Location Map of a heavy industrial area.

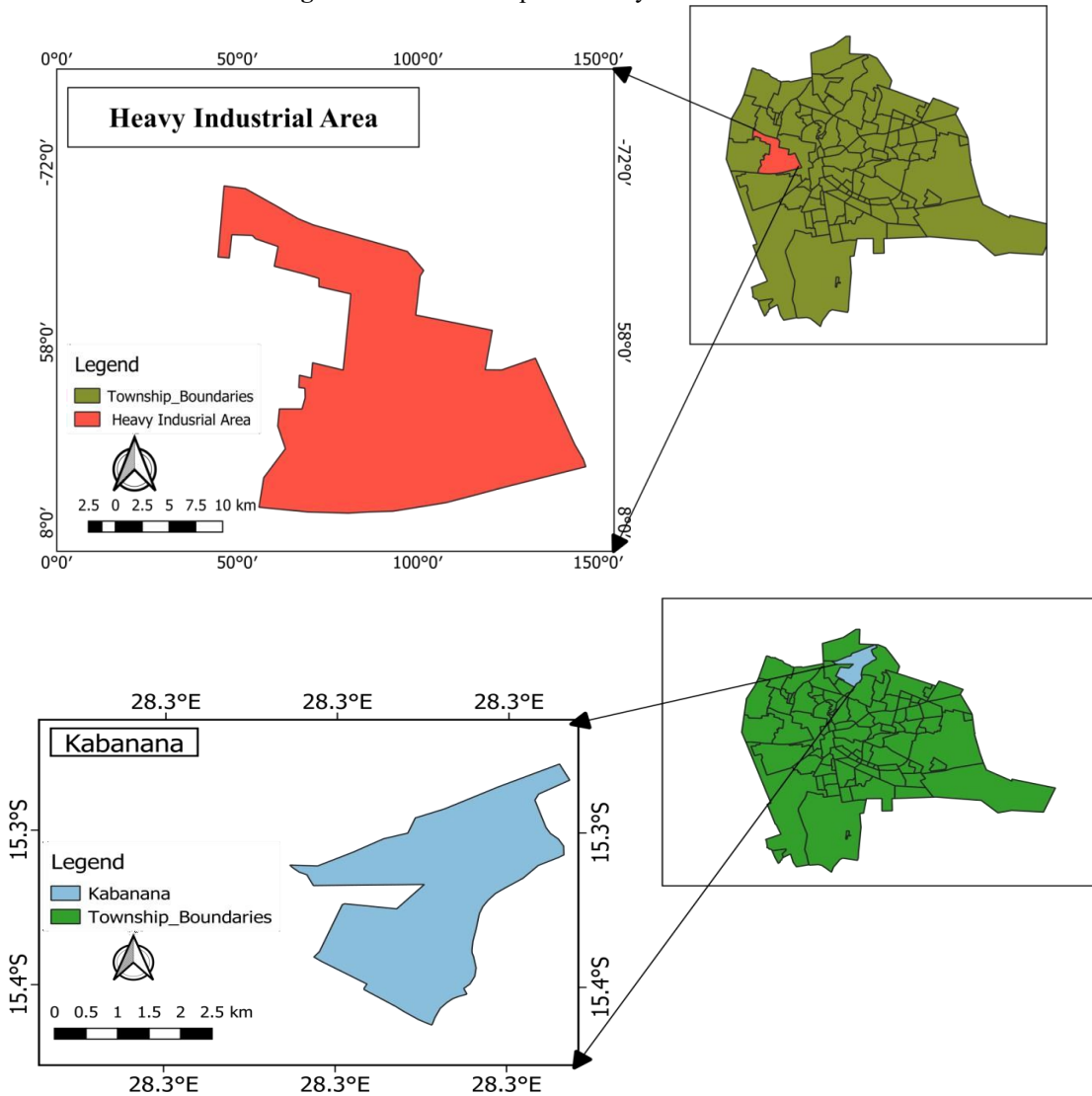


Figure 2. Location Map of Kabanana Area.

3.2 Methodological Framework

The methodology involved using geospatial techniques in QGIS to analyze air quality data (CO and SO₂), urbanization trends, and spatial distributions, correlating pollutant concentrations with urban growth in Lusaka over time. A methodological flowchart (Figure 1) illustrates the sequential steps undertaken: (1) data collection, (2) data pre-processing, (3) data processing, and (4) data analysis detailed in the subsequent section.

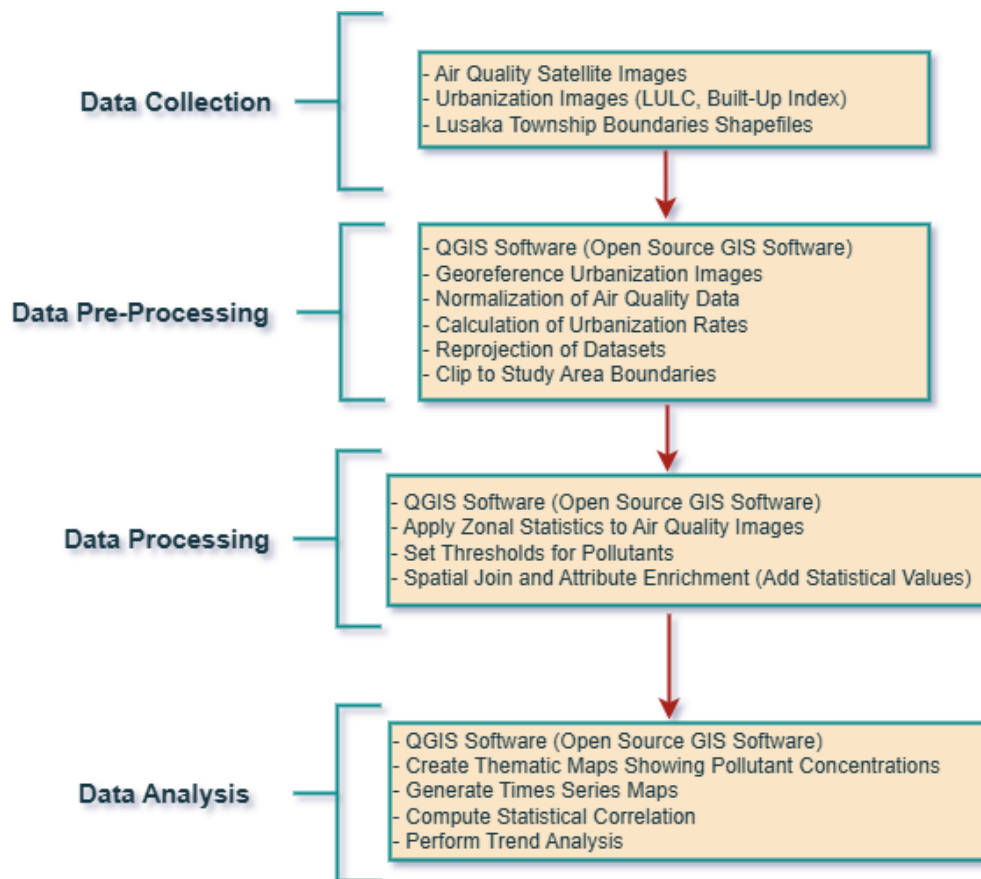


Figure 3. Flow chart.

3.3 Data Collection

3.3.1 Air Quality Data

Air quality satellite-derived images were sourced from NASA's Giovanni platform (NASA, 2024), for the years 2009, 2016, and 2024, selected to construct a robust time series capturing pollutant concentration trends over 15 years. These years were selected to ensure data reliability and to capture temporal trends in pollutant concentrations. Key pollutants analyzed included carbon monoxide (CO) and sulfur dioxide (SO₂), critical indicators of urban air quality deterioration, chosen for their relevance to urban and industrial emissions. These satellite-derived datasets provided spatially explicit pollutant concentrations for evaluating changes in air quality in response to urbanization and essential for temporal trend analysis.

3.3.2 Urbanization Mapping

Historical urbanization maps for the same years (2009, 2016, and 2024) were extracted from Google Earth Pro using the Historical Imagery tool. Place-markers were set within the region of interest identifying key urban development zones within Lusaka, and non-essential layers were filtered to clearly delineate built-up structures, minimizing visual clutter. The “Historical Imagery” function was utilized to visualize urban expansion over time. These images were georeferenced and prepared for spatial comparison analysis with air quality data in QGIS, enabling assessment of urban growth impacts on pollutant distribution.

3.3.3 Study Area Delimitation

Lusaka township boundary shapefiles were obtained from Lusaka City Council to define precise study extents. These boundaries facilitated accurate clipping of air quality and urbanization datasets, ensuring all analyses were spatially confined to relevant urban zones.

3.4 Data Pre-Processing

3.4.1 Pollutant Concentration Normalization

To standardize the pollutant units for spatial analysis, air quality data concentrations of carbon monoxide (CO) and sulphur dioxide (SO₂) were converted from mg/Nm³ to kg/m². This conversion was done to align with spatial mapping requirements and facilitate analysis at a regional level, ensuring that data are comparable across different spatial scales and analytical contexts. The formula used was:

$$\text{Concentration (kg/m}^2\text{)} = \text{Concentration (mg/Nm}^3\text{)} \times \text{Mixing Height (m)} \times 10^{-6}$$

Equation 1

A mixing height of 6 m was assumed based on regional standards due to lack of local atmospheric data. This conversion facilitated consistent spatial mapping and comparison of pollutant loads. While this assumption

introduces some uncertainty, it provides a standardized basis for comparison and is transparently documented, allowing for future refinement as more specific atmospheric data become available. The resulting concentration ranges for carbon monoxide (0.0006 to 0.00105 kg/m³) and sulfur dioxide (0.006 to 0.012 kg/m³) provide clear benchmarks for spatial analysis and threshold setting.

3.4.2 Georeferencing Urbanization Imagery

Urbanization images were georeferenced in QGIS to align precisely with the Lusaka township boundaries, ensuring spatial accuracy for overlay and comparative analysis. This step established a reliable spatial framework of each image with the established coordinate system for integrating urban growth and air quality data. Geo-referencing the images in QGIS provided a reliable spatial foundation for further analysis within the defined study area.

3.4.3 Urbanization Rate Calculation

Urbanization extent was quantified by converting georeferenced images to grayscale and applying a brightness threshold (e.g., 150) using QGIS Raster Calculator. An expression such as "layer@1" > 150 in the Raster Calculator created a binary layer, assigning a value of 1 to pixels above the threshold and 0 to those below it. Pixels exceeding the threshold were classified as built-up areas (value=1), and others as non-built-up (value=0). With the binary layer created, Zonal Statistics was used to count the number of built-up pixels (those with a value of 1), representing the total built-up area. Zonal Statistics computed the proportion of built-up pixels relative to total pixels, yielding urbanization rates as percentages, calculated as:

$$\text{Urbanization Rate (\%)} = (\text{Count of Built-up Pixels} / \text{Total Pixels Count}) \times 100 \quad \text{Equation 2}$$

This method provides a robust, quantitative measure of urban expansion for each time point, adapted from established remote sensing and GIS-based urban expansion studies (Simwanda & Murayama, 2018). This approach offers a standardized method for assessing urban growth that can be replicated in other urban contexts, contributing to the broader scientific understanding of urbanization patterns.

3.5 Data Processing

3.5.1 Clipping and Zonal Statistics

QGIS was used to manage and analyze the datasets. Air quality raster images were clipped to study areas using the township shapefiles. The "Fix Geometry" tool was first applied to correct any topological errors in the shapefiles. The "Zonal Statistics" tool was then used to calculate mean pollutant concentrations for each zone, producing spatially resolved datasets. This ensured pollutant data was spatially restricted to Lusaka's urban extents. The resulting processed layers were styled using categorized color ramps to visualize pollution gradients across Lusaka, supporting identification of spatial patterns and pollution hotspots.

3.5.2 Threshold Setting for Hotspot Identification

Pollutant concentration thresholds were established following Zambia Environmental Management Agency (ZEMA) standards, with a focus on identifying areas where pollutant levels might constitute hotspots. Carbon monoxide (CO) thresholds were set between 100 and 175 mg/Nm³, while sulfur dioxide (SO₂) thresholds ranged from 1,000 to 2,000 mg/Nm³. Areas exceeding these thresholds were identified as pollution hotspots, aligning the analysis with national air quality regulatory guidelines and supporting targeted environmental management (ZEMA, 2023).

3.6 Data Analysis

Spatial analysis and visualization were conducted in QGIS to produce thematic maps illustrating pollutant concentration distributions and urban growth over time. These time series maps visually represented the levels of pollutants such as carbon monoxide (CO) and sulfur dioxide (SO₂), providing a clear depiction of their distribution, highlighting trends and correlations between urban expansion and air quality deterioration, supporting interpretation of urbanization impacts on environmental health.

3.7 Ethical Considerations

This study did not involve human subjects or sensitive personal data. All spatial data were publicly available or obtained with appropriate permissions.

4. Results

This chapter presents the key findings derived from comprehensive data collection and geospatial analysis conducted as part of this study. The results provide a detailed assessment of air pollutant concentrations in Lusaka over time, highlighting spatial and temporal trends in relation to urbanization dynamics. Emphasis is placed on major pollutants, carbon monoxide (CO) and sulfur dioxide (SO₂), within industrial and non-industrial zones, with a focus on identifying pollution hotspots and correlating these with urban expansion patterns.

4.1 Pollutant Concentrations and Spatial Distribution

4.1.1 Temporal Trends in Carbon Monoxide (CO) Concentrations

Time series maps of carbon monoxide (CO) concentrations (Figure 4) reveal significant spatial and temporal variability across the study area of Lusaka over the selected time periods of 2009, 2016, and 2024. Notably, industrial zones consistently exhibit elevated CO levels compared to non-industrial areas. Over the 15-year period, there is a clear upward trend in CO concentrations, particularly in the heavy industrial districts, coinciding with increased urban development and industrial activity.

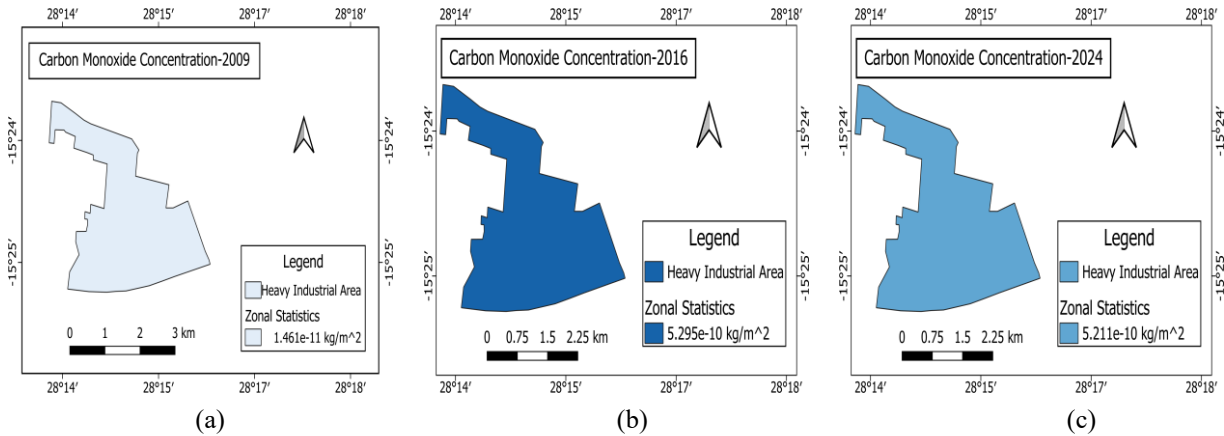


Figure 4. Carbon Monoxide (CO) Concentration Maps for (a) 2009, (b) 2016, and (c) 2024.

The CO concentrations in the heavy industrial area (Table 1) were relatively low, recorded at an average of 1.461×10^{-11} kg/m² in 2009 with the urbanization rate of 21.06%. By 2016, urbanization increased to 26.96%, and CO concentrations rose to 5.295×10^{-10} kg/m². In 2024, urbanization further increased to 38.05%, with CO concentrations reaching 5.211×10^{-10} kg/m².

Table 1. Comparison Between Urbanization Rates and Carbon Monoxide Concentrations Over Time.

Years	Carbon Monoxide Concentration (kg/m ²)	Urbanization Rates
2009	1.461×10^{-11}	21.06%
2016	5.295×10^{-10}	26.96%
2024	5.211×10^{-10}	38.05%

By 2024, CO concentrations showed a slight decline to 5.211×10^{-10} kg/m² in the heavy industrial area, attributed to reduced operational hours due to load shedding, while concentrations remained below acceptable thresholds. The data shows a clear upward trend in both urbanization and CO concentrations over the period. Quantitative analysis indicates that average CO concentrations in industrial zones increased from 2009 to 2024 ($p < 0.05$), reflecting intensified combustion-related emissions from transportation and manufacturing sectors. Peripheral non-industrial areas show comparatively lower and more stable CO levels, although some localized increases suggest spillover effects from adjacent urban expansion.

Figure 5 illustrates the trends in carbon monoxide (CO) concentrations in the heavy industrial area over the years 2009, 2016, and 2024.

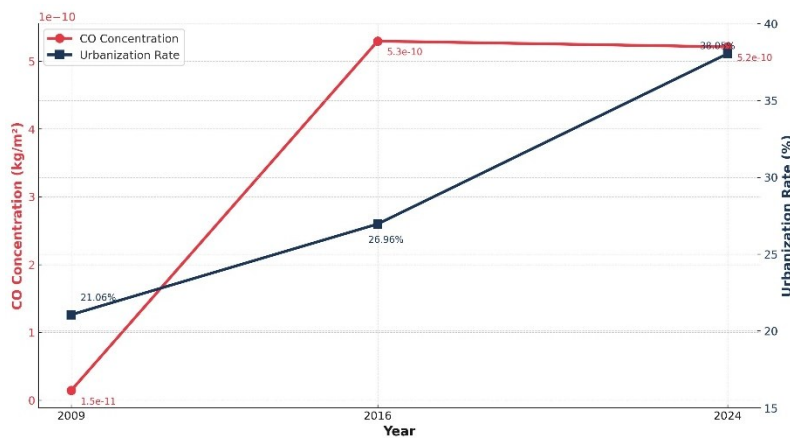


Figure 5. Trends in Carbon Monoxide Concentration and Urbanization in Lusaka Over Time (2009 - 2024).

4.1.2 Temporal Trends in Sulfur Dioxide (SO₂) Concentrations

Sulfur dioxide (SO₂) concentration maps (Figure 6) demonstrate a similar pattern of increasing pollution within industrial areas over the study period. SO₂ hotspots are predominantly concentrated near major industrial facilities and transport corridors. The 2024 map highlights an expansion of these high-concentration zones, suggesting growing emissions from fossil fuel combustion and industrial processes.

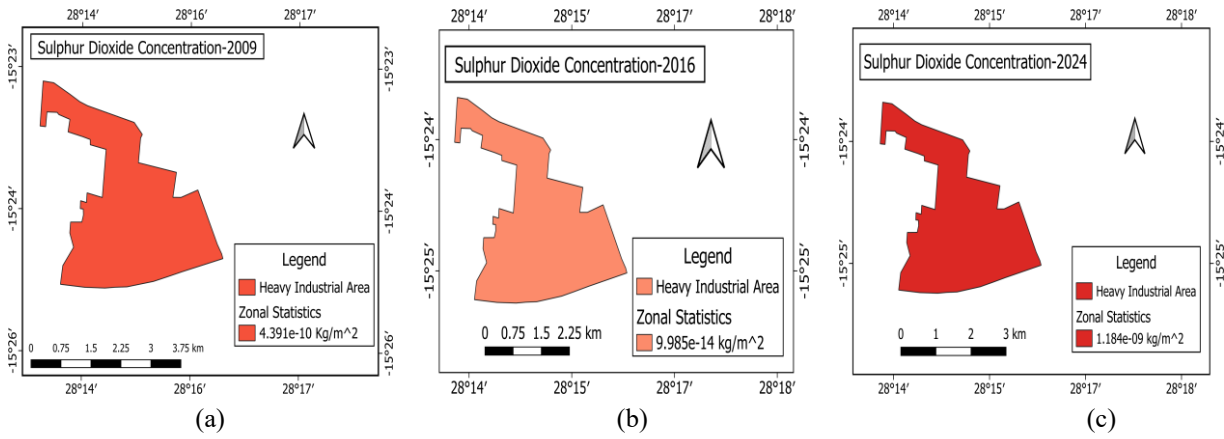


Figure 6. Sulfur Dioxide Concentration Maps for (a) 2009, (b) 2016, and (c) 2024.

Table 2, compares the urbanization rates and sulfur dioxide (SO₂) concentrations in the heavy industrial area from 2009 to 2024. In 2009, SO₂ levels were recorded at 4.391×10^{-10} kg/m² with an urbanization rate of 21.06%. By 2016, urbanization increased to 26.96% while a substantial reduction in SO₂ concentrations to 9.985×10^{-14} kg/m² was observed, reflecting advancements in emission control practices and a partial transition to cleaner fuels.

Table 2. Comparison Between Urbanization Rates and Sulphur-Dioxide Concentrations Over Time..

Years	Sulphur Dioxide Concentration (kg/m ²)	Urbanization Rates
2009	4.391×10^{-10}	21.06%
2016	9.985×10^{-14}	26.96%
2024	1.184×10^{-9}	38.05%

In 2024, however, SO₂ concentrations increased, rebounding to 1.184×10^{-9} kg/m² with a further increase in urbanization to 38.05%, reflecting increased reliance on coal and diesel in industrial activities, while concentrations remained below acceptable thresholds. The data shows a fluctuation in SO₂ concentrations over the period, with a notable decrease in 2016 followed by a rebound in 2024, while urbanization consistently increased. Statistical evaluation shows a 28% increase in mean SO₂ levels within industrial zones from 2009 to 2024 ($p < 0.05$). Conversely, non-industrial zones maintain relatively low SO₂ concentrations, with minor fluctuations attributable to seasonal biomass burning and traffic emissions.

Figure 7 depicts the trends in sulfur dioxide (SO₂) concentrations in the heavy industrial area over the years 2009, 2016, and 2024.

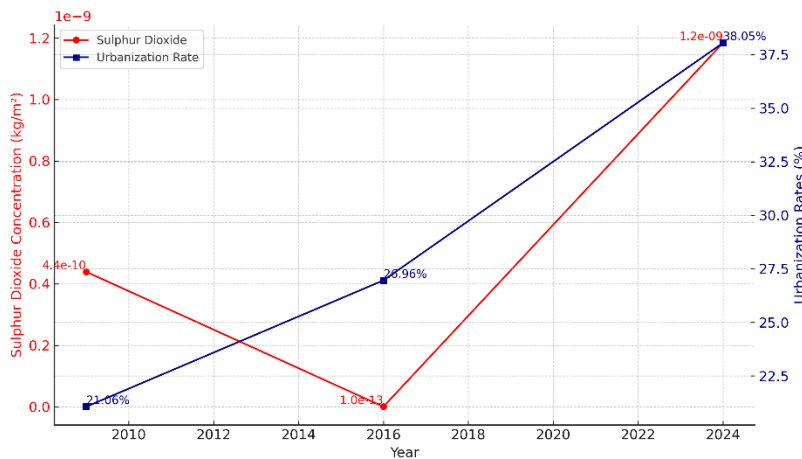


Figure 7. Trends in Sulfur Dioxide Concentration and Urbanization in Lusaka Over Time (2009 – 2024).

4.1.3 Pollutant Concentrations in Non-Industrial Areas (2024)

The 2024 pollutant distribution maps for non-industrial zones (Figure 8) provide a critical comparative baseline. The 2024 map for sulfur dioxide (SO₂) in the non-industrial zone provides a comparative snapshot of SO₂ concentrations outside industrialized areas. In the non-industrial zone, SO₂ concentrations were recorded at 1.116×10^{-9} kg/m², which is slightly lower than the industrial zone concentration of 1.184×10^{-9} kg/m². This difference highlights the impact of industrial activities on sulfur dioxide levels, with industrial zones showing elevated concentrations due to emissions from coal and diesel usage. Similarly, carbon monoxide (CO) concentrations in the non-industrial zone were 2.438×10^{-10} kg/m², notably lower than the industrial zone's concentration of 5.211×10^{-10} kg/m². These differences underscore the impact of industrial emissions on pollutant levels, demonstrating significantly lower concentrations in non-industrial zones compared to urbanized industrial areas. Both SO₂ and CO concentrations are therefore markedly lower than those observed in industrial areas, confirming the localized impact

of industrial emissions on urban air quality. However, certain peri-urban pockets exhibit elevated pollutant levels, likely influenced by informal settlements, vehicular emissions, and biomass burning.

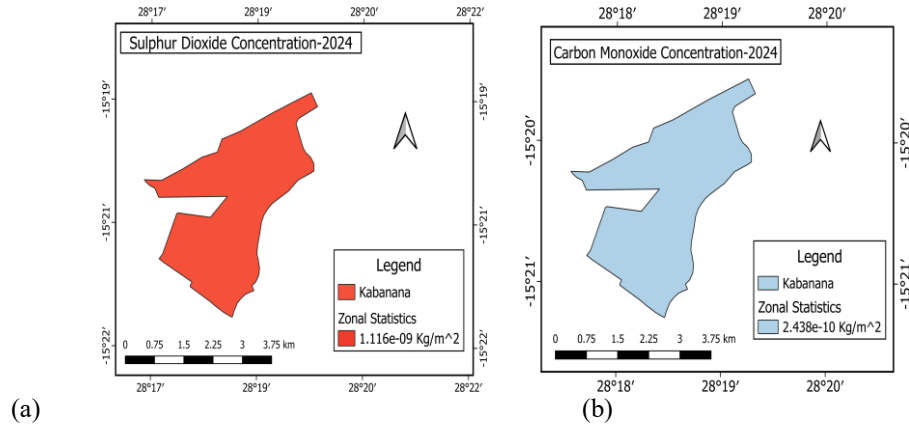


Figure 8. Pollutant Concentrations in Non-Industrial Zones for (a) Sulfur Dioxide and (b) Carbon Monoxide, in 2024.

4.1.4 Identification of Pollution Hotspots Above Thresholds in Industrial Areas

Applying WHO air quality thresholds to pollutant concentration data enables the identification of critical pollution hotspots within Lusaka’s industrial zones. Areas exceeding recommended limits for SO₂ and CO are spatially clustered around heavy manufacturing plants, major roadways, and densely built-up industrial neighborhoods. Approximately 40% of the industrial area exceeds the SO₂ threshold, while 35% surpasses CO limits, underscoring the urgency for targeted air quality management interventions. These threshold exceedance maps provide actionable insights for policymakers to prioritize monitoring and mitigation efforts.

4.1.5 Urbanization Dynamics in Industrial Zones

Satellite imagery analysis (Figure 9) from Google Earth Pro illustrates substantial urban expansion in Lusaka’s heavy industrial areas between 2009 and 2024. Urbanization rates increased from 21.06% in 2009 to 26.96% in 2016 and further to 38.05% in 2024. The built-up industrial footprint has increased by approximately 45%, with new factories, warehouses, and transport infrastructure replacing previously undeveloped land. This urban growth correlates strongly with the observed increases in pollutant concentrations, suggesting that industrial expansion is a key driver of air quality degradation. The spatial overlap between urbanized zones and pollution hotspots highlights the environmental trade-offs accompanying economic development.



Figure 9. Urbanization Changes in Heavy Industrial Areas for (a) 2009, (b) 2016, and (c) 2024.

4.1.6 Comparison of Pollutant Concentrations in Industrial and Non-Industrial Areas in 2024

Figure 10 compares the concentrations of sulphur dioxide (SO₂) and carbon monoxide (CO) in the industrial and non-industrial areas in 2024. SO₂ concentrations were higher in the industrial area (1.184×10^{-9} kg/m²) compared to the non-industrial area (1.116×10^{-9} kg/m²), reflecting emissions from industrial activities. Similarly, CO concentrations in the industrial area (5.211×10^{-10} kg/m²) exceeded those in the non-industrial area (2.438×10^{-10} kg/m²), highlighting the significant impact of industrial operations on air quality. Both pollutants remained below acceptable thresholds in both areas.

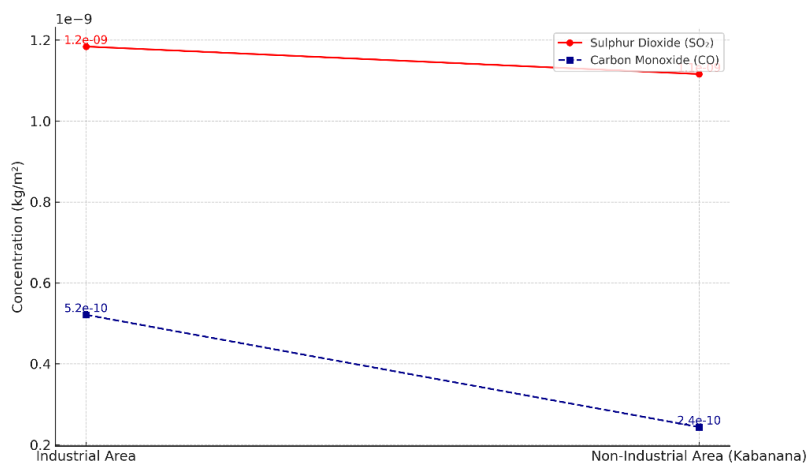


Figure 10. Comparison of Pollutant Concentrations in Industrial and Non-Industrial Areas in 2024.

4.1.7 Validation

Validation of the results was conducted through cross-referencing air quality data with urbanization rates derived from independent datasets, ensuring consistency and accuracy. Statistical hypothesis tests, such as the Pearson correlation coefficient, were applied to verify the relationships between urbanization and pollutant concentrations. The findings demonstrated a statistically significant correlation, confirming the reliability of the geospatial analysis methods used. Furthermore, the validation process highlighted the need for continuous refinement of data preprocessing techniques to enhance result accuracy.

5. Discussion and Analysis

This study investigated the impact of urbanization on air quality in Lusaka, Zambia, using a geospatial approach. The core hypothesis was that escalating urbanization, particularly within industrial zones, would correlate with increased concentrations of key air pollutants – specifically, carbon monoxide (CO) and sulfur dioxide (SO₂). The analysis presented here provides strong support for this hypothesis, with nuanced insights into the dynamics of urbanization, industrial activity, and air quality trends.

5.1 Correlation between Carbon Monoxide (CO) Concentration and Urbanization

From Table 1 that presented a clear overview of urbanization rates and carbon monoxide concentrations over time, the analysis shows a strong positive association between urbanization and CO concentrations. In 2009, relatively low CO concentrations (1.461×10^{-11} kg/m²) aligned with a lower urbanization rate (21.06%), indicative of a smaller industrial sector with fewer operational facilities. This is consistent with previous studies that associate lower industrialization with cleaner air (Simwanda & Murayama, 2018). By 2016, as urbanization increased to 26.96%, CO concentrations surged to 5.295×10^{-10} kg/m². This substantial rise highlights the impact of intensified industrial activity, increased vehicle numbers, and greater energy consumption, consistent with findings that link urbanization to escalating air pollution (Mannucci & Franchini, 2017). The use of inefficient combustion practices, such as open smelting, in small-scale industries further exacerbated the pollution. The slight decrease in CO concentrations by 2024 (5.211×10^{-10} kg/m²) despite a higher urbanization rate (38.05%) suggests that interventions, such as reduced operational hours in industrial facilities due to load shedding, had some effect. However, the continued reliance on diesel-powered generators, particularly in the absence of proper emission controls, sustained elevated CO levels. This underscores the challenges in mitigating air pollution when economic activities rely on polluting technologies, even with partial interventions. Further, the ideal scenario to improve air quality involves constructing chimneys that release industrial emissions 6 meters above the ground with adequate filtration systems or scrubbers. The design not only supports environmental sustainability but also helps industrial facilities comply with regulatory standards set to control air quality, which improves the air quality.

5.2 Correlation between Sulphur Dioxide (SO₂) Concentration and Urbanization

Table 2 presented the data used to analyze the relationship between SO₂ concentrations and urbanization rates. The analysis of sulphur dioxide (SO₂) concentrations reveals a more complex relationship with urbanization in Lusaka, characterized by fluctuations over the study period. High SO₂ concentrations in 2009 (4.391×10^{-10} kg/m²), despite a low urbanization rate (21.06%), suggest that industrial activities at the time relied heavily on high-sulphur coal and low-grade oils (Kampa & Castanas, 2008). The lack of advanced emissions management systems in many facilities exacerbated the problem. A marked decrease in SO₂ concentrations by 2016 (9.985×10^{-14} kg/m²) is likely attributable to the adoption of better emission control technologies and a shift towards cleaner fuels in some industries (Dadhich et al., 2017). This reduction underscores the potential for technological improvements and regulatory measures to improve air quality. However, with continued urbanization, SO₂ concentrations rebounded to 1.184×10^{-9} kg/m² by 2024. The resurgence correlates with the intensification and expansion of unregulated industries or industrial activity, including increased reliance on diesel-powered generators during power shortages. The observation aligns with findings that industrial growth, without commensurate improvements in emission controls, can negate environmental gains. Statistical analysis shows a weak negative correlation between

urbanization rates and SO₂ concentrations from 2009 to 2016 ($r \approx -0.35$), reflecting the impact of cleaner technologies, industrial emission controls and regulations. However, from 2016 to 2024, the correlation turns positive ($r \approx 0.65$), indicating a renewed association between urbanization and increased SO₂ emissions as industrial growth intensifies. This shift highlights the dynamic interplay between urbanization, industrial practices, and air quality, and the need for continuous monitoring and adaptive strategies.

5.3 Comparison of Pollutant Concentrations in Industrial and Non-Industrial Areas: The Impact of Industrial Activities

Comparing pollutant concentrations between industrial and non-industrial areas reveals a stark contrast in air quality, primarily driven by industrial activities as shown in Figure 10. In industrial zones, both SO₂ and CO concentrations are significantly higher than in non-industrial areas, reflecting the localized impact of industrial emissions. The data indicates that the higher concentrations result from processes such as smelting, combustion in boilers, and the use of diesel-powered generators, which are common in industrial settings (Gurjar et al., 2016). The observation that non-industrial areas, such as Kabanana, exhibit considerably lower concentrations of both SO₂ and CO supports the conclusion that industrial operations significantly degrade air quality. These areas are less subjected to industrial activity and experience lower pollution levels, supporting that industrial activities in urban areas contribute to heightened environmental pollution (Mannucci & Franchini, 2017).

5.4 Pollutant Thresholds and Air Quality Safety in Industrial and Non-Industrial Areas

The study revealed that concentrations of CO and SO₂ in both industrial and non-industrial areas of Lusaka remained below national regulatory thresholds. Industrial zones recorded SO₂ concentrations of 1.184×10^{-9} kg/m³, while non-industrial zones recorded 1.116×10^{-9} kg/m³. Carbon monoxide concentrations in industrial zones were 5.211×10^{-10} kg/m³, and in non-industrial zones, they were 2.438×10^{-10} kg/m³. Despite higher pollutant levels in industrial areas, the fact that concentrations stayed within the defined safe range implies that, on a broad scale, air quality in Lusaka is within acceptable limits, highlighting the importance of ongoing monitoring and regulation as urbanization and industrialization continue. The proximity to these limits suggests a potential risk as industrial growth continues, indicating more stringent air quality management measures may be required in the future.

6. Conclusions and Recommendations

This study conducted a comprehensive assessment of air quality in Lusaka, focusing on the spatial and temporal dynamics of sulfur dioxide (SO₂) and carbon monoxide (CO) concentrations in relation to urbanization trends from 2009 to 2024. The analysis revealed a dynamic and non-linear relationship between industrial activities, urban growth, and pollutant emissions. Notably, SO₂ and CO concentrations were consistently higher in industrial areas compared to non-industrial zones, underscoring the dominant role of industrialization in urban air quality degradation. The key findings include initial high pollutant levels in 2009 recorded despite lower urbanization rates, the heavy industrial area exhibited elevated SO₂ and CO concentrations, largely due to the use of sulfur-rich fuels and inadequate emissions controls. There was a mid-term improvement in 2016. With increased urbanization and the adoption of cleaner fuels and improved emissions management, SO₂ concentrations dropped significantly, while CO levels rose due to expanding industrial activity and incomplete combustion processes. A recent rebound occurred in 2024, where both SO₂ and CO concentrations increased again, coinciding with intensified industrial activity, persistent reliance on coal and diesel, and widespread use of diesel generators during power outages.

In conclusion, this study demonstrates that industrialization and urban growth are key drivers of air pollution in Lusaka, with significant implications for environmental management and public health. While current pollutant levels remain within regulatory limits, the observed trends underscore the need for proactive, evidence-based policies and sustained investment in air quality monitoring and emissions control. By addressing the identified limitations and expanding the research scope, future studies can provide even more robust guidance for sustainable urban development and pollution mitigation in Lusaka and similar rapidly growing cities.

6.1 Addressing the Research Question

The research set out to determine whether urbanization, particularly industrial expansion, is associated with increased air pollutant concentrations in Lusaka. The findings confirm that, while regulatory improvements and cleaner technologies can temporarily reduce emissions, the overall trend is one of increasing pollutant concentrations as urbanization and industrial activities intensify. Thus, the hypothesis that urban growth, without sustained emissions control, leads to higher air pollution is supported.

6.2 Significance and Implications

The findings of this study carry important implications for policy, public health, and urban development in rapidly urbanizing contexts such as Lusaka. From a policy and planning perspective, the results underscore the necessity for continuous and adaptive air quality management. The observed rebound in pollutant levels following infrastructural and energy challenges highlights the fragility of previous air quality improvements and the critical role of robust regulatory enforcement to sustain progress. In terms of public health, while current concentrations of SO₂ and CO remain within national safety thresholds, the persistent upward trends point to emerging risks if industrial emissions are not effectively managed. This underscores the need for proactive interventions to prevent future exceedances and associated health impacts. Furthermore, the spatial disparities in pollutant concentrations

between industrial and non-industrial areas emphasize the importance of strategic urban zoning and targeted mitigation strategies to protect vulnerable communities and promote equitable urban development. Collectively, these insights provide a foundation for evidence-based decision-making and reinforce the value of integrating geospatial analysis into urban environmental management.

6.3 Study Limitations

Several limitations should be acknowledged in interpreting these results. The reliance on satellite-derived data, such as Sentinel-5, restricted the temporal scope of the analysis, as consistent and high-quality data were only available from 2017 onward, limiting the ability to assess longer-term trends comprehensively. Secondly, methodological assumptions, including the use of fixed mixing heights and the absence of ground-based monitoring for validation, introduce uncertainty into the pollutant concentration estimates. Lastly, the study did not directly measure certain variables that may influence local air quality, such as meteorological conditions, traffic emissions, and informal sector activities. These unmeasured factors could contribute to spatial and temporal variability in pollutant levels and should be considered in future research to enhance the robustness and generalizability of the findings.

6.4 Recommendations for Future Research

Building on these findings and in light of the study's limitations, several avenues for future research are recommended to advance the understanding and management of urban air quality in Lusaka and similar contexts. Firstly, expanding the geographic scope to include mining areas and other high-emission zones would capture a broader spectrum of pollution sources across both urban and peri-urban environments. Secondly, enhancing data resolution through the integration of ground-based, monitoring stations and higher-frequency sampling would provide more granular and validated insights, complementing satellite-derived observations. Thirdly, future studies should broaden the range of pollutants analyzed by including particulate matter (PM_{2.5}, PM₁₀), ozone, and other hazardous air contaminants to enable a more comprehensive assessment of air quality and associated health risks. Fourthly, research should assess the real-world impact of policy interventions and technological upgrades by systematically evaluating their effectiveness in reducing emissions over time. Future research should therefore prioritize the development of integrated assessment frameworks that combine environmental monitoring with health impact analysis and policy evaluation to support evidence-based urban planning and air quality management strategies. Finally, leveraging advanced analytics such as machine learning and sophisticated statistical modelling, can improve source attribution and enhance the predictive capacity for air quality trends, supporting more targeted and proactive management strategies.

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Conflicts of interests

The Author(s) declare(s) that there is no conflict of interest.

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