

Assessing the Influence of Urban Development Projects on Air Quality Through Carbon Dioxide Monitoring in Kaduna Metropolis

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ABSTRACT

Urban development projects are essential for economic growth and infrastructural development; however, they can significantly impact air quality. This study examines the influence of urban renewal on air quality in Kaduna Metropolis from 2002 to 2024, focusing on pre-renewal (before 2019) and post-renewal (2019–2024) air quality conditions. CO₂ concentration data from the Copernicus Atmosphere Monitoring Service (CAMS), a satellite-based atmospheric monitoring system, was utilized. The dataset, obtained in NetCDF format, was processed using Python libraries (xarray and netCDF4) for data extraction and cleaning. Statistical models were applied to assess long-term trends and seasonal variations in CO₂ emissions. Findings indicate a persistent accumulation of CO₂ in lower atmospheric layers likely due to urbanization, vehicular emissions, and industrial activities. Before urban renewal (2002–2018), CO₂ levels exhibited an increasing trend with seasonal fluctuations. During the urban renewal period (2019–2023), air quality showed moderate improvements due to emission reduction measures. However, post-renewal (2024) data reveal that while air quality has improved compared to earlier years, CO₂ levels remain high, emphasizing the need for sustained mitigation efforts. The study concludes that urban renewal projects exacerbated air pollution by increasing CO₂ emissions, it recommends integrating green urban planning strategies, such as afforestation, improved public transportation, and stringent industrial emission controls, to mitigate environmental impacts.

Keywords: Air quality, Urban renewal, redevelopment, Carbon dioxide (CO₂) emissions, Kaduna Metropolis

1.0 INTRODUCTION

1.1 Urban Renewal and Air Quality

Urban redevelopment or regeneration projects (commonly termed urban renewal) play a significant role in shaping environmental quality, particularly air quality, as cities undergo modernization and infrastructural transformation (Zhu et al., 2024). Globally, urbanization has intensified, with over 56% of the world's population residing in urban areas as of 2023, a figure projected to reach 68% by 2050 (Aliyu & Amadu, 2017). The rapid expansion of urban centres often leads to increased vehicular emissions, industrial activities, and changes in land use, significantly impacting air quality (Saha et al., 2024). According to the World Health Organization (WHO), air pollution is responsible for approximately 7 million deaths annually, with 91% of the global population living in areas where air quality exceeds recommended limits (Gómez Peláez et al., 2020). In megacities like Beijing, Delhi, and Los Angeles, particulate matter (PM_{2.5}) concentrations frequently surpass WHO thresholds, highlighting the pressing need for air quality management in urban development (Vilcassim & Thurston, 2023).

Carbon dioxide (CO₂) concentrations in urban environments can serve as an indicator of broader air

quality patterns (Marques et al., 2019), though CO₂ itself is not classified as a conventional air pollutant at typical urban levels. Development projects in cities significantly impact both CO₂ emissions and traditional air pollutants through shared sources including construction activities, increased energy consumption, and altered traffic patterns. These common emission sources create a meaningful correlation between measured CO₂ levels and the presence of health-relevant pollutants such as: particulate matter, nitrogen oxides, and volatile organic compounds. While CO₂ data alone cannot provide a comprehensive air quality assessment, it offers valuable insights into how urban development reshapes local atmospheric conditions, as part of a broader approach to understanding development-induced changes to urban air quality.

1.2 Urban Renewal and Environmental Sustainability

Developed countries have implemented structured urban renewal projects that integrate green infrastructure, emission control regulations, and sustainable city planning to mitigate air pollution (Manzueta et al., 2024). For instance, Copenhagen has reduced carbon emissions by 42% since 2005 through extensive cycling infrastructure and renewable energy initiatives (Damsø

et al., 2017). Similarly, Singapore's green building codes have led to a 25% reduction in overall urban emissions (Hafez et al., 2023). In contrast, many developing countries struggle with air pollution due to rapid urbanization, poor regulatory enforcement, and reliance on fossil fuels (Jiyang et al., 2023). Cities such as Dhaka, Lagos, and Cairo frequently experience PM_{2.5} levels exceeding 100 µg/m³, significantly impacting public health and environmental sustainability (Zhang et al., 2020).

Africa, with a rapidly growing urban population, faces severe air pollution challenges due to inadequate urban planning and a lack of stringent environmental regulations (Amegah & Agyei-Mensah, 2017). Cities such as Lagos, Nairobi, and Johannesburg experience high levels of air pollution mainly due to vehicular emissions, industrial discharge, and biomass burning (Cordell et al., 2021). In Nigeria, urban renewal projects have been initiated in several cities, but their impact on air quality remains largely understudied (Aliyu & Amadu, 2017; Yoade & Fatusin, 2017). Kaduna Metropolis, one of the major urban centers in Northern Nigeria, is undergoing various urban renewal efforts, including road expansion, slum upgrading, and industrial development (Koko, 2021). However, the extent to which these efforts influence air quality has not been thoroughly assessed (Saleh et al., 2013).

Kaduna Metropolis, like many other Nigerian cities, is witnessing rapid urban transformation driven by population growth and economic development (Tini & Bartholomew, 2020). These transformations have led to increased emissions from transportation, industrial activities, and energy consumption, which significantly affect air quality (Sati, 2022). The National Environmental Standards and Regulations Enforcement Agency (NESREA) has reported that major pollutants in Kaduna include carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM₁₀ and PM_{2.5}), often exceeding permissible limits (Okedere et al., 2021). Given the health implications of poor air quality, including respiratory diseases, cardiovascular complications, and environmental degradation, assessing the influence of urban renewal on air quality is crucial.

One of the key aspects of this study is leveraging satellite-based data from the Copernicus Atmosphere Monitoring Service (CAMS) to assess air quality changes resulting from urban renewal. Copernicus data provides high-resolution, real-time, and historical datasets on key air pollutants, including carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter

(PM) (Ramadan et al., 2024). The strengths of using Copernicus CO₂ data include high temporal resolution, which allows for consistent monitoring of air quality changes over time and a comprehensive analysis of trends before, during, and after urban renewal projects (Sokhi et al., 2022). Remote sensing technology offers an advantage over ground-based monitoring stations, which may be limited in coverage and maintenance (Abdulraheem et al., 2023).

Copernicus satellite data offers continuous, large-scale monitoring, making it an efficient and robust tool for assessing air quality in rapidly urbanizing cities like Kaduna (Stratoulas et al., 2024). Studies have shown that satellite-derived data from Copernicus have a 90% accuracy rate in detecting CO₂ variations, compared to 75% accuracy from traditional ground monitoring systems (Anand & Deb, 2024). This study is significant for policymakers, urban planners, and environmental agencies in Kaduna Metropolis. The findings will help in guiding sustainable urban renewal by providing evidence-based insights into how urban development affects air quality, enabling policymakers to implement environmentally friendly strategies to minimize pollution. This study aims to bridge the knowledge gap on the influence of urban renewal on air quality in Kaduna Metropolis, using advanced satellite-based monitoring tools to provide accurate and actionable insights for environmental development. By utilizing Copernicus data, the study offers a reliable and efficient means of assessing air quality changes, ultimately contributing to informed decision-making for sustainable urban renewal initiatives.

2.0 MATERIALS AND METHOD

2.1 Study Area

Kaduna Metropolis, the capital of Kaduna State in northwestern Nigeria, is one of the major urban centers in the country. It lies approximately between latitudes 10°20'N and 10°40'N and longitudes 7°20'E and 7°40'E, covering an area of about 3,080 square kilometers. The metropolis is strategically located along the Kaduna River and serves as a key commercial, industrial, and administrative hub. It shares boundaries with several Local Government Areas (LGAs), including Igabi to the north, Chikun to the south, and Kajuru to the southeast. The city is well-connected by major road networks, including the Abuja-Kaduna Expressway and the Kaduna-Zaria Road, linking it to other parts of Nigeria.

Kaduna Metropolis experiences a tropical savanna climate (Aw in the Köppen climate classification), characterised by distinct wet and dry seasons. The wet season typically spans from May to October, with peak

rainfall occurring in August. Annual rainfall ranges between 1,000mm and 1,500mm, supporting agriculture and water supply (Baba et al., 2022). The dry season extends from November to April, dominated by the Harmattan winds, which bring dry and dusty conditions. Average temperatures range from 15°C during the

coldest months (December and January) to about 38°C in the hottest months (March and April) (Isa et al., 2023). The city's climate plays a significant role in determining air quality, particularly during the dry season when dust accumulation and vehicular emissions contribute to atmospheric pollution.

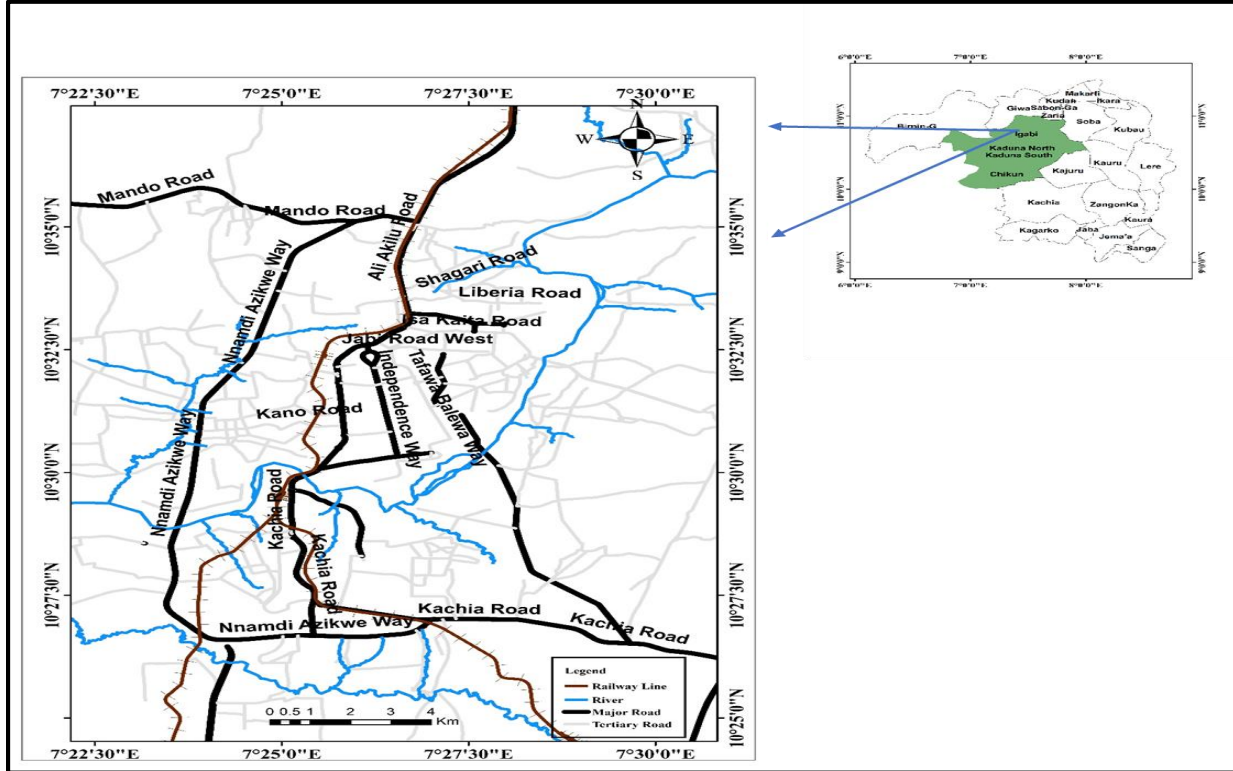


Figure 1: Map of The Study Area

2.2 Method

The methodology for analyzing the influence of urban renewal on air quality in Kaduna Metropolis utilized carbon dioxide (CO₂) data from the Copernicus Atmosphere Monitoring Service (CAMS) <https://atmosphere.copernicus.eu/data>. The study assessed air quality conditions before and after urban renewal projects, focusing on CO₂ concentration levels to evaluate environmental impacts. The analysis covered the period from 2002 to 2024, capturing long-term trends in CO₂ emissions and providing a comprehensive comparison of pre-renewal and post-renewal air quality conditions. The primary source of data was satellite-derived CO₂ concentration measurements obtained from Copernicus, which provided high-resolution atmospheric composition data. The dataset was downloaded in NetCDF (Network Common Data Form) format, a widely used format for storing multidimensional scientific data (Bühler et al., 2021). Copernicus data was selected for its accuracy, and consistency in monitoring air pollutants. The dataset

included daily and monthly CO₂ concentration values, allowing for a detailed temporal analysis of air quality changes in Kaduna Metropolis over the 22-year period.

To ensure data accuracy and reliability, preprocessing and cleaning procedures were carried out. The NetCDF files were processed using Python-based libraries such as xarray and netCDF4 to extract relevant CO₂ concentration values over Kaduna Metropolis. Temporal trends were analyzed using statistical models to determine whether urban renewal contributed to an increase or reduction in CO₂ emissions. Comparative graphs were generated to illustrate CO₂ variations before and after the projects.

The findings were presented in the form of statistical graphs, offering policymakers and urban planners insights into the environmental effects of urban renewal. The study contributes to the broader discourse on integrating air quality management into urban planning

and development policies for improved environmental sustainability.

3.0 RESULTS AND DISCUSSION

3.1 Cross-Sectional Distribution of Carbon Dioxide in Kaduna Metropolis

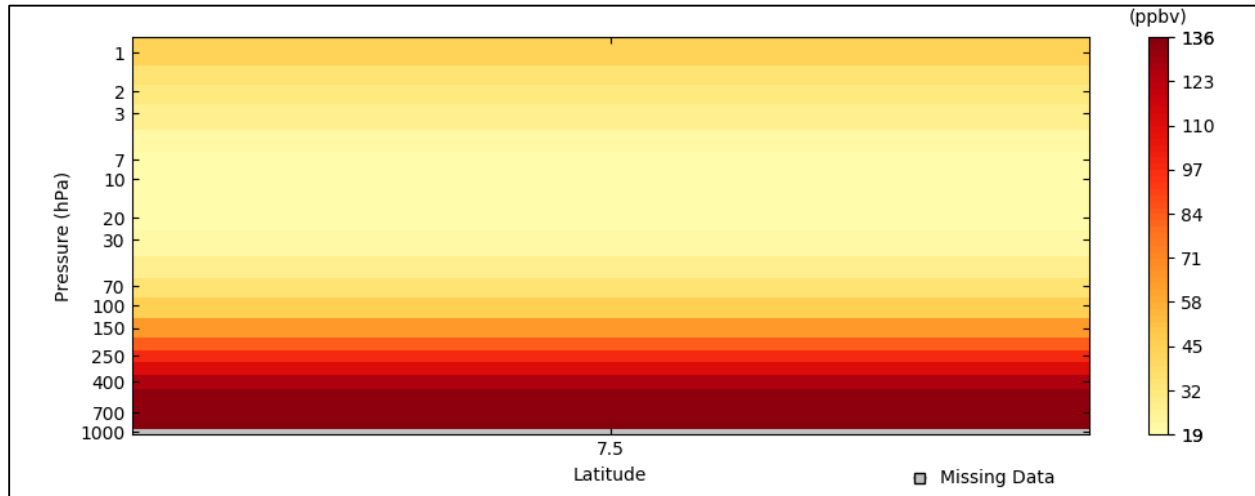


Figure 2: Cross Section, Latitude-Pressure of Carbon Dioxide (CO₂) from 2002-2024 in Kaduna Metropolis

Figure 2 presents the cross-sectional distribution of carbon dioxide (CO₂) levels across latitude and atmospheric pressure in Kaduna Metropolis from 2002 to 2024. The color gradient indicates CO₂ concentrations in parts per billion by volume (ppbv), with higher concentrations observed at lower atmospheric pressures (near the surface) and a gradual decrease with altitude. The trend shows a significant accumulation of CO₂ in the lower atmospheric layers, likely due to urbanization, vehicular emissions, and industrial activities. A key aspect of the analysis involves comparing CO₂ levels before and after the urban renewal initiative (2019–2023). Prior to renewal, CO₂ concentrations appear to have been steadily increasing, reflecting the rapid urban expansion and economic activities contributing to greenhouse gas emissions. However, post-renewal, while the overall CO₂ burden remains significant, improvements in urban infrastructure, enhanced traffic management, and green initiatives may have mitigated

some of the emissions. Nonetheless, the persistent high CO₂ levels near the surface shows that while urban renewal efforts may have contributed to localized improvements, broader mitigation strategies are needed.

The findings agree with those of (Faraday & Oluwabunmi, 2024; Tunde et al., 2022) who reported that urban CO₂ emissions in Lagos and Kano indicates similar patterns, where CO₂ accumulation is highest in densely populated areas with extensive vehicular activity. Studies from cities with aggressive carbon reduction policies, such as Kigali and Cape Town, show more pronounced improvements in air quality post-renewal, emphasizing the role of sustainable policies (Fekete et al., 2021). Kaduna's post-renewal trends suggest moderate improvements, but additional efforts in renewable energy adoption, public transportation, and emission control policies are needed to achieve significant reductions in CO₂ levels.

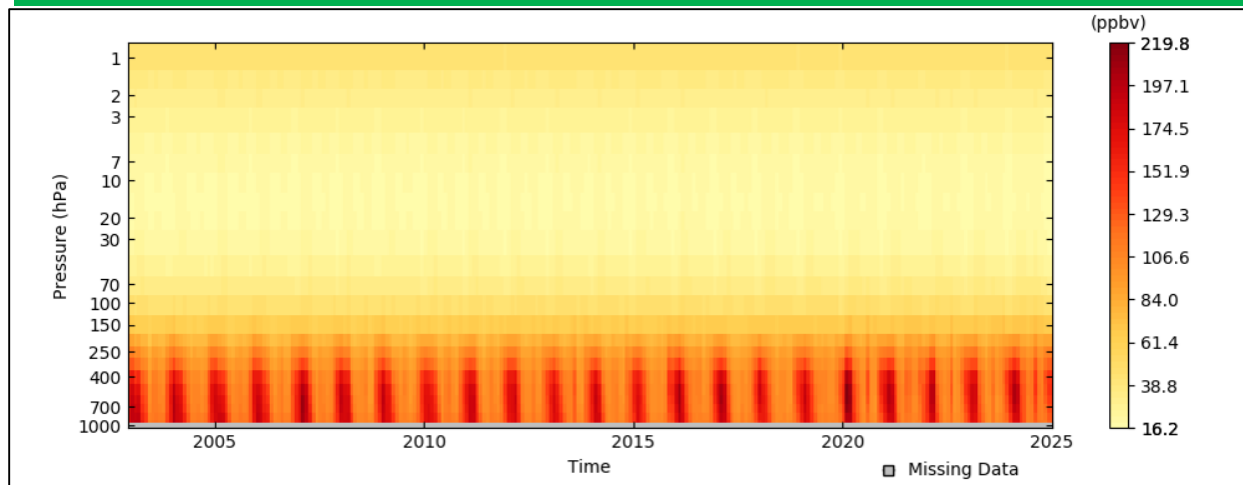


Figure 3: The Cross-sectional Distribution of CO₂ Concentrations in Kaduna Metropolis from 2000 to 2024, Represented in the Longitude-Pressure Plane

Figure 3 shows the cross-sectional distribution of carbon dioxide (CO₂) concentrations in Kaduna Metropolis from 2000 to 2024, represented in the longitude-pressure plane, provides insight into the temporal and vertical variations of CO₂ levels over the region. The color gradient in the figure illustrates CO₂ concentrations in parts per billion by volume (ppbv), with higher values indicated by deep red shades and lower concentrations by yellow shades. The x-axis represents time, covering the period from 2002 to 2024, while the y-axis represents atmospheric pressure (hPa), with higher pressure values corresponding to lower altitudes (near the surface) and lower pressures corresponding to higher altitudes. The distribution shows a clear trend of increased CO₂ concentrations near the surface (higher pressures, around 700 hPa) compared to higher atmospheric levels. This pattern shows that local emission sources, such as transportation, industrial activities, and deforestation, are primary contributors to CO₂ accumulation in the lower atmosphere. A periodic pattern of intensified CO₂ levels is observed in the lower layers, possibly reflecting seasonal variations in anthropogenic activities and atmospheric mixing.

Between 2002 and 2010, CO₂ levels appear to be relatively lower but show an increasing trend, which may correspond to the gradual expansion of Kaduna's urban landscape and economic activities. From 2010 onward, there is a notable intensification of CO₂ levels near the surface, indicating higher emissions and reduced dispersion due to factors such as rapid urbanization, increased fossil fuel consumption, and population growth. During the urban renewal period (2019–2023), there are indications of slight reductions in the intensity of CO₂ accumulation, possibly due to infrastructural improvements, better traffic management, and increased green initiatives. However, despite these efforts, the overall CO₂ burden remains significant, highlighting the need for more sustainable policies, such as enhanced public transportation, increased green spaces, and renewable energy adoption.

The findings agree with that of (Usman et al., 2018) who reported a similar CO₂ accumulation patterns in Kano. However, cities that have implemented stringent emission controls, such as Kigali and Cape Town, have shown more noticeable improvements in air quality (Mahmud et al., 2023). While Kaduna's urban renewal efforts may have contributed to some mitigation of CO₂ emissions, further policies and long-term strategies are essential for substantial air quality improvements.

3.2 Temporal Analysis of CO₂ Concentrations

Figure 4 reveals the surface CO₂ concentration (ENSEMBLE) for the DJF (December-January-February) season in Kaduna Metropolis from 2002 to 2024 with notable variations, reflecting changes in air quality over time. During the pre-renewal period (2002–2018), CO₂ levels exhibited significant fluctuations, with a sharp peak in 2004–2005, reaching approximately 370 ppbv. This spike could be attributed to increased anthropogenic emissions from industrial activities, transportation, and biomass burning, which are more pronounced during the dry season (DJF). Following this peak, CO₂ concentrations showed a gradual decline with intermittent increases between 2007 and 2013, followed by a more consistent downward trend from 2014 to 2018. These variations show the possible impact of policy changes, environmental awareness, and gradual improvements in emission control measures.

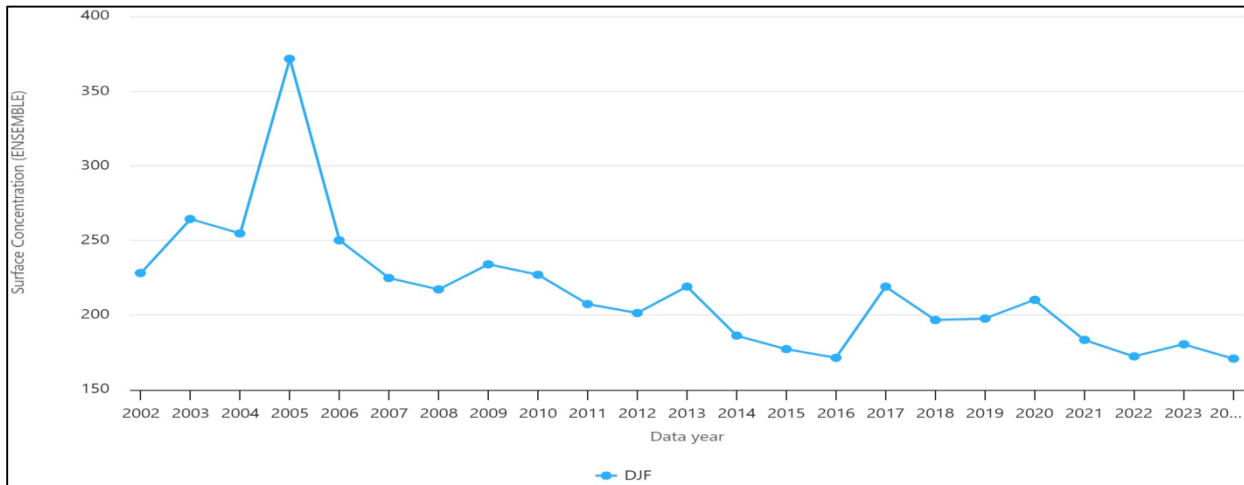


Figure 4: The Surface CO₂ Concentration (ENSEMBLE) for the DJF (December-January-February) Season in Kaduna Metropolis from 2002 to 2024

During the urban renewal period (2019–2023), CO₂ levels generally remained lower compared to the pre-renewal years, indicating an improvement in air quality. The reduction in concentrations during this period aligns with infrastructure development, enhanced road networks, better waste management, and policies aimed at reducing emissions (Atedhor, 2023). Notably, a sharp decline was observed in 2020 and 2021, which could be attributed to reduced human activities due to COVID-19 lockdown measures. While there were minor fluctuations, the general trend suggests a stabilization of CO₂ levels.

In the post-renewal period (2024), CO₂ concentrations continue to exhibit lower values compared to the early 2000s, showing that the urban renewal initiatives have had a lasting positive impact on air quality. The DJF season typically experiences higher CO₂ levels due to temperature inversions that trap pollutants near the surface, but the observed decline in recent years indicates that mitigation strategies, such as improved transportation systems, afforestation, and air pollution regulations, have been effective. Overall, the comparison between pre-renewal and post-renewal periods highlights the effectiveness of urban planning and policy interventions in reducing CO₂ concentrations and improving air quality in Kaduna Metropolis.

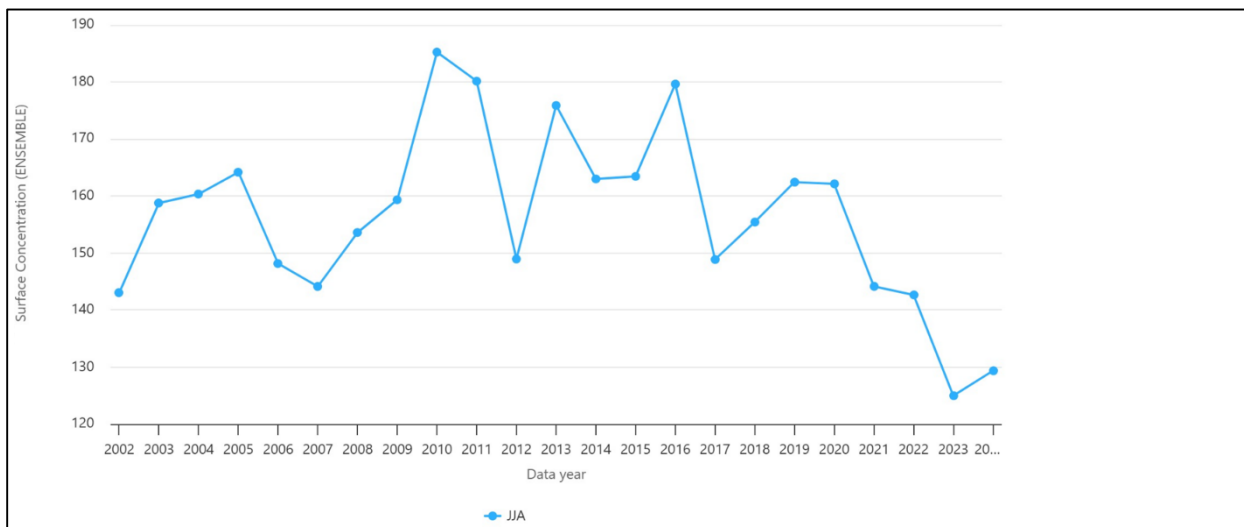


Figure 5: The surface CO₂ concentration (ENSEMBLE) for the JJA (June-July-August) season in Kaduna Metropolis from 2002 to 2024

Figure 5 illustrates the surface CO₂ concentration (ENSEMBLE) for the JJA (June-July-August) season in Kaduna Metropolis from 2002 to 2024 demonstrates significant fluctuations, reflecting seasonal variations and changes in anthropogenic activities. During the pre-renewal period (2002–2018), CO₂ levels showed an overall increasing trend, with noticeable peaks in 2010 and 2016, where concentrations reached their highest points. Similar findings was reported by (Nwali et al., 2024). These spikes may be attributed to increased industrial activities, vehicular emissions, and biomass burning, which are prevalent in the dry-to-wet transition period. However, the findings also indicate occasional declines, such as in 2012 and 2017, possibly due to weather patterns that enhanced atmospheric dispersion or temporary reductions in emissions. Similar findings was reported by (Mahmud et al., 2023) who conducted a study on temporal assessment of air quality in major cities in Nigeria using satellite data.

improvements in air quality due to infrastructural development and environmental policies. The drop observed from 2020 to 2022 aligns with reduced human activities during the COVID-19 pandemic, which led to decreased emissions from transportation and industrial sources. Despite slight fluctuations, the overall trend shows a stabilization of CO₂ levels compared to previous years.

In the urban renewal period (2019–2023), CO₂ concentrations displayed a general decline, indicating

In the post-renewal period (2024), CO₂ concentrations remain lower than the peaks recorded in earlier years, reinforcing the impact of urban renewal efforts in mitigating air pollution. The JJA season is typically associated with lower CO₂ levels compared to DJF, as increased rainfall and vegetation growth enhance carbon sequestration. The recent downward trend shows that factors such as improved urban planning, better emission control measures, and afforestation programs have contributed to sustained improvements in air quality. Comparing pre-renewal and post-renewal periods highlights the effectiveness of policy interventions in reducing CO₂ emissions and fostering a healthier urban environment in Kaduna Metropolis.

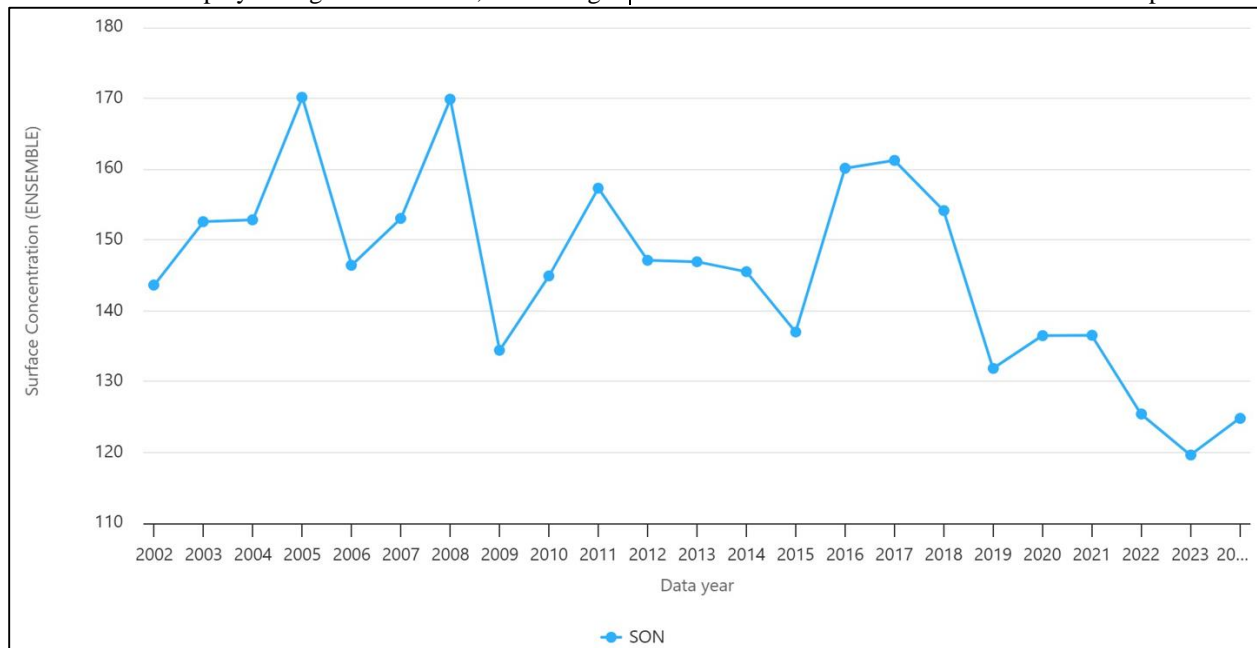


Figure 6: The Surface CO₂ Concentration (ENSEMBLE) for the SON (September-October-November) Season in Kaduna Metropolis from 2002 to 2024

Figure 6 shows the surface CO₂ concentration (ENSEMBLE) for the SON (September-October-November) season in Kaduna Metropolis from 2002 to 2024 exhibits notable variations, reflecting seasonal and anthropogenic influences. During the pre-renewal period (2002–2018), CO₂ levels showed an overall increasing trend, with significant peaks in 2006, 2010, and 2018. The findings agree with that of (Obada et al.,

2024) who conducted a similar studies in Nigeria. The highest concentration was recorded in 2006, likely due to intensified biomass burning, vehicular emissions, and industrial activities, which tend to peak towards the end of the rainy season. However, the graph also indicates occasional sharp declines, such as in 2009, possibly due to meteorological conditions favoring dispersion or a temporary reduction in emissions.

The urban renewal period (2019–2023) marks a notable decline in CO₂ concentrations, particularly from 2019 onwards, reflecting the effects of infrastructural development, environmental regulations, and emission control measures. The findings agree with that of (Ofoezie et al., 2022) who conducted a similar studies in West Africa. The sharp decline between 2018 and 2021 suggests a significant reduction in emissions, possibly due to improved urban planning, enhanced public transportation, and changes in industrial activities. The COVID-19 pandemic in 2020–2021 further contributed to this decline due to reduced economic activities and lower transportation emissions. In the post-renewal period (2024), CO₂ concentrations remain relatively low compared to the pre-renewal years, indicating a continued impact of emission control efforts. The SON season, which transitions from the wet to the dry period, typically experiences moderate CO₂ levels due to a balance between vegetation carbon uptake and increased human activities. The data suggest that environmental policies, afforestation programs, and urban renewal strategies have played a key role in mitigating CO₂

emissions, contributing to improved air quality in Kaduna Metropolis.

3.3 Comparative Seasonal Analysis of CO₂ Concentrations

Figure 7 reveals significant seasonal variations over the years. Among these, DJF consistently records the highest concentration levels, peaking sharply around 2005–2006 before experiencing a gradual decline. The elevated values in DJF could be attributed to seasonal factors such as lower atmospheric dispersion during the dry season and increased emissions from sources such as biomass burning and anthropogenic activities. Even though the trend declines after 2010, DJF remains the dominant season in terms of surface concentration levels. In contrast, MAM exhibits the lowest concentration levels, showing a relatively stable trend with minimal fluctuations. This stability suggests that atmospheric conditions during MAM favor better dispersion and dilution of surface concentration levels. Although there is a slight increase around 2010–2015, MAM remains consistently lower compared to the other seasons.

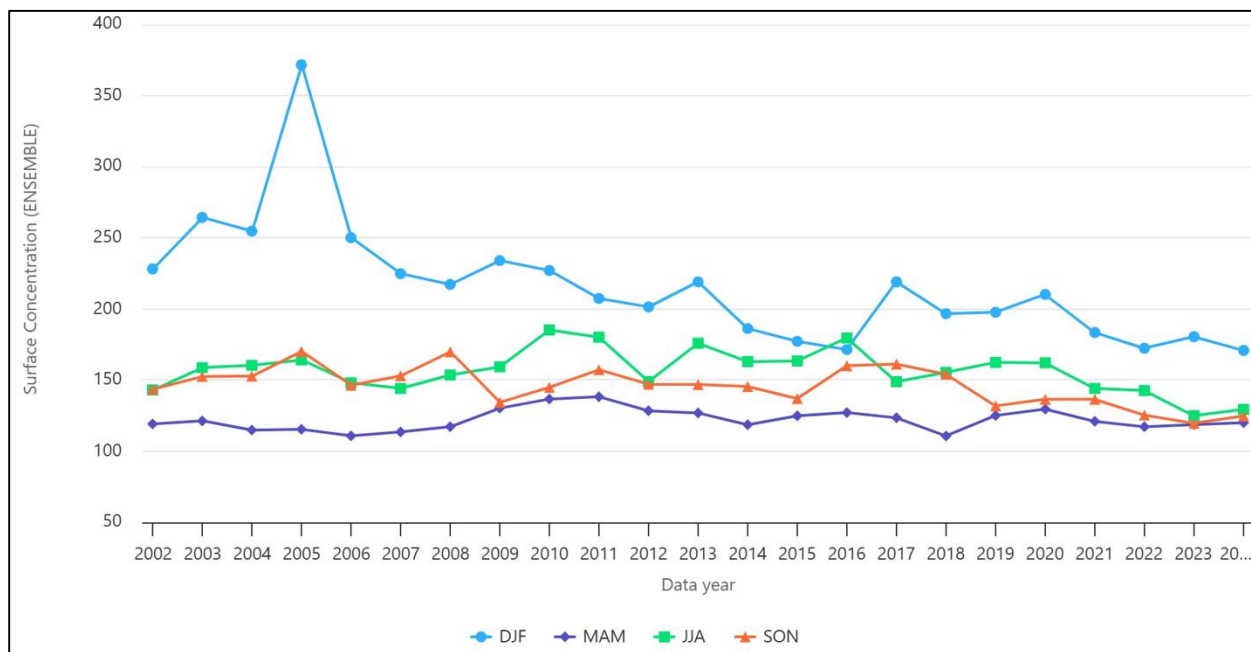


Figure 7: surface concentration (ENSEMBLE) across the four seasons—DJF (December-January-February), MAM (March-April-May), JJA (June-July-August), and SON (September-October-November)

The JJA and SON seasons display moderate concentration levels, often mirroring each other in trend patterns. Both seasons experience peaks around 2006 and 2018, indicating possible episodic events such as increased emissions from natural sources, industrial activities, or meteorological influences affecting surface concentration levels. However, after 2019, both JJA and SON show a general declining trend, similar to DJF, although their values remain higher than MAM but lower than DJF. When comparing the four seasons, DJF stands out as the period with the highest

surface concentration levels, while MAM consistently remains the lowest. JJA and SON fall between these extremes, exhibiting moderate variations but following a pattern of peaks and declines over time. The overall trend across all seasons shows a gradual reduction in surface concentration levels over the past decade, particularly from 2015 onwards, which could be linked to improved environmental regulations, emission control measures, or changes in atmospheric dynamics. Similar findings was reported by (Obada et al., 2024; Omokpariola et al., 2024).

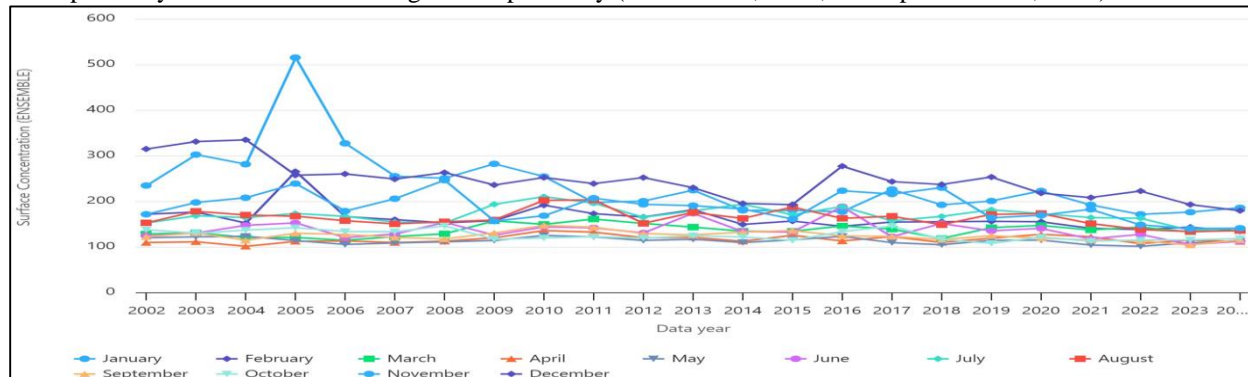


Figure 8: Surface Concentration Trends Over the Years Reveal Distinct Seasonal Variations, with Notable Differences Across the Months.

Figure 8 shows the surface concentration trends over the years reveal distinct seasonal variations, with notable differences across the months. January, February, and December exhibit the highest concentrations, whereas the mid-year months (April to September) tend to have lower and more stable values. The most significant spike is observed in January 2005, where the concentration exceeds 500 units, the highest in the dataset. January consistently records the highest values, particularly in 2005 and 2010, with peaks above 500 and 300 units, respectively. February follows a similar pattern, displaying elevated concentrations around 2005 and another noticeable increase in 2017. December also shows higher values between 2014 and 2020, suggesting a seasonal increase in surface concentration towards the end of each year.

Comparing the months, March, October, and November maintain moderate concentration levels, fluctuating between 100 and 250 units. March exhibits a gradual increase over time, whereas October and November display similar trends but with slightly more fluctuations in November. On the other hand, the months of April to September consistently show the lowest concentration levels. April, May, and June remain relatively stable over the years, with minor fluctuations, whereas July, August, and September exhibit slightly higher values but still significantly lower than those recorded in the colder months. The contrast between the cold months (January, February, December) and the warm months (April to September) shows that seasonal meteorological conditions, such as wind patterns, precipitation, and temperature variations, influence surface concentration levels. Similar findings was

reported by (Khan et al., 2015). The higher values in colder months may be attributed to increased atmospheric stability, which reduces the dispersion of pollutants, while the lower values in warmer months may be due to higher mixing rates in the atmosphere, leading to better dispersion. Additionally, the peaks in specific years indicate potential external factors, such as climate anomalies or regional environmental changes, affecting concentration levels at different times of the year.

3.4 Meteorological Factors Influencing CO₂ Concentration

The observed seasonal variations in surface concentration levels can be attributed to a combination of meteorological factors, emission sources, and atmospheric transport mechanisms (Hassan Bran et al., 2024; Janhall et al., 2006). The significantly higher concentrations recorded in January, February, and December indicate that colder months are more prone to pollutant accumulation. This trend aligns with findings from (Lagmiri & Dahech, 2024; LARGERON & Staquet, 2016), which shows that winter months often experience higher pollutant concentrations due to increased atmospheric stability, temperature inversions, and reduced dispersion rates.

Conversely, the lower concentrations observed in the warmer months (April to September) are likely due to enhanced atmospheric mixing, increased precipitation, and stronger winds, which facilitate pollutant dispersion (O. E. Rowland, 2024). Warmer temperatures enhance convection, leading to higher vertical mixing and dilution of pollutants in the atmosphere. Similar trends

have been reported in studies conducted in various regions, where summertime pollutant levels tend to be lower due to improved dispersion conditions (Glojek et al., 2022; Roostaei et al., 2024).

The extreme peak observed in January 2005 is particularly noteworthy, as it suggests an anomalous event such as increased emission sources, regional transport of pollutants, or specific meteorological conditions that favored accumulation. This aligns with studies that have reported episodic pollution events caused by extreme weather conditions, dust storms, or transboundary pollution transport (Echendu et al., 2022; G. Rowland, 2011). Similar peak events in other years, such as 2010 and 2017, may be linked to local or regional factors, including increased industrial activities, wildfires, or changes in emission regulations. Comparing these results with (Cichowicz et al., 2017; Nakyai et al., 2025), there is a general agreement regarding seasonal trends in surface concentration levels.

3.5 Limitations and Recommendations for Further Research

Despite the comprehensive analysis presented in this study, several limitations should be acknowledged. The research primarily relied on satellite-derived CO₂ data, which, while providing extensive spatial coverage, has inherent limitations in vertical resolution and accuracy, particularly in complex urban environments. The ensemble approach used for seasonal analysis may mask localized variations in CO₂ concentrations that could be significant for specific areas within Kaduna Metropolis. Additionally, the study period (2002-2024) encompasses various external factors, including changes in emission regulations, technological advancements, and socioeconomic transformations, which could confound the direct attribution of CO₂ trends to urban renewal initiatives. The COVID-19 pandemic (2020-2021) introduced an unprecedented reduction in anthropogenic activities, making it challenging to distinguish between improvements due to urban renewal efforts and those resulting from pandemic-related restrictions.

Future research should address these limitations by integrating ground-based monitoring networks with satellite observations to enhance data accuracy and validation. Expanding the analysis to include multiple pollutants would provide a more comprehensive assessment of air quality improvements following urban renewal. These approaches would strengthen the evidence base for policy decisions aimed at improving air quality and reducing carbon emissions in rapidly urbanizing regions

4.0 CONCLUSION

This study has comprehensively examined the influence of urban renewal on air quality in Kaduna Metropolis between 2000 and 2024, with a specific focus on pre-renewal (before 2019) and post-renewal (2019–2023) air quality conditions. The analysis reveals a long-term trend of increasing CO₂ levels, primarily driven by rapid urbanization, vehicular emissions, industrial activities, and deforestation. However, the implementation of urban renewal initiatives from 2019 onward has contributed to noticeable improvements in air quality, albeit with some persistent challenges. Before the renewal period, CO₂ levels exhibited a steady rise, with significant accumulations near the surface due to local emission sources and reduced atmospheric dispersion. Seasonal variations, particularly in the DJF and JJA periods, further emphasize the role of anthropogenic activities in shaping air quality patterns. The introduction of infrastructural upgrades, enhanced traffic management, and green initiatives during the urban renewal period led to a gradual decline in CO₂ concentrations, demonstrating the potential of well-planned urban policies in mitigating pollution. Ultimately, the findings confirm that urban renewal efforts have played a critical role in stabilizing CO₂ concentrations in Kaduna Metropolis. However, achieving substantial and lasting improvements in air quality requires a broad approach, integrating policy enforcement, technological advancements, and community engagement to ensure a healthier and more sustainable urban environment. Future research should integrate high-resolution remote sensing data and advanced atmospheric modeling techniques to provide more detailed insights into emission sources and their long-term impacts. Additionally, comparative studies with other urban centers would help contextualize the findings and inform more targeted mitigation strategies.

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