SPATIOTEMPORAL PATTERNS OF AIR QUALITY IN RELATION TO URBAN DENSITY IN RAJSHAHI CITY

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ABSTRACT

Urban densification will most likely be the key driver of deteriorated air quality with severe effects on environmental sustainability and public health of fast-growing cities. Rajshahi City of Bangladesh has been experiencing rapid urbanization in the last decades, particularly in central and south wards, where high-density development and traffic flow are the homogeneities. This study analyzes the impact of spatiotemporal urban expansion in urban density from 2018 to 2024 on the dispersion and concentration of the large air pollutants. The built-up growth density was quantified using Landsat-based parameters like Normalized Difference Built-up Index (NDBI) and Normalized Burn Ratio 2 (NBR2). Air quality data were obtained from Sentinel-5P (TROPOMI) that provided estimates of the most significant pollutants such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), methane (CH_4), and ozone (O_3). Geographically Weighted Regression (GWR) and transect profile analysis were applied to map the spatially varying density–pollution interactions and identify hotspots of significance. Results indicate that most polluted were urban core high-density wards, with NO_2 and CO most closely associated with traffic and congested road networks. SO_2 and CH_4 concentrations were more pronounced close to industrial clusters and inner cities with intense energy consumption. Additionally, high-density wards with inadequate air circulation had greater ozone accumulation, enhancing respiratory health risks. In comparison, lower density and greater vegetation cover peripheral zones had comparatively cleaner air, of significance to the role of green space in pollutant dispersion and atmospheric equilibrium. Results show not only that densification raises the urban heat island but also accelerates the buildup of toxic contaminants, generating microclimatic stress and loads to health. The study concludes that integrated strategies such as stricter emission controls, financing mass transit, regulating zoning, and preserving urban green belts, are central to addressing these problems. By bridging density growth with air quality dynamics, this study provides actionable evidence for climate-responsive planning as well as environmental governance for Rajshahi and yields a transferable model for other medium-scale South Asian cities undergoing rapid densification.

Keywords: *Urban Density, Air Quality, Geographically Weighted Regression*

1. INTRODUCTION

Air quality signifies the degree to which air is free from impurities in a certain place and it shows the level of different pollutants and toxins that might be present in the atmosphere, which could come from both nature and human activities (Sium et al., 2024). Its determination depends greatly on what and how much of PM2.5, PM10, ground-level O_3, NO_2, CO, SO_2, and volatile organic compounds are present and in what concentration. The state of air quality affects people's lives considerably, the health of the public, and even climate change (Sium et al., 2024). Air pollution has not only become a major environmental problem in Asia but also worldwide (Carslaw & Ropkins, 2012), with urbanization and land-use changes making it worse, especially in overpopulated areas (Sium et al., 2024). Growing cities very often enlarge UHI and climatic risk zones, so that the local microclimates are changed and the human health, environmental comfort, and the liveability of urban areas are all negatively affected (Esfandeh et al., 2021). The increment of air pollution is coming along with very serious threats to environmental quality, public health, and urban sustainability, not to mention the social well-being.

In this case, the main research aim is to study the urban density-related spatiotemporal patterns of air quality in Rajshahi City by the example of the above-mentioned pollutants NO_2, SO_2, CO, CH_4, and O_3 in the last years. Importing urban density mapping with the data of pollutant concentration, the paper leads to the recognition of the fact that urban growing along with land-use transformations is one of the main factors which the local air quality depends on. This research yields beneficial knowledge for decision-makers, city planners, and ecological managers on how to make strategies for the reduction of pollution, public health improvement, and the overall environmental sustainability and resilience of rapidly urbanizing mid-size cities.

2. METHODOLOGY

2.1 Description of The Study Area

Rajshahi City Corporation (RCC) is the main city of the northwestern part of Bangladesh. Situated in the coordinates 24°20′N to 24°24′N and 88°32′E to 88°40′E, it measures approximately 96.68 km^2 and is a big centre for administration, education, and economy (BBS, 2022). The city is located on an alluvial plain that is only 1.3 m above sea level, which makes the terrain very flat and therefore allows for fast but mainly unplanned urban growth that takes over farmland and green areas with non-permeable surfaces, thus raising the flood threat (Kafy et al., 2020; Marufuzzaman et al., 2021). The hot humid subtropical climate of the city, characterized by excessive heat and little rain, aggravates droughts, heat stresses, and the urban heat island effect (BMD, 2022; Zaki et al., 2019). With a population of 553,288 and a literacy rate of 74.4%, socio-economic disparities and environmental pressure through dense development and inadequate infrastructure in some areas are among the problems Rajshahi faces (BBS, 2022). The city's increasing vulnerability to climatic and urban stresses renders it an important case for investigating environmental resilience and sustainable urban planning in South Asian cities.

2.2 Description of Data

To examine the spatiotemporal dynamics of air quality in the city, this investigation applied multi-source satellite datasets that collected both spectral and atmospheric parameters for air quality indicators. The concentrations of air quality indicators (NO_2, SO_2, CO, CH_4, and O_3) were generated from the Sentinel-5P (TROPOMI) platform for air quality indicators, while urban density indicators (NDBI and NBR2) were created using multi-temporal Landsat imagery (Landsat 5 TM, Landsat 8 OLI/TIRS, and Landsat 9 OLI/TIRS). The administrative boundaries were collected from national GIS portals and global datasets such as USGS and LGED for accurate spatial reference.

2.3 Calculation of Urban Density

The measurement of urban density in Rajshahi City was carried out by using two Landsat-derived spectral indices, both of which are quite effective in illustrating the size and power of built-up areas. One of the indices being the Normalized Difference Built-up Index (NDBI), this index shows urban surfaces by contrasting SWIR and NIR reflectance (Zha et al., 2003), and the higher the value the denser the built-up areas:

$$NDBI = (SWIR - NIR) / (SWIR + NIR) \quad (1)$$

Next, the Normalized Burn Ratio 2 (NBR2) indirectly indicates surface and vegetation loss as a consequence of urbanization by the following equation:

$$NBR2 = (SWIR1 - SWIR2) / (SWIR1 + SWIR2) \quad (2)$$

The thresholds for both indices were meticulously determined to distinguish built-up areas from soil and vegetation. The indices were used to create urban density maps by finding the mean built-up proportion within a three-by-three pixel window for the years 2004, 2014, and 2024. These maps not only measure urban growth over the two decades but also provide the basis for studying the spatial impacts of urbanization on local climate variables and air quality which in turn help in understanding how densification influences the environmental conditions across the city in a more detailed manner.

2.4 Extraction of Air Quality Parameters

Air quality parameters have been taken out from the Sentinel-5P (TROPOMI) datasets using the Google Earth Engine platform for 2018/2019 and 2024, in accordance with the data availability. The pollutants analyzed were nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), methane (CH_4), and ozone (O_3), which were derived respectively from the NO2_column_number_density, SO2_column_number_density, CO_column_number_density, CH4_column_volume_mixing_ratio_dry_air, and O3_column_number_density bands (Veefkind et al., 2012). These are the total column densities (mol/m^2) or atmospheric mixing ratios (ppb) which are indicative of emissions from the transport, industrial, and combustion sources. All pollutant values were seasonally averaged and standardized to comparable measurement units in order to achieve temporal consistency and reduce meteorological influence. Despite the unavailability of ground truthing data, the pattern of our result is consistent with the previous studies conducted in Bangladesh on Sentinel-5P (TROPOMI) data, supporting the accuracy of satellite observations (Sharmin et al., 2025).

2.5 Assessment of Spatiotemporal Relations

The impact of urbanization on air quality in Rajshahi City, Bangladesh, including the concentration patterns of pollutants due to urban density and land use changes, was the main focus of this research. The spatially varying relationships were examined with the help of Geographically Weighted Regression (GWR) based on the following model:

$$y(u) = \beta 0(u) + \beta 1(u)x1 + \beta 2(u)x2 + \ldots + \beta m(u)xm \quad (3)$$

In this model, y(u) is the air quality parameter measured at location u, $x_1 \ldots x_m$ are the explanatory variables like urban density or vegetation cover, and β(u) are the coefficients specific to that location. The GWR outcomes marked areas where the pollution levels for NO_2, CO, and SO_2 were under the greatest influence of heavily built areas and little or no greenery (Faka et al., 2023). Moreover, the longitudinal profile analysis was performed in conjunction with the study of main urban axes, which (Faridatul, 2017) was to demonstrate the overlapping of spatial gradients of urban growth and destruction with the varying levels of pollutant concentrations throughout the city.

3. RESULT AND DISCUSSIONS

3.1 Mapping of Urban Density

The urban density pattern of Rajshahi City from 2004 to 2024 is presented in Figure 1 along with ward-level analysis. Low-density areas, at a percentage of 44.15%, mainly in the northern and peripheral wards, dominated the city while very high-density zones (24.84%) were concentrated around the urban core, near the river, surrounded by medium and high-density areas (13.39% and 17.61%). The year 2014 witnessed a rapid conversion of very high-density areas from low-density areas, thus, the figure of very high-density areas in Rajshahi City more than doubled, and it reached to 30.43%. Low-density zones were cut down to 24.27%, and high-density areas were three times the number compared to 2004. By 2024, very high-density areas continued to encroach further into areas with a population density of 42.84% covering central and southern wards, while low-density zones diminished down to 12.27%, and high-density zones in other wards increased up to 26.16%. The changes in the urban landscape show the increasing trend of the vibrancy of residential areas with the corresponding decreasing trend of green and less populated areas.

Table 1: Catagories of Urban Density With Their Area

Class	2004 (%)	2014 (%)	2024 (%)
Low	44.15	24.37	12.27
Medium	13.39	20.79	18.74
High	17.61	24.42	26.16
Very High	24.84	30.43	42.84

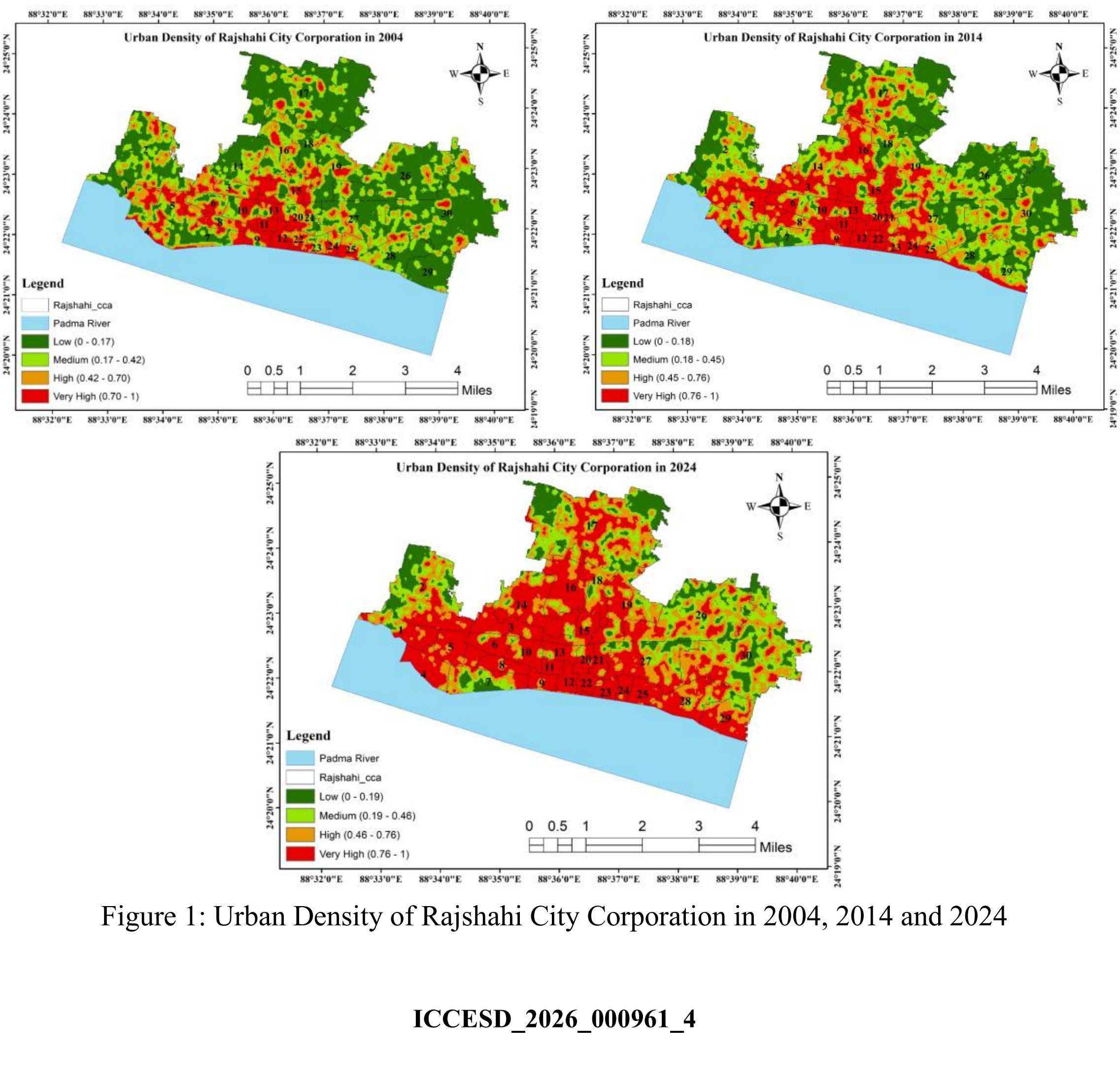

Figure 1: Urban Density of Rajshahi City Corporation in 2004, 2014 and 2024

3.2 Mapping of Air Quality Parameters

3.2.1 Nitrogen Dioxide (NO_2)

The levels of NO_2 in Rajshahi City for the years 2018 and 2024 are illustrated in Figure 2. As for the year 2018, the highest concentrations were located in the eastern and western wards, whereas the peripheral wards had very low levels of NO_2. The situation changed in 2024 when the central and western areas experienced an increase in NO_2, while the peripheral zones still had relatively cleaner air. The overall average NO_2 level showed a slight rise, which was the result of urbanization, more vehicles in use, and industries getting active, thereby indicating the urgency for air quality management.

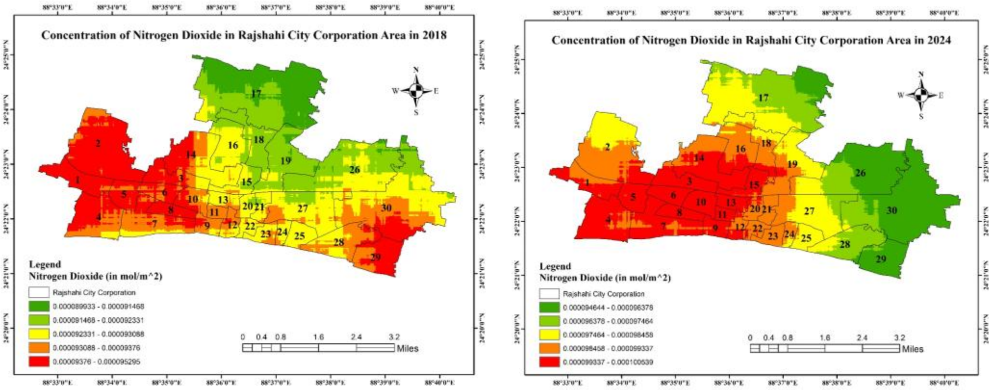

Figure 2: NO_2 of Rajshahi City Corporation in 2018 and 2014

3.2.2 Sulfur Dioxide (SO_2)

Figure 3 presents the levels of SO_2 in Rajshahi City for the years 2019 and 2024. The maximum concentrations of SO_2 were in the central and southeastern wards with the majority of urban population and industrial operations, while the northern wards had lower concentration levels. The central and southern areas showed a further rise in SO_2 by 2024 (5–11), while the northern wards were still keeping the same low levels. The highest and average concentrations reflected an increase that was the result of the deteriorating air quality in urbanized areas, traffics, and industrial estates.

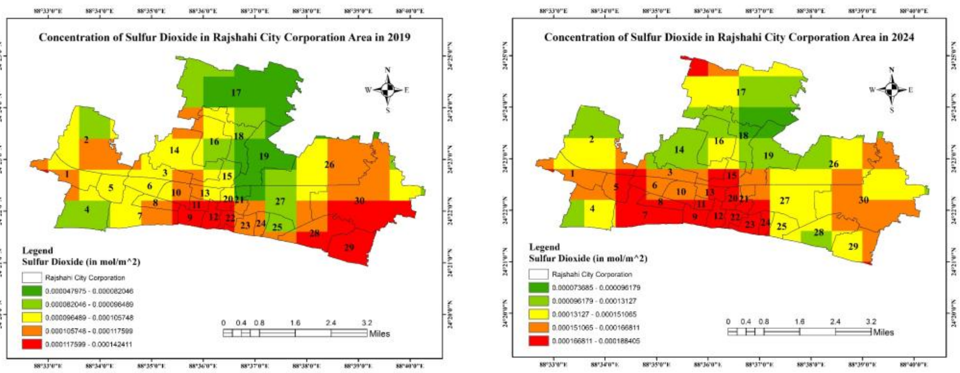

Figure 3: SO_2 of Rajshahi City Corporation in 2019 and 2024

3.2.3 Carbon Monoxide (CO)

Figure 4 depicts the CO pollution levels in Rajshahi City for the years 2018 and 2024. The southern and southwestern wards, where traffic and industry were heavily concentrated, reported the highest levels in 2018. In contrast, northern and remote wards experienced the least amount of pollution. The future scenario for 2024 shows an increase in CO levels in the heart and the south part of the city suggesting that urbanization and transport emissions are the causes, while the north part of the city is relatively clean.

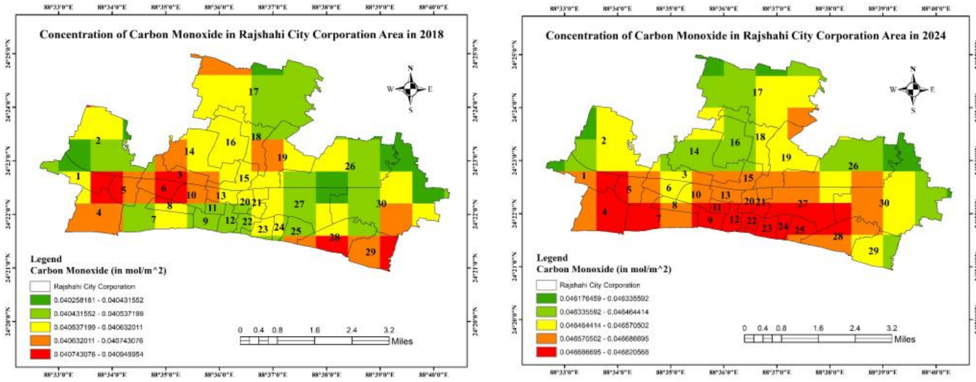

Figure 4: CO of Rajshahi City Corporation in 2018 and 2024

3.2.4 Methane (CH_4)

Figure 5 presents the distribution of CH_4 concentrations in Rajshahi City for the years 2019 and 2024. The year 2019 recorded the highest CH_4 concentrations in the southwest wards, which were characterized by heavy population and industrial activities, whereas the northern wards were less polluted. Methane continued to gain in central and southwestern areas in 2024, meanwhile traffic and industry remained the predominant reason for the increase in these regions.

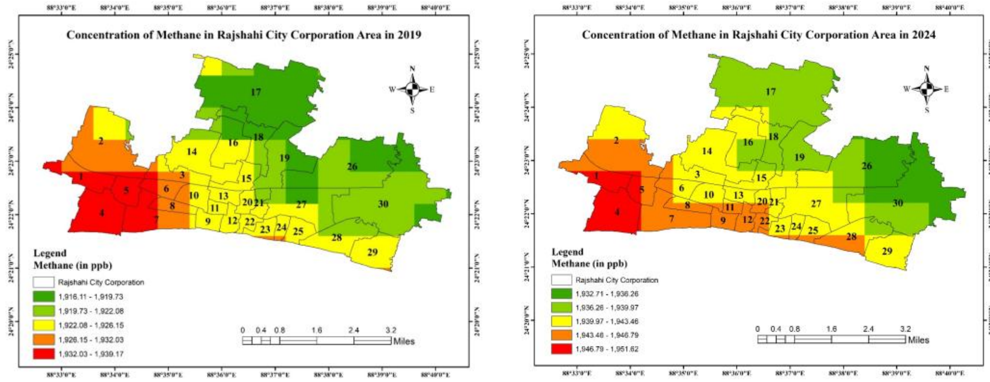

Figure 5: CH_4 of Rajshahi City Corporation in 2019 and 2024

3.2.5 Ozone (O_3)

Figure 6 depicts the presence of CH_4 in Rajshahi City during 2019 and 2024. The highest concentration of methane in 2019 was in the southwestern wards, and northern wards had the lowest concentrations. Over the years, for the year 2024, methane was central and southwestern areas that were due to increased traffic and industry, the northern wards remained comparatively low.

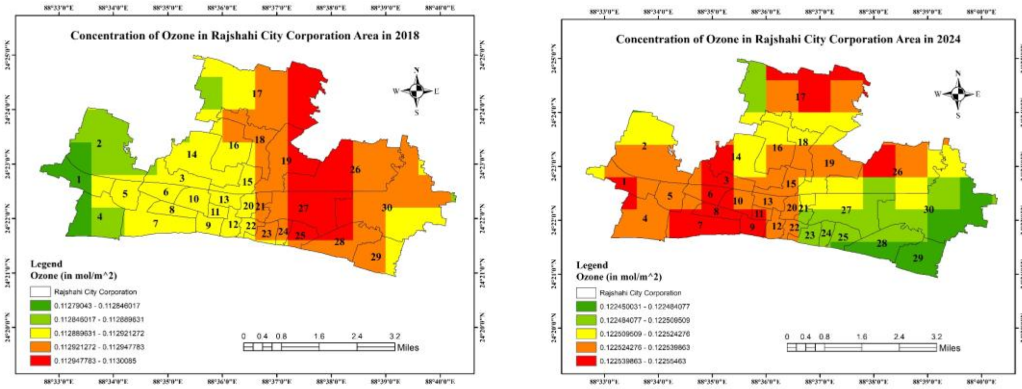

Figure 6: O_3 of Rajshahi City Corporation in 2018 and 2024

3.3 Analysis of Urban Density Impact on Air Pollutants

3.3.1 GWR-Based Urban Density Impact on Nitrogen Dioxide (NO_2)

Figure 7 illustrates the urban density-NO_2 relationship in Rajshahi City for 2018 and 2024. The correlation among the wards 8, 29, and 30 was very high in 2018, while the correlation among the wards 2, 5, 6, 10, 11, 13–16, and 20 was medium, and wards 15, 17–19, and 26 were of low correlation. By the year 2024, correlations were high in wards 4, 10, 11, 13, 15, 25, and 28; medium in 5, 6, 9, 12, 14, 16, and 19; and low in wards 2, 17, 18, 26, 27, 29, and 30.

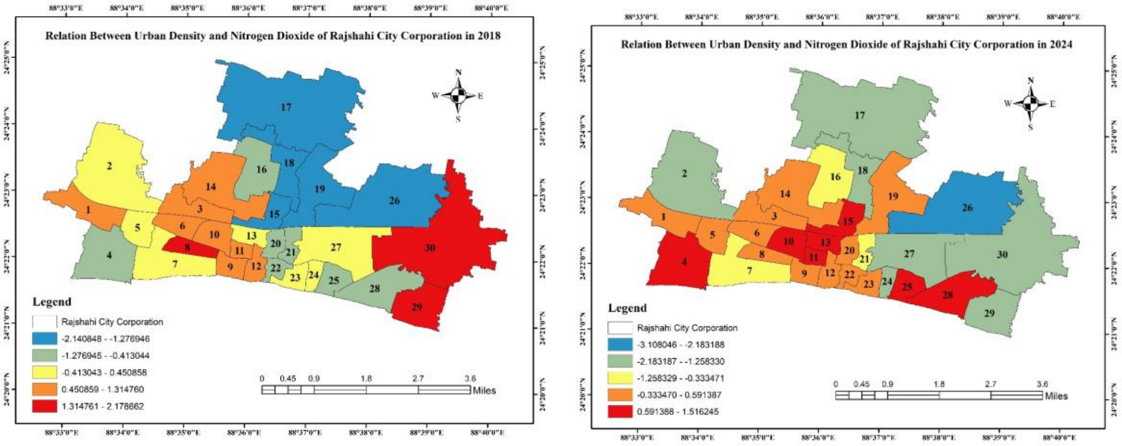

Figure 7: Urban Density Impact on NO_2 in 2018 and 2024

3.3.2 GWR-Based Urban Density Impact on Sulfur Dioxide (SO_2)

Figure 8 illustrates the connection between urban density and SO_2 emission in Rajshahi City for the years 2019 and 2024. In 2019, there were four wards with a high correlation: 9, 11, 12, and 22; wards 1, 5-8, 13-18, and 20 had medium and the least urbanized wards around the city had low correlation. It was in 2024 that there was a high correlation found in wards 4, 7, 9, 11, 12, 13, 15, 20, 22, 23, 29, and 30; medium in wards 1, 3, 5, 6, 8, 10, 11, 12, 14, and 17; and lowest in ward 18.

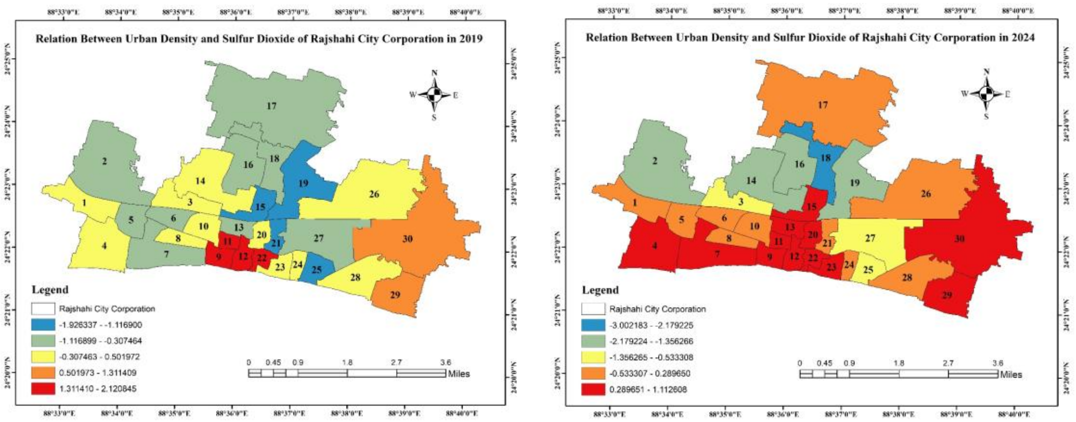

Figure 8: Urban Density Impact on SO_2 in 2019 and 2024

3.3.3 GWR-Based Urban Density Impact on Carbon Monoxide (CO)

Figure 9 reveals how urban density and CH_4 were related in Rajshahi City during 2019 and 2024. High correlation was noted in wards 1, 5, 6, and 7 in 2019 while medium in wards 3–13, 15, and 16 and low in wards 14, 17–19, and 26. In 2024, high correlation was still seen in wards 1, 5, and 7; medium in wards 2, 4, 8-19; and low in wards 6, 13, and 20–30. Higher CH_4 emissions were observed in densely urbanized areas with little or no green space, while the areas with vegetation and less development kept the levels lower.

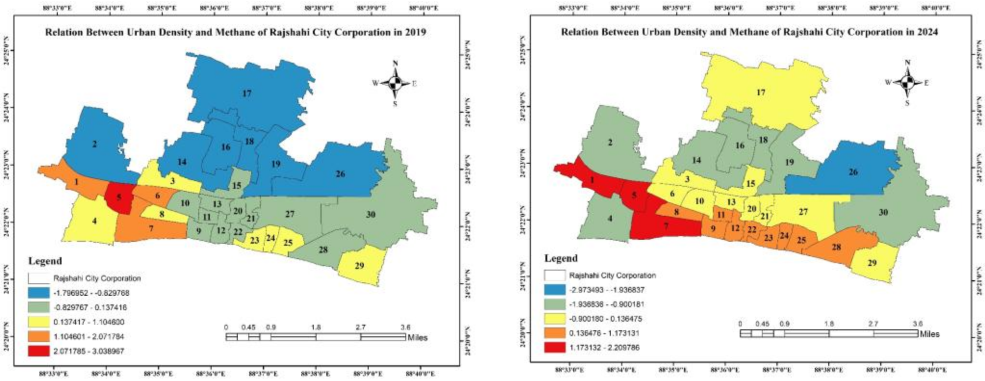

Figure 9: Urban Density Impact on CH_4 in 2019 and 2024

3.3.4 GWR-Based Urban Density Impact on Methane (CH_4)

Figure 10 illustrates urban density and CO relationship in Rajshahi City for the years 2018 and 2024. Wards 3–6 and 10 presented a high correlation in 2018, wards 8, 12, and 15–21 were medium, and wards 1, 2, 7, 9, 11, 22, 25, and 26 were low. High correlation was observed in wards 4, 5, 7, 9, 24, and 25 in 2024; medium in wards 1, 3, 6, 8, 17–19, 27, 28, and 30; and low was found in wards 2, 14, 16, 26, and 29.

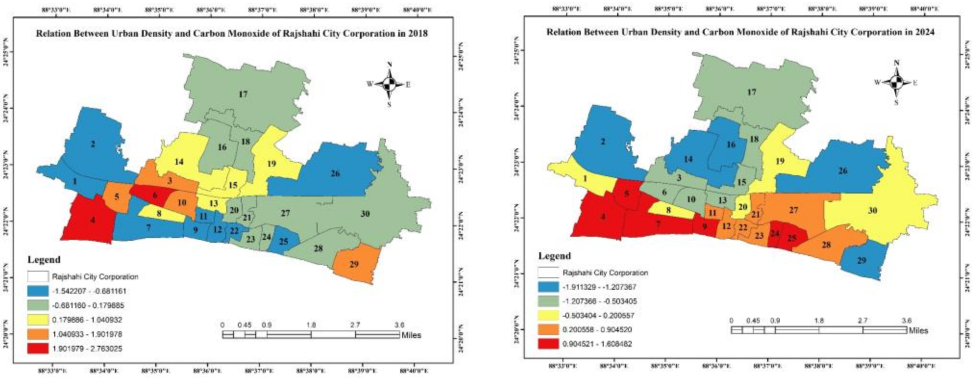

Figure 10: Urban Density Impact on CO in 2018 and 2024

3.3.5 GWR-Based Urban Density Impact on Ozone (O_3)

Figure 11 depicts the urban density-ozone relationship in Rajshahi City for the years 2018 and 2024. The strongest correlation was found in wards 4, 21, and 27 in 2018, while the remaining central wards (1–20) had a moderate one, and wards 29 and 30 were the least correlated. High correlation was found in wards 8, 9, 11, 19, 26, and 28 in 2024, medium in wards 1, 2, 5–7, 14, 23–25, and 29, and low in wards 24, 27, and 30.

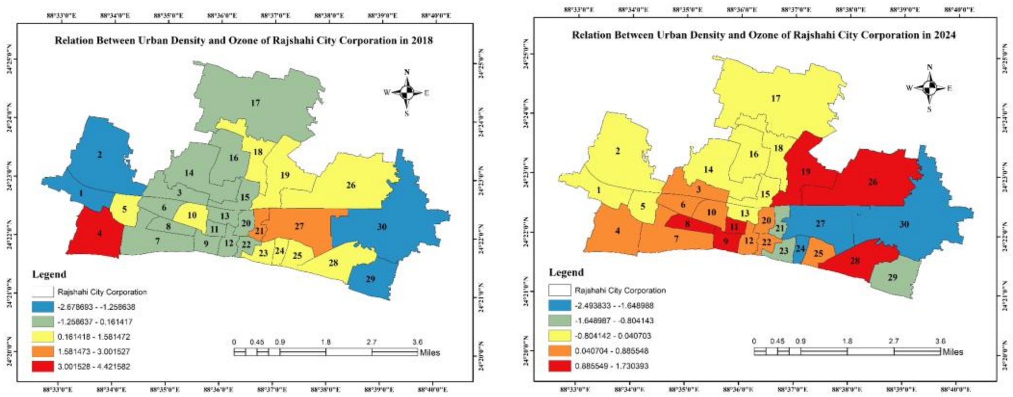

Figure 11: Urban Density Impact on O_3 in 2018 and 2024

3.4 Vertical Assessment of Air Quality Parameters

In the period covering 2018-2024, the concentration of NO_2 in the river and surrounding areas of Rajshahi remained almost stable, owing to low levels of urbanization and pollution sources, but had a slight rise in the city center due to an increase in traffic and industrialization. For SO_2 too, 2019-2024 witnessed stable concentrations in the river and surrounding areas, but had a moderate rise in the city center, owing to stepped-up urbanization. The air in the city center remained polluted, creating health hazards, but the surrounding areas remained clean. As the concentration of gases in mol/m² remained very small, it is represented in Dobson Unit (1 DU = 2.69×10^{20} mol m^{-2}) in the graphs to show the variations over the years.

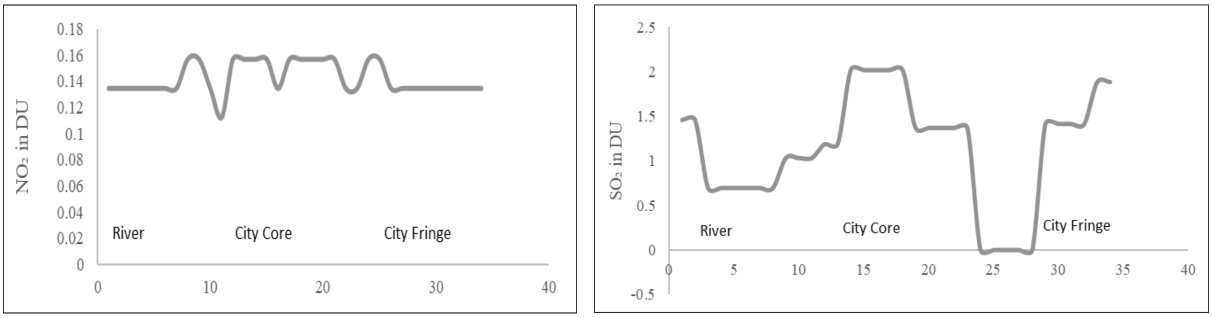

Figure 12: Impacts of NO_2 Changes in 2018-2024 and SO_2 in 2019-2024

From 2019 to 2024, the river zone of Rajshahi exhibited modest variation in CH_4 concentrations, likely due to natural processes or changes in land use of areas adjacent to the river. The city core and city fringe saw increasing CH_4 concentrations as a result of the expanding urban environment, industrial activity, and waste. CO concentrations increased slightly in the river zone from 2018 to 2024, while the city core and fringe saw a decreasing trend. The reductions in CO demonstrate continued efforts to control emissions and manage air quality. O_3 concentrations in the river area increased slightly, but decreased in the city core and fringe, suggesting appropriate pollution control measures and comparatively more seasoned air conditions in less urbanized areas.

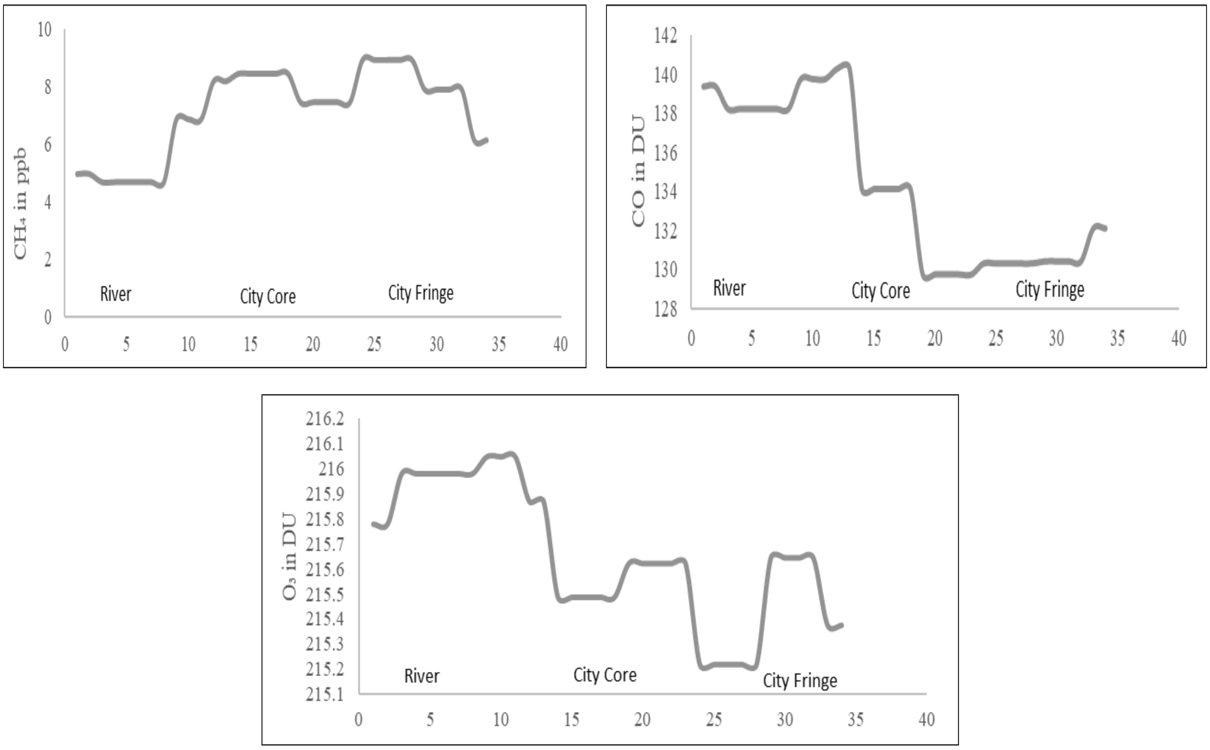

Figure 13: Impacts of CH_4 Changes in 2019-2024, and CO, O_3 Changes in 2018-2024

3.5 Horizontal Assessment of Air Quality Parameters

The periods from 2018 to 2024 were marked by a significant increase in NO_2 levels in the city core mainly because of the rise in vehicular emissions, industrial activities, and quick urbanization, which was a signal of deteriorating air quality along with the health risks. The same pattern was observed for SO_2 levels that were high but showed variations between 2019 and 2024, revealing the continued pollution from vehicles and factories. In general, the city's center scenario regarding air quality has not changed much, making it imperative for the authorities to come up with stricter regulations on emissions and pollution control strategies.

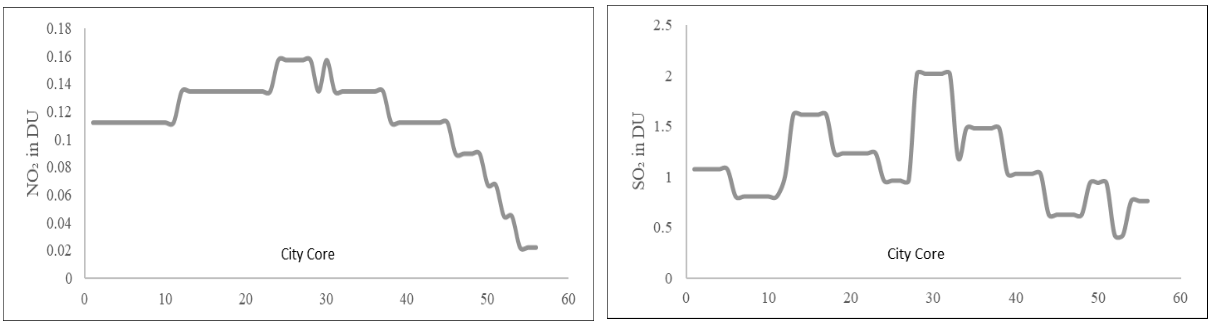

Figure 14: Impacts of NO_2 Changes in 2018-2024 and SO_2 in 2019-2024

In the period of 2019-2024, a significant increase was observed in the CH_4 concentration in the city center, which was mainly the result of industrial operations, poor waste management, and heavy traffic; thus, it was an indicator of the decline of air quality and the worsening of climate impacts. Also, there was a gradual build-up of CO from 2018 to 2024 due to urban sprawl and car emissions; therefore, it was a health hazard. O_3, on the other hand, had a decreasing trend, which served as an indicator that the pollution control measures and emission regulations had positively affected the city's air quality in its central area. In conclusion, all these trends demonstrate the urgency of continuation of efforts to control urban emissions and to lessen their negative impact on the environment and human health.

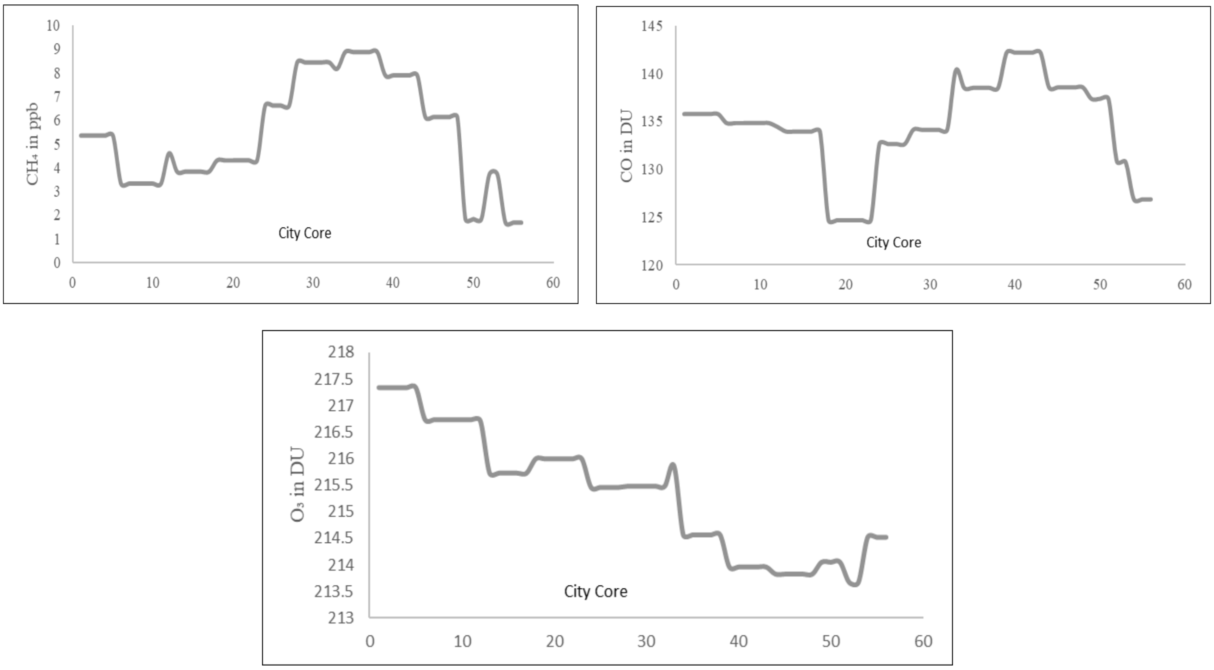

Figure 15: Impacts of CH_4 Changes in 2019-2024, and CO, O_3 Changes in 2018-2024

4. CONCLUSIONS

The urban sprawl in Rajshahi has a major influence on air quality with the core of the city being the most affected area. Here, the limited vegetation plus the emissions from cars, industries, and construction activities have led to the accumulation of pollutants. Air in the outskirts with more plants and less activity is comparatively cleaner as the vegetation acts as a microclimatic buffer, thus, being supportive of better environmental conditions around. The study indicates that there is no time to waste in introducing policy measures that deal with the preservation of green spaces, the establishment of pollution control, and the encouraging of sustainable urban development. The suggested actions will not only help to reduce health issues caused by air pollution, such as asthma and heart problems but also make the city more resilient to environmental stressors. The combination of the effective air quality management and the climate-sensitive urban planning is the key to ensuring the long-term liveability and sustainability in the rapidly urbanizing areas.

Declaration of Use of AI

The use of artificial intelligent systems assisted in linguistic editing, paraphrasing, coding, and facilitating formulation on the understanding of graphical and spatial outcomes. The research process and methodology in this work, including all research designs, handling of information, results, and interpretations, together with conclusions, are exclusively produced and created by the researcher. The research results were not generated, analysed, or contained any scientific outcomes through AI.

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