SPATIOTEMPORAL DYNAMICS OF URBAN HEAT ISLANDS AND ASSOCIATED AIR POLLUTION IN DHAKA: A GIS-BASED ANALYSIS

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ABSTRACT

Rapid urbanization in the Dhaka Metropolitan Area (DMA) has resulted in widespread conversion of natural land into impervious surfaces, which is intensifying both Urban Heat Island (UHI) effects and air pollution. These changes are raising health and environmental risks for residents of Dhaka. This study examines the long-term evolution of UHI and its spatial interactions with major gaseous pollutants to identify the hotspots of compound vulnerability across Dhaka. Multi-temporal Landsat 7 and 8 (2010–2025), Land Surface Temperature (LST) data, and Sentinel-5P (2020–2025) air pollutant products (CO, NO_2, SO_2, O_3) were processed in a GIS framework. UHI maps were generated for both summer and winter seasons and integrated to create a composite UHI intensity map. Pollution rasters were aggregated to compute a composite air pollution exposure map. Both datasets were normalized and spatially correlated to determine the combined heat-pollution risk. Results show that moderate UHI intensity dominates 37% (102.1 km²) of the DMA, followed by high UHI, which covers 72.4 km² of the area, mainly concentrated in Tejgaon, Badda, Motijheel, Dhanmondi, Mirpur, and Jatrabari. Cooler conditions persist in the Uttarkhan, Demra, and Cantonment regions, with very low to low UHI over the DMA's extent. Temporal analysis reveals stronger UHI intensification during winter ($R^2 = 0.70$) than in summer ($R^2 = 0.32$), which indicates growing heat retention in the city's urban core. Pollutant analysis shows CO peaking in 2024, affecting the city (notably Lalbagh and Chak Bazar), while NO_2 and SO_2 depict the highest loadings in industrial and traffic-dominated zones. Overall, UHI exhibits positive correlations with CO, NO_2, and SO_2 in both seasons, whereas O_3 shows a negative relationship, because of the downwind photochemical processes. The combined vulnerability assessment highlights that 31% of the DMA is exposed to high or very high dual-stress levels, placing populations in Biman Bandar, Uttara, Turag, and Badda at greatest environmental risk. This research provides evidence of how Dhaka's rapid urban growth is simultaneously accelerating thermal stress and deteriorating air quality. The findings underscore the necessity of expanding green-blue infrastructure, enforcing industrial emission controls, and incorporating climate resilience land-use planning to safeguard public health and urban livability.

Keywords: *Urban Heat Island, Air Quality, GIS, Sentinel 5P, Dhaka Metropolitan Area*

1. INTRODUCTION

The process of rapid urbanization has significantly changed the physical and socio-environmental structure of urban areas across the globe, with the creation of serious impacts on the surface energy balance, local climate, air quality, and population health. One of the most evident effects of urbanization is the urban heat island phenomenon, in which, compared to rural areas, the heat absorbed by the built surfaces is higher due to a lower vegetation cover and a more impermeable surface (Wang et al., 2021). On the other hand, the UHI effect depends on the geographical location and land cover type (Clinton and Gong, 2013). The intensified UHI can increase cooling energy needs, increase heat-related morbidity and mortality, and may interact with air pollution to further elevate health risks among vulnerable urban dwellers.

Dhaka Metropolitan Area (DMA) is the most rapidly developing urban area in South Asia, where rapid land change and population growth have increased the levels of environmental stress and reduced green cover significantly (Hasan et al., 2023). These changes increase the magnitude of UHI and raise concentration levels of the criterion air pollutants such as CO, NO_2, SO_2, and O_3 (Begum et al., 2018). The continued urban growth in Bangladesh, especially in Dhaka, is a result of rural migration and centralisation of economic activities. This pattern of urban development strains the limited remaining green and blue spaces, while concentrating emissions from transport and industry, which contribute to higher UHI intensity and deteriorating air quality.

Remote sensing is the key tool for quantifying the spatiotemporal variation of UHI. Recent missions have a thermal infrared sensor on the Landsat programme, which presents multi-decadal Land Surface Temperature (LST) and land-surface products that can be used to analyse urban studies at a moderate spatial resolution (Landsat, 2020). The presence of Landsat Collection 2 Level-2 datasets ensures standardized surface temperature and reflectance retrievals, enabling comparison of UHI dynamics over 2010-2025. Meanwhile, Sentinel-5P provides daily measurements of major tropospheric trace gases (NO_2, SO_2, CO, O_3, etc.), which allows mapping the distributions of pollutants and patterns of their occurrence over time at the urban levels systematically once processed by platforms such as Google Earth Engine (Pavelyev et al., 2012). Integrative analyses combining Landsat and Sentinel-5P data allow simultaneous assessment of thermal patterns, land-use and land-cover transitions, vegetation and built-up indices, and concentrations of gaseous pollutants, thereby improving the understanding of environmental stress in rapidly urbanizing cities.

Despite the fact that a number of studies have reported the existence of UHI and its causes in Dhaka, a large number of analyses have been either temporally (small observational time frames) or thematically (excluding atmospheric composition and exposures to populations) limited. In recent studies, it highlighted the seasonal differences in UHI intensity in Dhaka and how urban morphology and heat waves mediate UHI effects. However, a thorough, multi-temporal combination of land use and land cover conversion, the trends of NDVI, NDBI, and pollutant fields, obtained by Sentinel over the past ten years, is limited. Investigations with a local focus that combine mapping of UHI with high resolution population distribution and pollutant field are especially demanded to define areas of compound vulnerability and to help develop mitigation (Tabassum et al., 2024). To overcome these shortcomings, this paper utilizes a GIS-based, multi-temporal remote-sensing framework to analyze the changing UHI dynamics of the Dhaka Metropolitan Area between 2010 and 2025 and how these dynamics are spatially correlated with major air pollutants (CO, NO_2, SO_2, O_3) retrieved by Sentinel-5P. This study aims at creating a more comprehensive view of the co-occurrence of urban warming and air-quality burdens in densely populated neighbourhoods through the incorporation of long-term Landsat-based records of surface temperatures, troposphere pollutant fields. The targeted objectives of the study are: (1) to analyze the spatiotemporal trends of UHI and major air pollutants (CO, NO_2, SO_2, O_3); (2) to assess the spatial distribution and combined heat-pollution vulnerability to identify high-risk hotspots; (3) to examine the relationship between UHI intensity and air pollutant concentrations.

2. METHODOLOGY

2.1 Study Area:

The capital and the largest economic center of Bangladesh is the Dhaka Metropolitan Area (DMA). It is located at 23°57'11" N and 90°27'1" E (Figure 1). The city experiences a humid subtropical climate, which is hot and wet in summer with the presence of a lot of monsoon rainfall and mild winters. Such climatic conditions, rapid urbanization, and dense built-up areas increased the surface temperature and air pollution challenges in the city (Chakraborty, 2019).

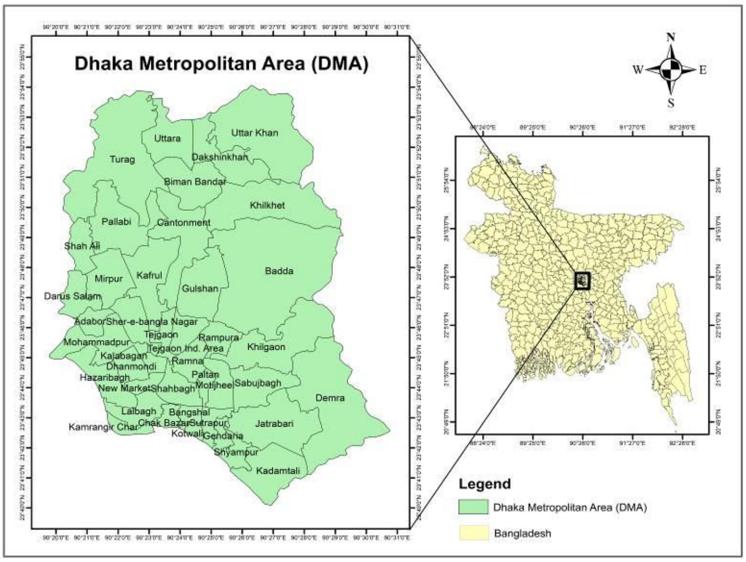

Figure 1: Study Area

2.2 Materials and Methods

This study uses the multi-temporal satellite data to determine the relationship between the intensity of Urban Heat Island (UHI) and air pollution in the Dhaka Metropolitan Area (DMA) shown in Table 1.

Table 1: Data Sources and Time Periods Used for UHI and Air Pollutant Analysis

Data Type	Source	Time Period
Landsat 7, 8	USGS EE	2010–2025
Air Pollutants (CO, NO_2, SO_3, O_3)	Sentinel-5P TROPOMI	2020–2025

2.3 Urban Heat Island (UHI) Mapping

The intensity of UHI was measured using LST based on the thermal infrared bands of Landsat 7 and 8. The Urban Heat Island (UHI) phenomenon is conceptually defined by the temperature difference between urban and non-urban surfaces, reflecting the higher heat absorption and retention of built-up areas compared to vegetated or water-covered surfaces. In this study, however, UHI intensity was operationally quantified using a standardized land surface temperature-based approach, which does not require explicit delineation of urban and non-urban reference areas. This method captures relative thermal anomalies and allows consistent spatial and temporal comparison without requiring explicit urban-rural delineation. Initially, the thermal bands of Landsat 7 and 8 were transformed from Digital Number (DN) to spectral radiance, which was utilized to determine the Brightness Temperature (BT). Normalized Difference Vegetation Index (NDVI) was subsequently estimated to determine surface emissivity from which LST were estimated. To represent the spatial variability of UHI intensity, a standardized LST-based UHI index was computed (Rahman et al., 2022) using Eq. (1) in this study. The index expresses the relative deviation of land surface temperature from the mean thermal condition of the study area and enables consistent spatial and temporal comparison.

The following equation was used in calculating (UHI):

$$UHI = (LST - LSTm)/SD \quad (1)$$

Here,
UHI= Urban Heat Islands
LST= Land Surface Temperature
LSTm= The mean temperature of the land surface temperature in the study area
SD= Standard deviation of temperature

Separate UHI maps were produced for summer and winter seasons for 2010, 2015, 2020, and 2025 to capture temporal variability. All seasonal maps were integrated using the Cell Statistics function in ArcMap, averaging summer and winter UHI rasters to generate a composite UHI intensity map representing the long-term heat profile. This approach captures long-term spatial patterns while minimizing inter-annual variability. The raster was normalized (0-1 scale) to enable integration with pollutant indices.

2.4 Air Pollutant Mapping

The Google Earth Engine (GEE) was used to process Sentinel-5P TROPOMI data for each pollutant constituent (CO, NO_2, SO_2, and O_3) covering the period from 2020 to 2025. For each pollutant, the data were temporally averaged to generate annual mean concentration rasters. These rasters were then resampled to a uniform spatial resolution, normalized, and clipped to the boundary of the Dhaka Metropolitan Area (DMA) to ensure spatial consistency. The processed pollutant rasters were integrated in ArcGIS using the raster calculator by assigning equal weights due to the absence of locally validated exposure weighting factors to produce a composite air pollution exposure map. This equal-weight approach is commonly used in urban environmental exposure studies. This map represents the cumulative concentration and combined stress of multiple air pollutants across the city, highlighting spatial variations and pollution hotspots associated with industrial and densely populated urban areas.

2.5 Integration of UHI and Air Pollution Indices

The UHI-Air Pollution Vulnerability Map was developed by integrating the normalized composite UHI raster with the composite air pollution exposure raster using the Raster Calculator tool in ArcGIS. Both datasets were standardized to a common scale (0-1) using min–max normalization to maintain comparability across indices. This integration process allowed the identification of areas under dual environmental stress, where both surface heating and pollutant accumulation are prominent. The resulting map delineates zones of high, moderate, and low vulnerability, providing spatial insights into regions facing simultaneous exposure to extreme heat and degraded air quality.

Although UHI dynamics were analyzed for the period 2010-2025 to capture long-term urban thermal evolution, air pollution analysis was limited to 2020-2025 due to Sentinel-5P data limitations. Therefore, the combined UHI-air pollution vulnerability analysis reflects recent environmental states instead of long-term interdependence. Such integrated mapping serves as an essential decision-support tool for urban planners and policymakers, emphasizing the urgent need for sustainable land-use management, emission reduction, and urban greening strategies to mitigate combined heat and pollution impacts in Dhaka. The relationship between UHI intensity and air pollutants was assessed through visual comparison of the corresponding spatial maps.

3. RESULTS AND DISCUSSION

3.1 Seasonal Spatial Pattern of Urban Heat Island

The seasonal UHI maps (Figure 2) showed a gradual increase in surface temperature between 2010 and 2025, with higher intensity during summer compared to winter. Noticeable heat concentration was found in Tejgaon Industrial Area, Mohammadpur, Hazaribagh, Kafrul, Badda, Turag Thana, and Jatrabari during summer, mainly due to dense industrial activities and the continuous decline of vegetation. On the other hand, areas such as Demra, Uttarkhan, and Khilgaon remained relatively cooler, supported by the presence of vegetation and lower built-up area. Other areas of the city showed a low to moderate UHI intensity throughout the summer for the last fifteen years. Though there was an overall downdrift in heat both in summer and winter in 2020, because of lower industrial activities due to COVID-19.

During the winter, the overall temperature (Figure 3) was lower compared to summer, thus the UHI intensity was also lower. However, Shah Ali and Uttar Khan remained coolest in winter. Whereas, Badda, Tejgaon Industrial Area, and Jatrabari showed the highest UHI intensity for the last fifteen years during winter. On the other hand, though Biman Bandar, Hazaribag, Kalabagan, Pallabi had lower UHI intensity, but increased significantly in 2024. However, there was an increase in UHI intensity in most of the thanas of Dhaka city in 2024.

The composite map (Figure 4) represents the spatial distribution of Urban Heat Island (UHI) intensity in the Dhaka Metropolitan Area over the period 2010-2025 by combining multi-temporal LST data. Since Sentinel-5P TROPOMI data are available at a coarser spatial resolution than Landsat-derived land surface temperature, the air-pollutant datasets were resampled to achieve spatial consistency before being integrated with the thermal data for analysis. The map classifies the UHI intensity into Very Low, Low, Moderate, High, and Very High zones. The central and highly urbanized parts of the DMA, including Motijheel, Tejgaon, Dhanmondi, Mohammadpur, Mirpur, Lalbagh, Hazaribagh, and Badda, show High to Very High UHI intensity. The northern, southern, and eastern edges of the DMA, such as Uttara, Cantonment area, Keraniganj, and fringe settlements, show Low to Very Low intensity. The composite UHI map clearly demonstrates that as the Dhaka Metropolitan Area has expanded rapidly, central wards have become significantly heat-stressed, while peripheral areas still retain relatively cooler microclimates. Effective urban planning strategies are urgently needed to mitigate rising UHI intensity in the DMA.

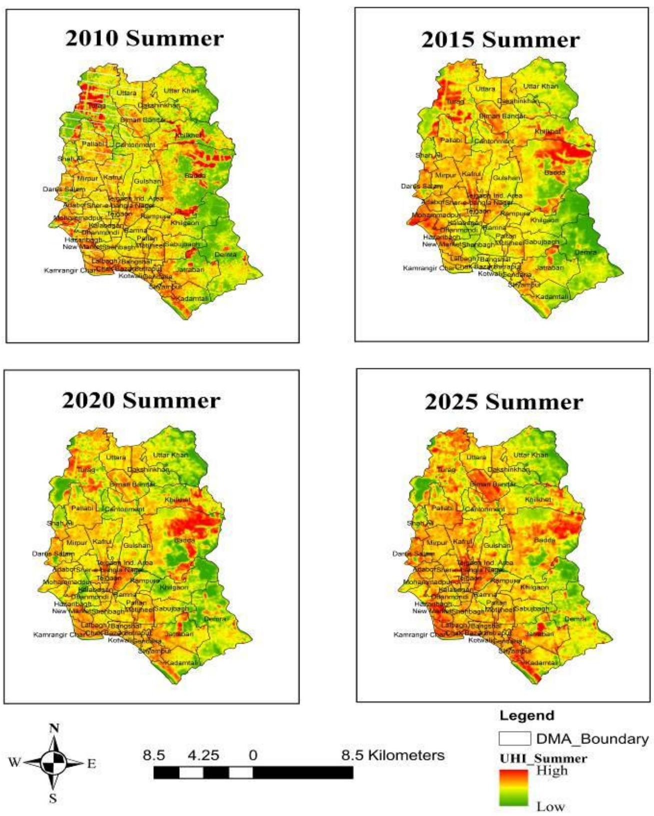

Figure 2: Urban Heat Island (UHI) Intensity Map of Dhaka during Summer (2010-2025)

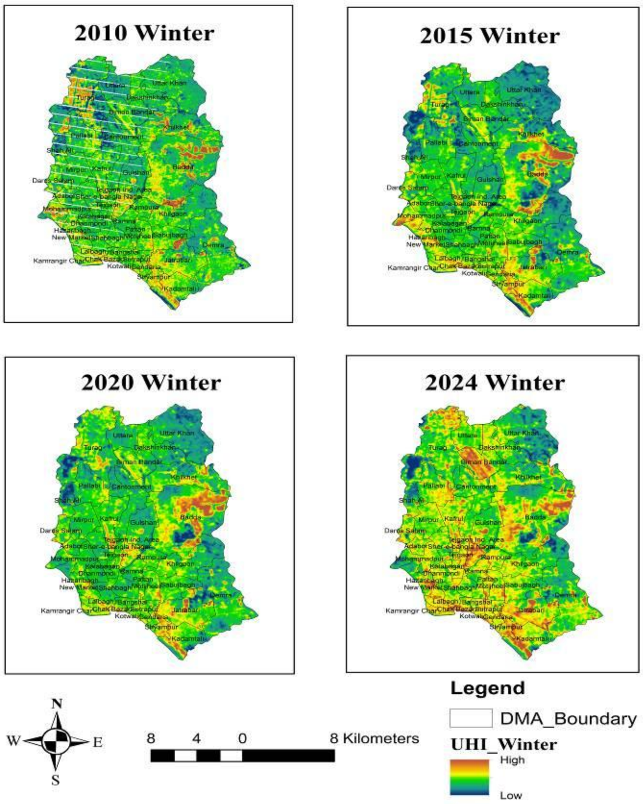

Figure 3: Urban Heat Island (UHI) Intensity Map of Dhaka during Winter (2010-2025)

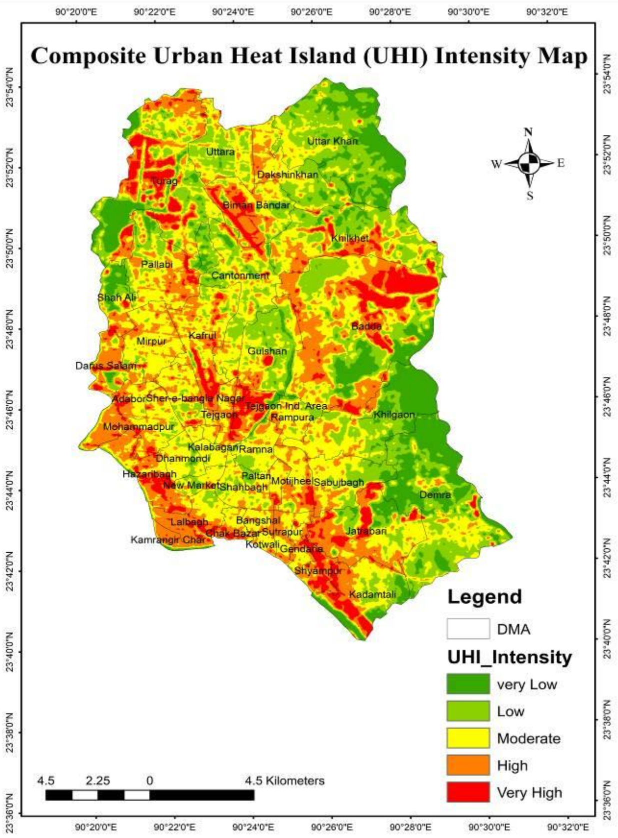

Figure 4: Composite Urban Heat Island (UHI) Intensity Map of Dhaka (2010-2025)

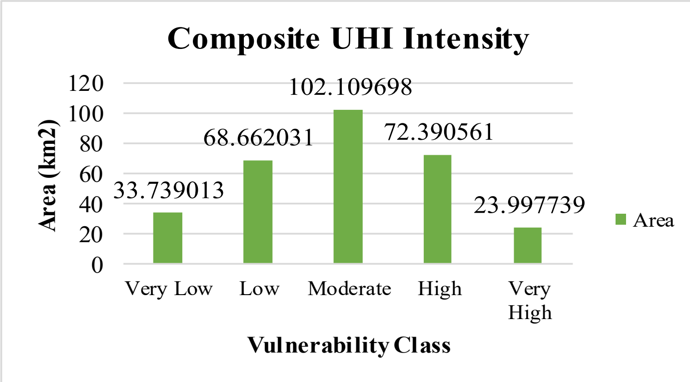

Figure 5: Area distribution of different vulnerability classes based on composite UHI intensity

The class-wise area distribution (Figure 5) highlights the spatial dominance of moderate vulnerability zones across Dhaka. In the composite UHI intensity map, approximately 102.1 km² (37%) of the total area falls under the moderate class, followed by high (72.4 km²) and low (68.7 km²) intensity zones. This indicates that a significant portion of the city experiences considerable thermal stress, particularly in dense urban cores.

3.2 Temporal Trend Analysis of Urban Heat Island Intensity

The temporal trend of UHI intensity between 2010 and 2025 shows (Figure 6) a clear increasing pattern across the Dhaka Metropolitan Area. During the summer season, UHI values fluctuated slightly but exhibited an overall upward trend ($R^2 = 0.32$), indicating the gradual intensification of heat accumulation in built-up areas. Winter UHI exhibited a stronger and more consistent increase ($R^2 = 0.70$), suggesting that heat retention during cooler months is becoming more pronounced due to limited atmospheric dispersion. The annual mean UHI trend ($R^2 = 0.57$) further confirms the progressive amplification of urban thermal conditions over time. The increase in UHI intensity by 2025 is primarily in areas such as Tejgaon, Badda, and Pallabi. Overall, the results indicate that Dhaka's urban thermal environment is gradually intensifying, with a more significant rise during winter.

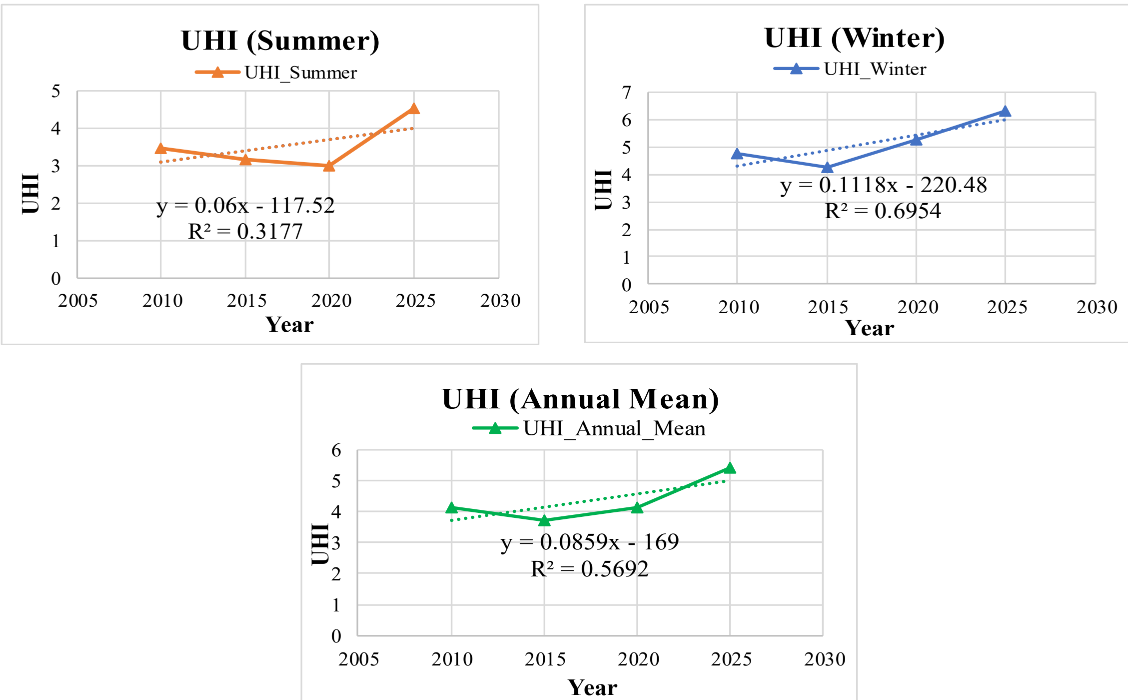

Figure 6: Maximum UHI in the summer, winter, and annual mean

3.3 Air Pollution Distribution and Trends

The yearly pollutant maps revealed clear spatial variations across Dhaka. High CO concentrations were recorded in 2021 and 2025, with the highest concentrations of 0.059 mol/m^2 and 0.055 mol/m^{2,} respectively (Figure 7). Carbon monoxide (CO) concentrations were consistently high in Tejgaon Industrial Area, Biman Bandar, Pallabi, and Mirpur in most years for the last five years.

Elevated NO_2 levels were observed mainly in the northern parts of the city, including Uttara, Demra, and Pallabi, whereas the lowest concentration was constantly found in Mohammadpur, Hazaribag, Adabor, Lalbagh, and Kamrangir Char (Figure 8). Though the difference between the highest and lowest concentration of NO_2 was very small last five years.

SO_2 concentrations showed fluctuating concentrations and no constant pattern for the last fifteen years (Figure 9). The highest concentrations of SO_2 were recorded in 2024, with a value of 0.00066 mol/m^2 in Mirpur, Adabor, and Khilgaon. Conversely, the lowest value of SO_2 of 0.000 mol/m^2 was found in 2020 and 2022 in Khilgaon and Jatrabari, respectively.

In contrast, O_3 showed an opposing trend with lower levels in the northeastern and southern areas, such as Demra, Uttar Khan, and Khilkhet, and higher concentrations in the northwestern and western thanas like Turag, Mohammadpur, and Hazaribag (Figure 10). This inverse relation indicates that O_3 formation is photochemically enhanced in less polluted peripheral zones downwind of emission sources.

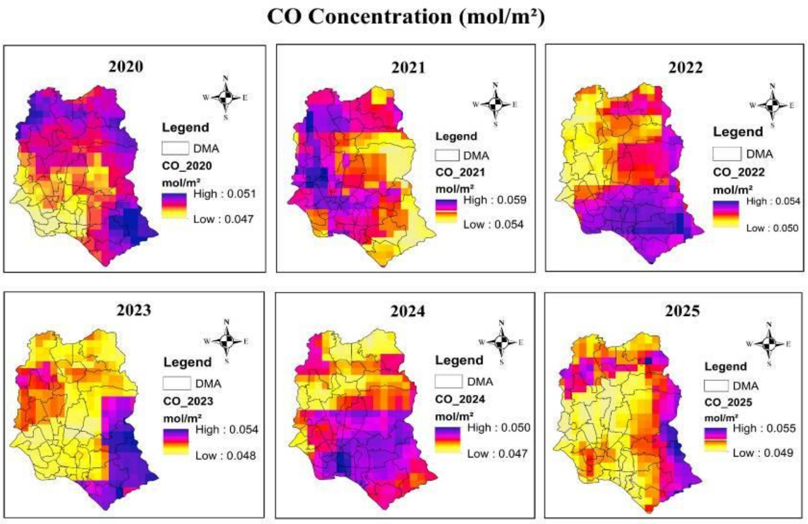

Figure 7: Spatial distribution of CO concentration (2020-2025)

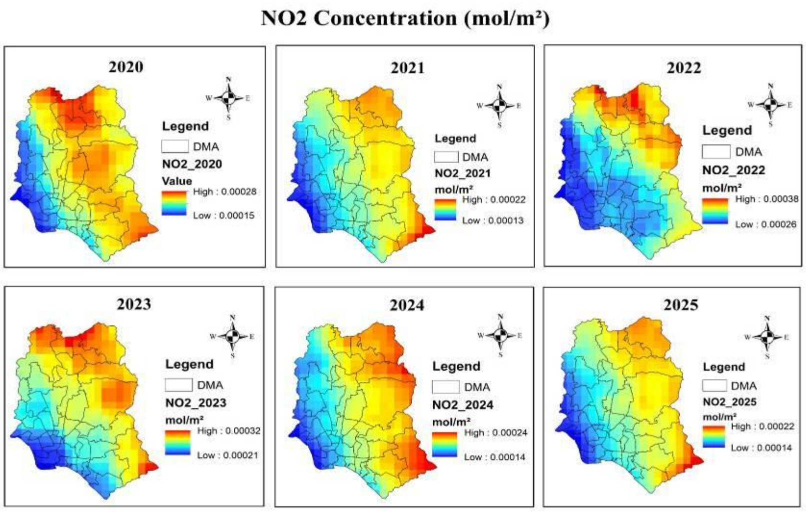

Figure 8: Spatial distribution of NO_2 concentration (2020-2025)

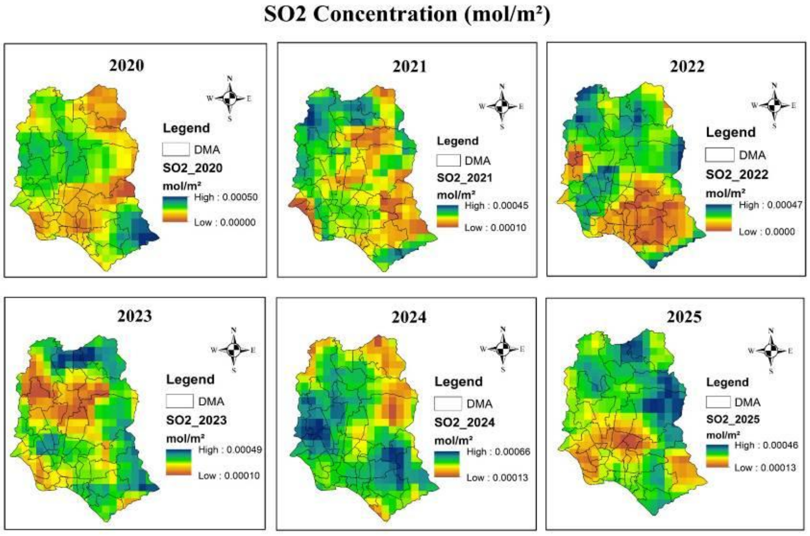

Figure 9: Spatial distribution of SO_2 concentration (2020-2025)

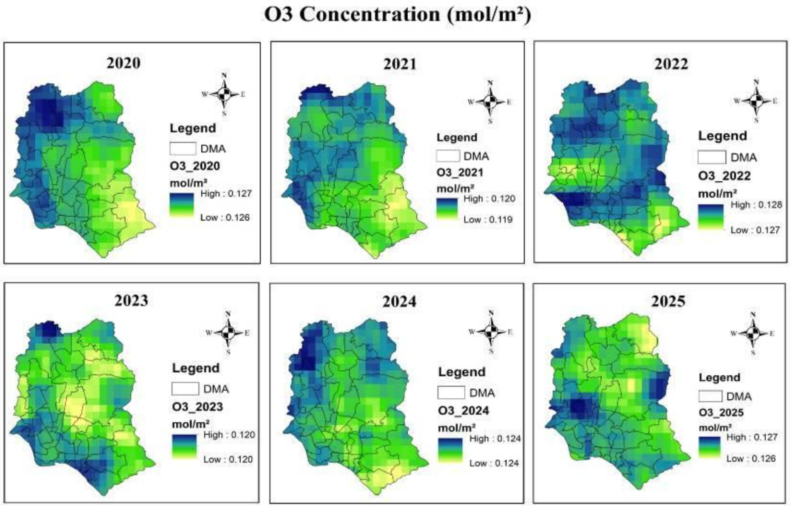

Figure 10: Spatial distribution of O_3 concentration (2020-2025)

3.4 Combined Heat-Pollution Vulnerability

Urban residents are adversely affected by the urban heat island effect through increased thermal stress, whereas air pollution primarily impacts respiratory health and contributes to heat- and skin-related diseases. The combined influence of elevated temperature and poor air quality intensifies environmental stress and significantly reduces human comfort, especially among susceptible urban populations (Hankey and Marshall, 2017; Huang et al., 2020). The UHI-Air Pollution Vulnerability Map showed the areas impacted highly due to both UHI and air pollutants across Dhaka (Figure 11). Areas such as Badda, Biman Bandar, Mirpur, Mohammadpur, Uttara, Dakshinkhan, Turag, Kafrul, and Jatrabari emerged as zones of high to very high vulnerability, where residents face combined exposure to intense heat and poor air quality. Moderate vulnerability was noted in Pallabi, Dhanmondi, and Tejgaon. The lowest vulnerability was observed at Bangshal, Paltan, Gulshan, Rampura, Shahbagh, Ramna, and Khilkhet.

Overall, the findings indicate that unplanned land-use changes and rapid industrial expansion have jointly intensified surface heating and pollutant buildup, increasing potential risks to public health.

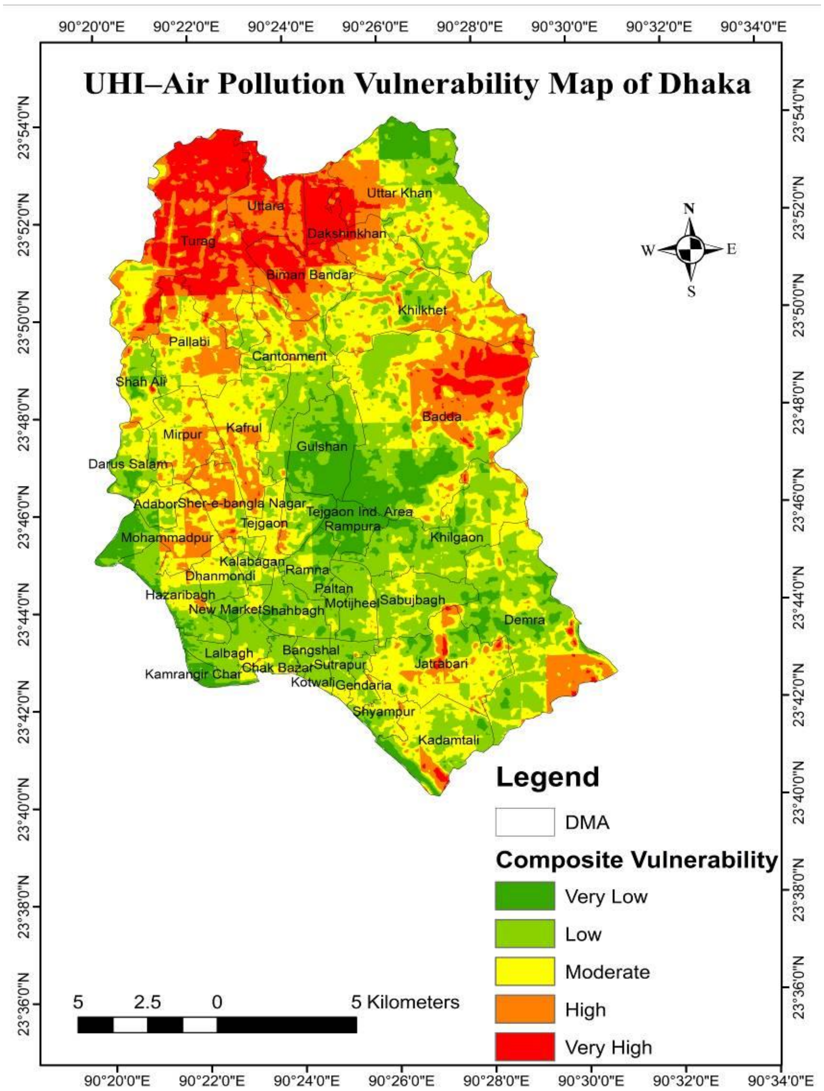

Figure 11: UHI–Air Pollution Vulnerability Map of Dhaka (2010–2025). Red zones indicate areas of high combined heat and pollution exposure

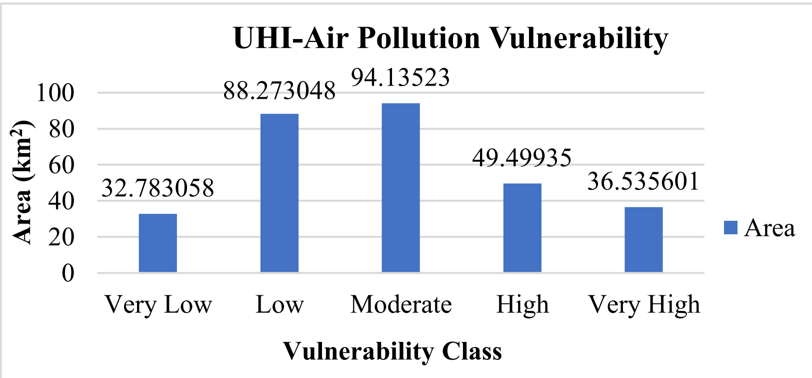

Figure 12: Area distribution of combined UHI–air pollution vulnerability classes

The combined vulnerability map (Figure 12) demonstrates moderate (94.1 km²) and low (88.3 km²) classes again dominated the landscape, while high and very high categories collectively occupied around 31% of the total area. These findings imply that while Dhaka's overall vulnerability remains moderate, several localized hotspots persist, particularly in Tejgaon, Uttara, and Jatrabari, where cumulative thermal and pollution exposure is pronounced.

3.5 Relationship between Urban Heat Island Intensity and Air Pollutants

The relationship between UHI intensity and air pollutants was evaluated using a spatial comparison of the generated maps. The comparative analysis between UHI intensity and major air pollutants (Table 2) revealed a consistent positive association between UHI and CO, NO_2, and SO_2 across all seasons, implying that areas with higher temperatures also experience higher pollutant concentrations. The relationship with O_3 was negative, indicating that ozone formation is less prominent in high-temperature zones, possibly due to complex photochemical reactions and pollutant dispersion patterns. Overall, the findings suggest that unplanned land-use changes, rapid urbanization, and industrial growth have contributed to both enhanced surface heating and pollutant accumulation, intensifying environmental stress and posing potential risks to public health in Dhaka.

Table 2: Relationship between UHI intensity and Air Pollutants

Season	**CO**	**NO_2**	**SO_2**	**O_3**
Summer	Positive	Positive	Weak Positive	Negative
Winter	Positive	Positive	Positive	Negative
Annual (Mean)	Positive	Positive	Moderate Positive	Negative

4. CONCLUSIONS

The present research illustrated the spatial and temporal variation of UHI intensity, as well as its association with key air pollutants in Dhaka. Results showed a significant increase in surface temperature, especially for industrial and built-up urban areas like Tejgaon, Badda, Mohammadpur, and Jatrabari. In general, the increasing trend of UHI is evident both in summer and winter, but winter shows a more significant growth, which is indicative of greater heat retention during this period in the city centers due to reduced vegetation and high impervious surface coverage. Analysis of air pollutants showed that all three, including CO, NO_2, and SO_2, were higher in places where the heat was more intense, while O_3 showed an opposite trend. Integrated heat-pollution vulnerability analysis revealed Badda, Biman Bandar, Mirpur, and Kafrul were the hotspots of dual-exposure to temperature and air pollution with high vulnerability to extreme environmental risks as well as adverse health outcomes. The related impacts of uncontrolled industrial growth and increasing pressure on land were also addressed. The findings highlight the need for sustainable urban strategies that incorporate green infrastructure, emissions control, and effective land-use governance. It should be noted that these results are based on satellite-derived datasets, which carry uncertainties related to sensor resolution, atmospheric correction, and cloud contamination. Limited and inconsistent ground-based monitoring in Dhaka prevented direct validation, so the findings should be interpreted primarily in terms of relative spatial patterns and temporal trends rather than absolute values. Based on these findings, both thermal and air-quality aspects should be considered in future planning to reduce environmental stress and make Dhaka city more resilient and livable.

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DECLARATION OF USE OF AI

The data analysis, methodology, results, interpretations, and conclusions are entirely the work of the authors. No AI tools were used to generate data, perform analysis, or influence scientific decisions.

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