IMPACTS OF URBAN DENSITY ON SURFACE HEAT: LST AND UTFVI ANALYSIS IN RAJSHAHI CITY

Riya Islam*[1], Md. Kamrul Islam[2]

[1] *GRADUATE STUDENT, Chittagong University of Engineering & Technology, Bangladesh, e-mail:* u1905003@student.cuet.ac.bd

[2] *ASSISTANT PROFESSOR , Chittagong University of Engineering & Technology, Bangladesh, e-mail:* kamrul.islam.cuet10@cuet.ac.bd

***Corresponding Author**

ABSTRACT

South Asian city growth has enhanced concerns over the Urban Heat Island (UHI) effect and related hazards of thermal suffering and microclimatic degradation. Rajshahi City, Bangladesh—a mid-sized riverine metropolis experiencing rapid and largely uncontrolled growth—is a foremost case study for a study of such processes. This research examines the effect of 2004-2024 spatiotemporal urban density variations on Land Surface Temperature (LST) and the Urban Thermal Field Variance Index (UTFVI), two of the most significant measures of surface heat and thermal stress. To quantify densification of the urban region, multi-date Landsat images were processed using the Normalized Difference Built-up Index (NDBI) and Normalized Burn Ratio 2 (NBR2). Landsat 5, 8, and 9 thermal bands were employed to supply the LST estimates, and UTFVI values were derived to measure relative thermal discomfort. Analytical methodologies comprised Geographically Weighted Regression (GWR) to spot the local relationships and transect profile analysis to scrutinize horizontal and vertical differences across the city. The outcome reveals significant densification of inner and south wards, which led to the conversion of agricultural land and open spaces into compact residential and commercial structures. Such high-density areas consistently possessed LST values more than 5°C higher than low-density peripheral areas. UTFVI analysis validated more thermal stress for densely developed areas with high impervious surface cover and lower vegetation, whereas peripheral wards had high green cover and relatively stable microclimatic conditions. In addition, it was found that enhancing density not only raised daytime surface temperatures but also reduced nocturnal cooling, generating warmer and drier microclimates. The study concludes that unplanned densification of the city is one of the most important drivers of thermal stress in Rajshahi, enhancing the UHI effect and compromising environmental livability. These issues can be addressed by giving priority to ward-level green interventions such as road side tree plantation, protection of remaining peripheral vegetation, and introducing permeable paving in public spaces while preparing a climate-resilient urban plan for Rajshahi City. These findings provide context-specific, evidence-based guidance for Rajshahi City Corporation to enhance thermal resilience, while also providing insights applicable to other mid-sized South Asian cities facing similar urbanization pressures.

Keywords: *Urban Density, Land Surface Temperature, Urban Thermal Field Variance Index, Urban Heat Island*

1. INTRODUCTION

Rapid urbanization is seen to be a major contributing cause to the worsening effects of climate change on the built and natural surroundings (Grimm et al., 2008). Urban density significantly impacts urban energy use and the quality of life of urban residents (Güneralp et al., 2016). Increased urbanized land cover is referred to as urban growth (Abbasi et al., 2021). Land use change, traffic congestion, air and water pollution, the loss of urban plant cover and biodiversity, rising urban land surface temperatures, and their effects on the environment and human health are among the complex urban issues that are linked to it (Huang et al., 2021).The radiative temperature from the outer layer of the land that is produced by solar radiation is known as land surface temperature (LST) (Imran et al., 2021). Increased LST deteriorates the meteorological condition in urban areas and causes the Surface Urban Heat Island (SUHI) effect. SUHI occurs when anthropogenic land surface alterations cause urban or metropolitan regions to have noticeably higher temperatures than their rural surroundings (Naim and kafy, 2021). The constant loss of green spaces due to unchecked urban expansion induces urban heat island (UHI), and it changes the urban micro-climate (Arshad et al., 2022). The Surface Urban Heat Island (SUHI) impact may be more precisely described using the commonly used UTFVI index. The concentration of UTFVI is higher in areas that are significantly warmer than the nearby rural regions. Among the noteworthy consequences of UTFVI are negative effects on the local wind, humidity, and air quality, as well as decreased comfort, a higher death rate, indirect economic loss, and more (Naim and Kafy, 2021).

The present study investigates the relationship between the density of the city and surface temperature variations in the case of the city of Rajshahi, utilizing a spatial and temporal approach based on multi-temporal Landsat data. The thermal stresses present in the various density classes are estimated by the analysis of the Land Surface Temperature (LST) and the Urban Thermal Field Variance Index (UTFVI), in collaboration with the Geographically Weighted Regression technique. The central object of the present study consists in the spatial analysis and interpretation of the surface temperature variations in the urban areas, rather than the determination of precise recommendations. Although some planning recommendations are briefly discussed, the objectives of the remarks are illustrative in nature, aiming to better capture the spatial implications of the findings, rather than following a prescriptive approach. The study essentially provides additional spatial evidence on the impact of urban densification on the thermal characteristics of the city of Rajshahi, offering analytical information that may be utilized in the future by planning initiatives in similar contexts.

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 km² 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

The research aimed at analysing changes in thermal and environmental conditions in the city using multi-temporal Landsat images—Landsat 5 TM for 2004, Landsat 8 OLI/TIRS for 2014, and Landsat 9 OLI/TIRS for 2024, all processed separately using Google Earth Engine. All the images were standardized to remove any effects of radiation and atmosphere, and the bands were registered to provide 30m resolution images for calculating indices NDBI, NBR2, LST, and UTFVI. The administrative maps were obtained from global GIS resources.

Table 1: Data Sources and Units

Parameter	Source	Years	Unit
Land Surface Temperature (LST)	Landsat Thermal Bands	2004, 2014, 2024	°C
Urban Thermal Field Variance Index (UTFVI)	LST & mean LST	2004, 2014, 2024	Index (unitless)
Urban Density	Landsat	2004, 2014, 2024	Proportion (0–1)

2.3 Calculation of Urban Density

The urban density was measured by two indices. The Normalized Difference Built-up Index (NDBI) reveals built-up regions by indicating that the SWIR band has higher reflectance than the NIR band (Zha et al., 2003). It is calculated using the equation (1):

$$NDBI = (SWIR - NIR) / (SWIR + NIR) \tag{1}$$

The Normalized Burn Ratio 2 (NBR2) is a measure of the areas in city and plant cover that have decreased due to urbanization. The equation to calculate this is:

$$NBR2 = (SWIR1 - SWIR2) / (SWIR1 + SWIR2) \tag{2}$$

The combinations of NDBI > -0.1 and NBR2 < 0.2 were used to clearly separate built areas from soil and vegetation, and it was these reference samples that used to refine the results. The urban density was calculated as the mean of built-up pixels by a neighbourhood in a 3-pixel window, leading to a continuous surface for the years 2004, 2014, and 2024 with values 0–1.

The classification for the year 2024 was checked against the building footprints obtained from OpenStreetMap (OSM). The building shapes were changed into centroids so as to form a point density raster which is the proxy for ground-truth. Random sampling was done at certain points and the values obtained were compared with those coming from classification employing extraction tools. This showed a high degree of spatial correspondence between the identified and the real built-up spaces. Although it is not giving an exact rate of precision, the cross-validation has confirmed the urban density mapping reliability.

2.4 Calculation of LST and UTFVI

2.4.1 Land Surface Temperature (LST)

LST is the return of heat from different land cover types and was derived from the thermal infrared bands of Landsat 5 (Band 6), Landsat 8 (Bands 10 and 11), and Landsat 9 following NASA and USGS procedures (Faridatul, 2017). The process initiated by converting the digital number (DN) values into spectral radiance by means of:

$$L\lambda = [(Lmax\lambda - Lmin\lambda) / (QCalmax - QCalmin)] \times (QCal - QCalmin) + Lmin\lambda \quad (3)$$

Then radiance was determined through:

$$L\lambda = ML \times QCal + AL \quad (4)$$

The next step was to get the brightness temperature (T) from the radiance using the calibration constants (K_1, K_2):

$$T = K_2 / \ln((K_1 / L\lambda) + 1) - 273.1 \quad (5)$$

Lastly, surface emissivity (ε) and vegetation proportion (Pv) were added to get the real LST:

$$LST = T / [1 + (\lambda T / \rho) \times \ln(\varepsilon)] \quad (6)$$

where $\varepsilon = 0.004 \times Pv + 0.986$ and $Pv = [(NDVI - NDVImin) / (NDVImax - NDVImin)]^2$

2.4.2 Urban Thermal Field Variance Index (UTFVI)

The calculation of UTFVI was based on the landsat surface temperature and mean LST to assess thermal intensity in urban areas:

$$UTFVI = (Ts - Tm) / Tm \quad (7)$$

where Ts is LST, and Tm is the mean LST. The areas with high values of UTFVI are warmer, and more heat-stressed urban areas.

2.5 Assessment of Spatiotemporal Relations

The study investigates the urbanization's spatial effects on the local climate of Rajshahi City, Bangladesh, particularly pointing out how the changes in urban density and land cover impact LST, microclimate, and environmental quality. The application of Geographically Weighted Regression (GWR) helped to reveal such spatially varying relationships which were depicted by the model:

$$y(u) = \beta0(u) + \beta1(u)x1 + \beta2(u)x2 + \ldots + \beta m(u)xm \quad (8)$$

Here, y(u) stands for the dependent variable at the location u, x1…xm are the independent variables, and β(u) are the coefficients specific to that location. GWR has also spotted areas where the urban density has a strong influence on LST and UTFVI (Faka et al., 2023). Transect profile analysis provided additional support by sampling data along horizontal and vertical lines, and thus it demonstrated how the changes in land cover and urban expansion have transformed the local microclimates (Faridatul, 2017).

3. RESULT AND DISCUSSIONS

3.1 Mapping of Urban Density

The urban density scenario in Rajshahi city can be depicted through Figure 1 and the corresponding analyses at the ward level during the period from 2004 to 2024. Low-density regions mostly occupied the area in 2004 (44.15%), such regions being mainly northern and peripheral wards; on the other hand, very high-density areas (24.84%) were found in the urban core of the city, which is the historical center of the population near the river, in the southern and central wards, thus forming a pattern of density distribution. The areas of medium density and high density constituted around the core, respectively (by 13.39% and 17.61%). The changes in spatial and temporal distribution of urban density took place quickly over that period, where, by 2014, very high-density areas more than doubled to 30.43%, while other densities reflected a dramatic conversion of land from low-central to high-density urban, making the urban area with high density three times larger than in 2004. This latter trend was mirrored in the increase of the area of low-density zones down to 24.27%. Monstrous proliferation of high-density areas to 42.84% in the second future date, taking over the entire area of the central and southern wards, was reversed accordingly in the case of 12.27% for low-density. In other wards, high-density zones increased again to 26.16%. The development of rank urban density, residential area, and the gradual elimination of green land and sparsely populated regions are thus illustrated with the trends and values presented.

Table 2: 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

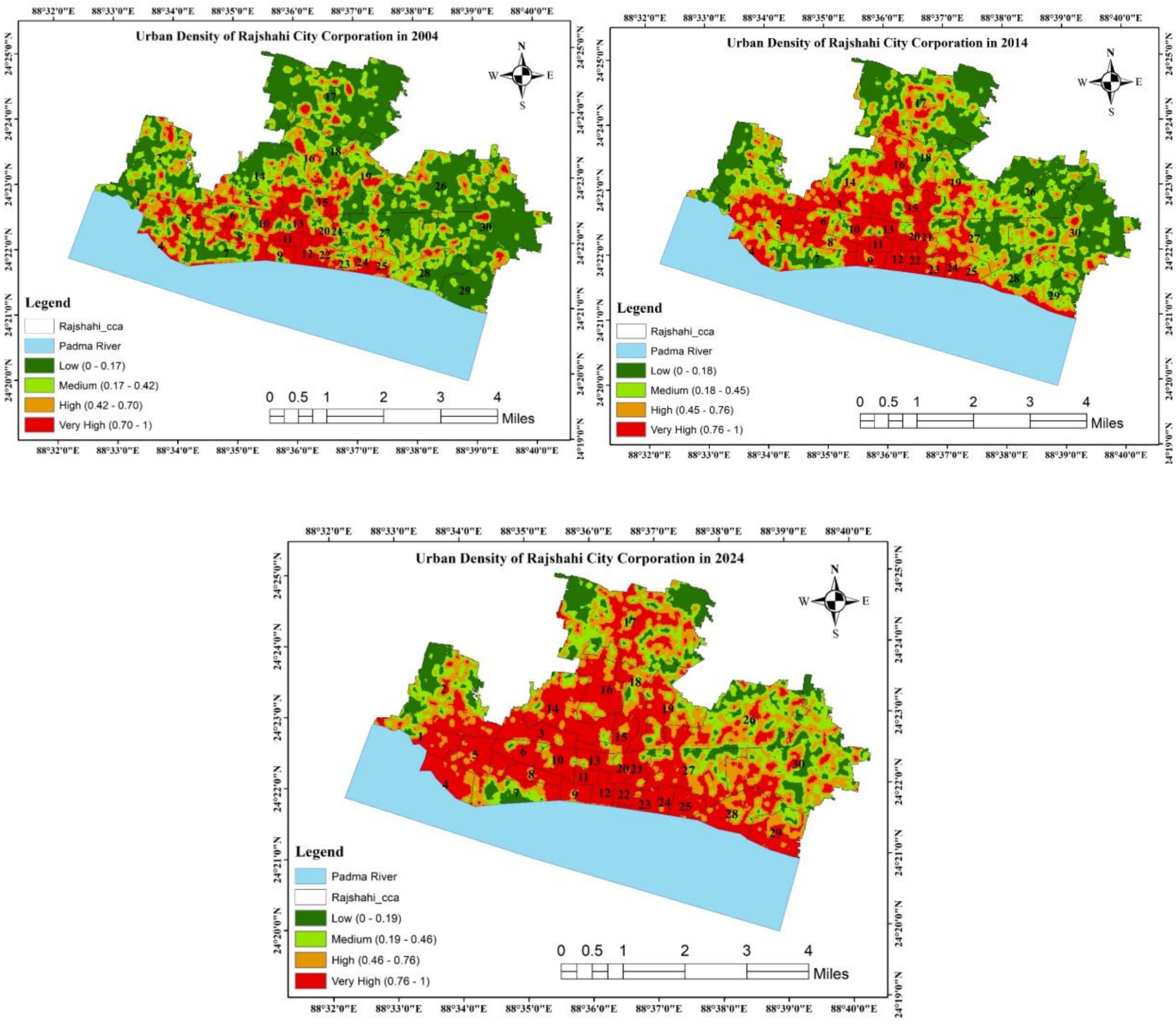


Figure 1: Urban Density of Rajshahi City Corporation in 2004, 2014 and 2024

3.1.1 Validation of Urban Density Map of 2024

The urban density map was tested using a point density evaluation technique with 100 points randomly generated in the Rajshahi City Corporation area. Comparison between the actual and satellite-classified density classes based on the confusion matrix indicates a high degree of accuracy in the classification, especially in the highly dense class. The accuracy level of the overall map was 91% in the validation test.

Table 3: Confusion Matrix

Real \ Predicted	Low	Medium	High	Very High	Total
Low	9	0	0	0	9
Medium	1	3	0	1	5
High	0	0	3	3	6
Very High	0	1	3	76	80
Total	10	4	6	80	100

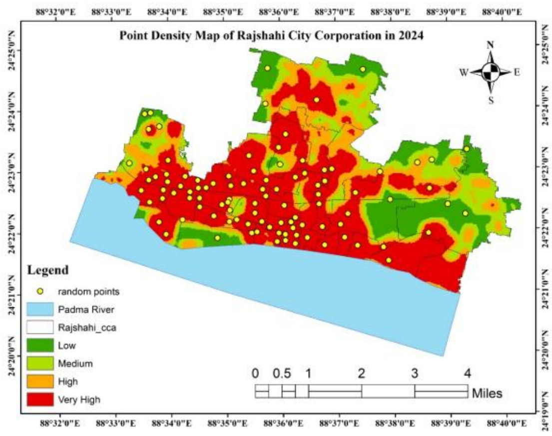
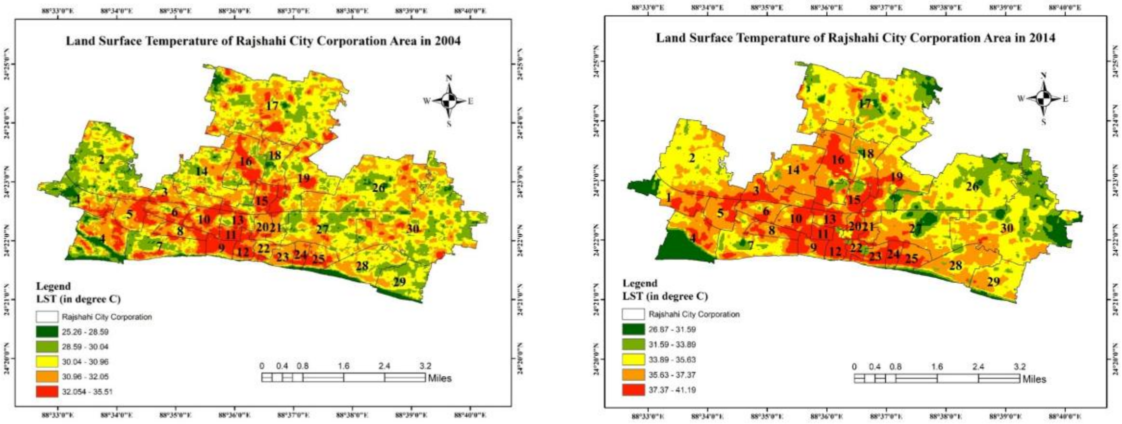


Figure 2: Validation Map for Urban Density of 2024

3.2 Mapping of LST and UTFVI

3.2.1 Land Surface Temperature (LST)

Figure 3 above indicates a progressive rise in LST in the Rajshahi region from 2004 to 2024 due to the effects of urbanization. In 2004, the high LST values were mainly in the south wards (5, 6, 8, 9, 10, 11, 13, 15, and 16), above 32°C, while the outer wards were cool (25-28°C). In 2014, the high temperature values above 37°C were mainly in the central wards (9, 10, 11, 12, 13, 23, and 24), after the destruction of vegetation. In 2024, the entire central and southern parts of the city had high temperatures above 36.8°C, except for the northern parts (2, 4) and the southeastern parts (26 and 30), which were cool. The graph clearly confirms a gradual increase in the values for minimum, maximum, and mean LST.



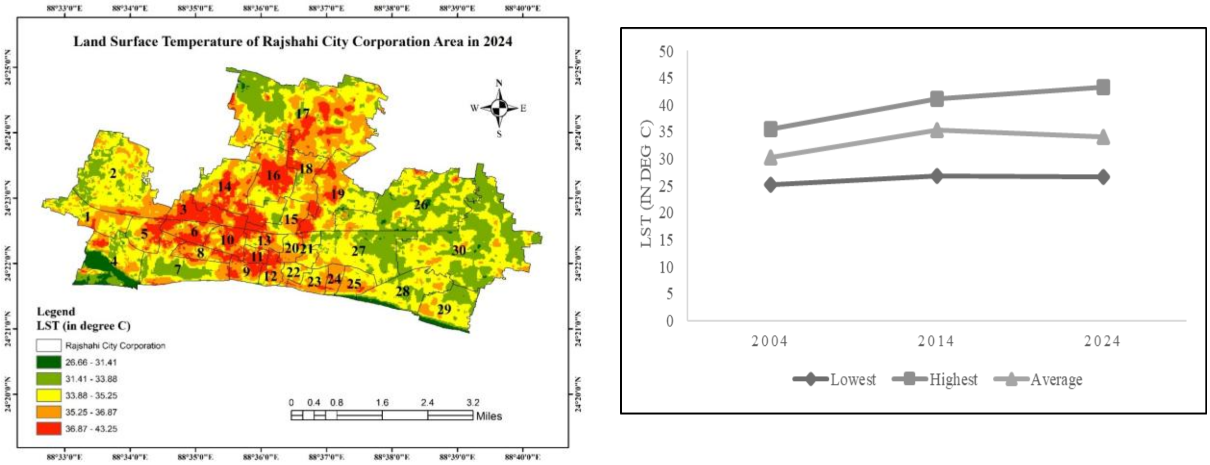


Figure 3: LST of Rajshahi City Corporation in 2004, 2014, 2024 and Trend of LST in ˚C

3.2.2 Urban Thermal Field Variance Index (UTFVI)

Figure 4 depicts the thermal stress increasing and the heat distribution in Rajshahi being uneven from the year 2004 up to 2024. In 2004, the central and southern wards (6, 10, 11, 13, 21) that had high UTFVI values, were by 2014 expanded to wards 12, 15–18, and 22–25 because of the dense development and the loss of vegetation. Extreme thermal stress was reached by 2024 in the majority of the central and southern areas (5–13, 20–25), while only the outskirts (4, 26, 28, 29) wards were still cooler. Rising maximum and falling minimum UTFVI signify the severe thermal stress and the declining urban comfort.

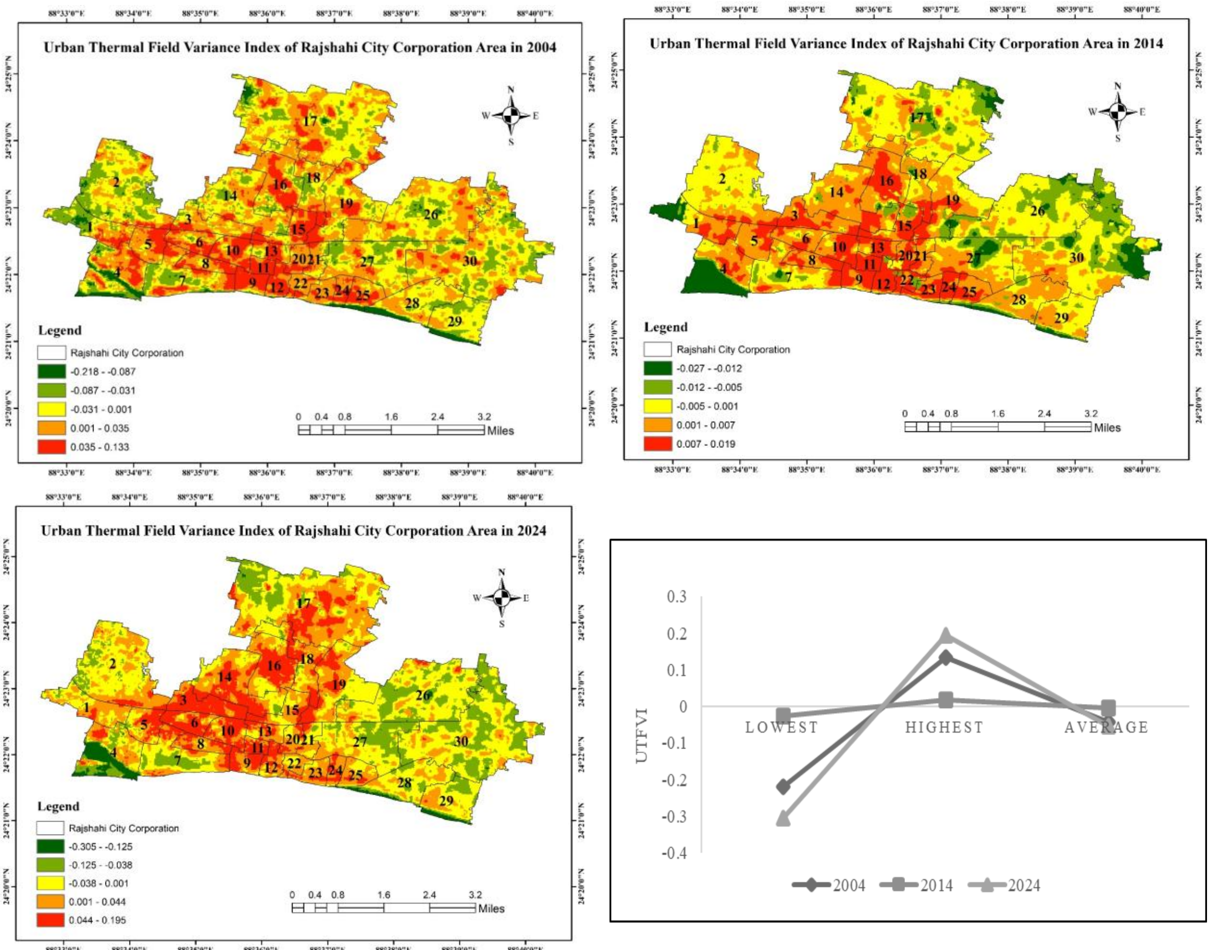


Figure 4: UTFVI of Rajshahi City Corporation in 2004, 2014, 2024 and Trend of UTFVI

3.3 Analysis of Urban Density Impact on LST and UTFVI

3.3.1 GWR-Based Urban Density Impact on LST

Figure 5 shows an increasing trend of correlation regarding the density-Urban LST relationship in the Rajshahi region from 2004 to 2024. Note that in 2004, GWR hotspots occurred in wards 4 & 9, showing the initial accumulation of LST in densely built-up regions. Meanwhile, low values were observed in peripheral regions that represented cooling effects due to vegetation. As of 2014, the increase of GWR hotspots in wards 4, 9, 11, 12 & 24 showed the progress of denser development at the expense of green vegetation. Finally, as of 2024, GWR hotspots predominantly occurred in wards 1, 11, 24 & 25, which emphasized the effect of compact development as well as impervious surfaces.

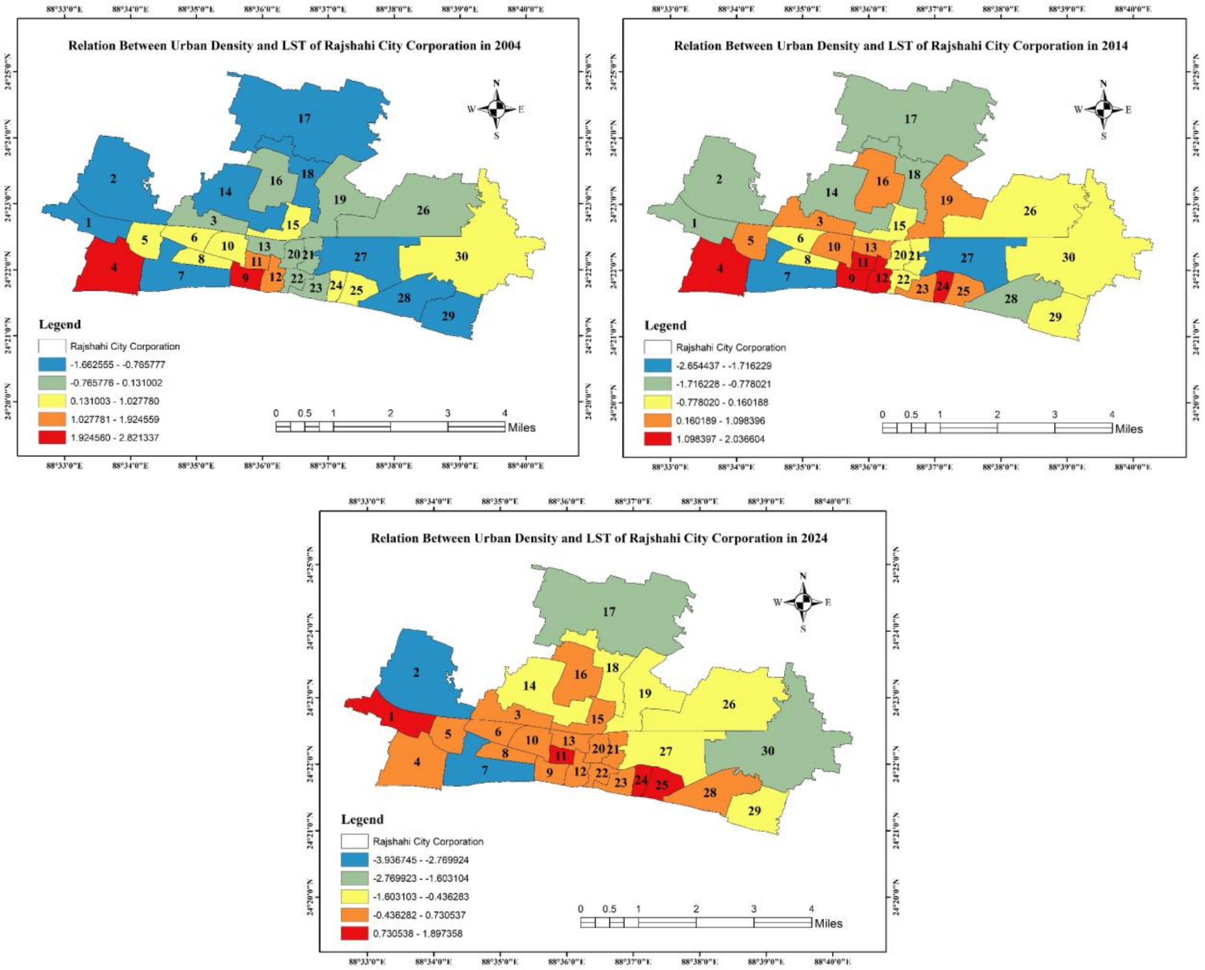


Figure 5: Urban Density Impact on LST in 2004, 2014 and 2024

3.3.2 GWR-Based Urban Density Impact on UTFVI

Figure 6 shows the change of interaction between city density and UTFVI in Rajshahi from 2004 to 2024. Initially, high relationships were noticed in wards 4, 9, and 11, where the highly built-up areas resulted in a strong thermal variation, while the greener wards showed low values. The same strong relationships were observed in wards 4 and 11 in 2014, and the increase of urbanization around these wards slightly allowed high relationships to be seen in the nearby wards. The situation in 2024 was such that wards 1, 11, 24, and 25 displayed the highest correlations, whereas most of the outskirts wards remained low due to dense vegetation. Still, the overall trend was that in every part of the city the hotness consistently increased with the rising trend of urbanization.

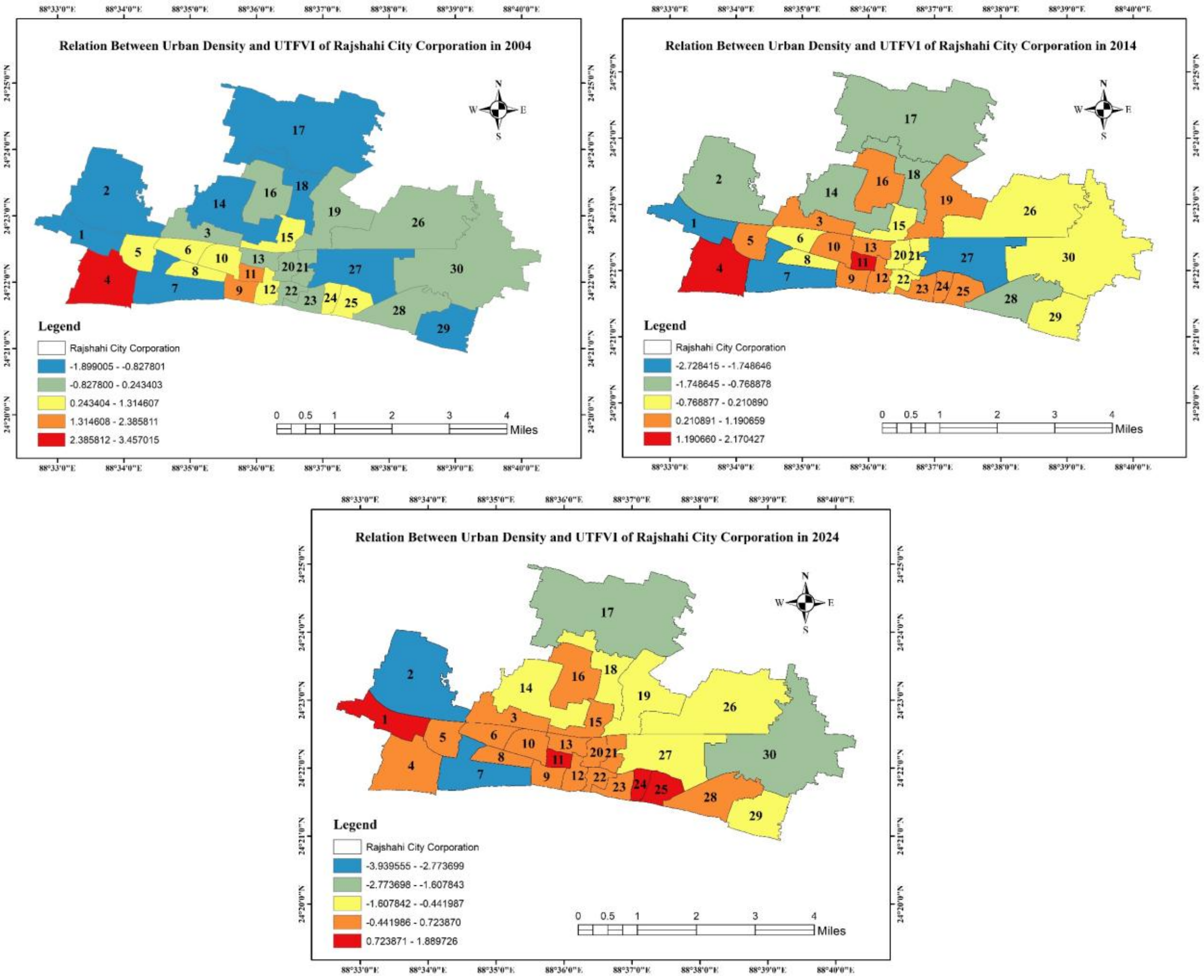


Figure 6: Urban Density Impact on UTFVI in 2004, 2014 and 2024

3.4 Horizontal Assessment of LST and UTFVI

3.4.1 Impact of Changes in LST

Urbanization between 2004 and 2014 caused a marked increase in Land Surface Temperature in the city core, which was due to the increase in impervious surfaces and the reduction of vegetation. During 2014-2024, the LST change was negligible or partially negative, which meant that both environmental and urban interventions were able to maintain or even lower the temperatures in the urban core.

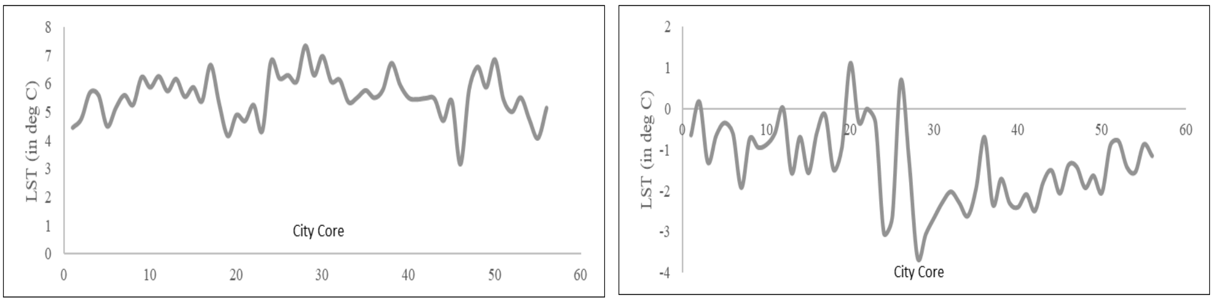


Figure 7: Impacts of LST Changes in 2014-2004 and 2024-2014

3.4.2 Impact of Changes in UTFVI

The Urban Thermal Field Variance Index in the city center experienced significant fluctuations from 2004 to 2014 owing to the high rate of urbanization and the creation of more impervious surfaces. Over 2014 to 2024, though the changes in UTFVI were lesser in magnitude, slight increases continued to be observed.

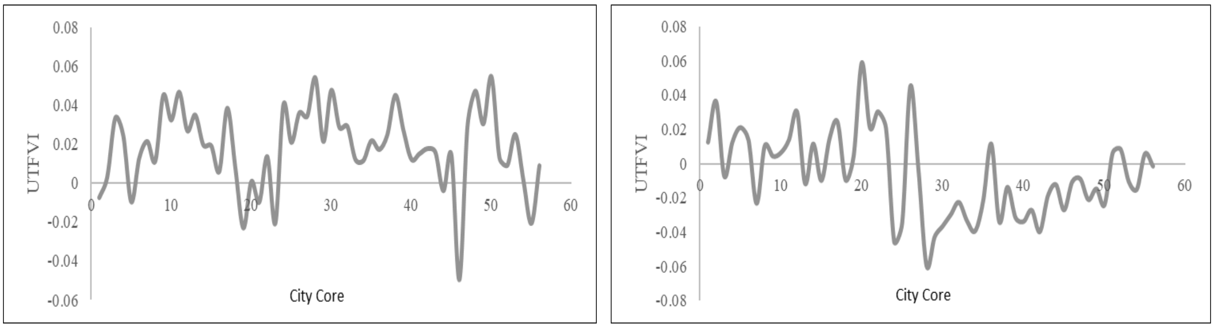


Figure 8: Impacts of UTFVI Changes in 2014-2004 and 2024-2014

3.5 Vertical Assessment of LST and UTFVI

3.5.1 Impact of Changes in LST

During the period from 2004 to 2014, the river area exhibited a gradual increase in land surface temperature (LST) because of the decreased water bodies, whereas the city center experienced a slight cooling effect that could be attributed to either the planting of new trees or the improvement of infrastructure. The outer city area continued to be the coolest part with almost no temperature change. However, from 2014 to 2024, the river area and city center got a little hotter while the fringe area remained unchanged thus, indicating the unequal effects of urbanization and environmental change on the different areas.

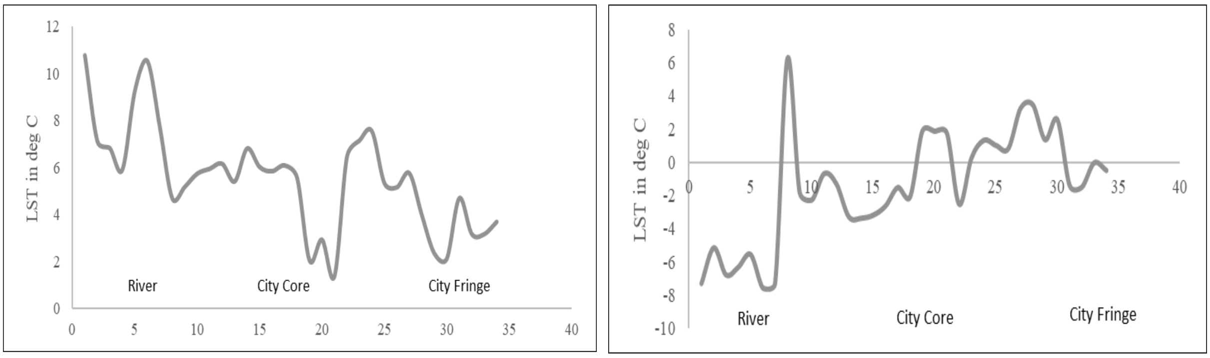


Figure 9: Impacts of LST Changes in 2014-2004 and 2024-2014

3.5.2 Impact of Changes in UTFVI

From 2004 to 2014, the river area recorded the highest UTFVI which indicates strong heat variation caused by the presence of bare surfaces and limited vegetation, while urban areas, the city core, and fringe had moderate to low values. The period from 2014 to 2024, witnessed a significant increase in UTFVI of the city core and fringe which indicates that urbanization, which was the main contributor, had a more intense heat retention effect, whereas the river area experienced more pronounced fluctuations due to possible alterations in water and land conditions surrounding it.

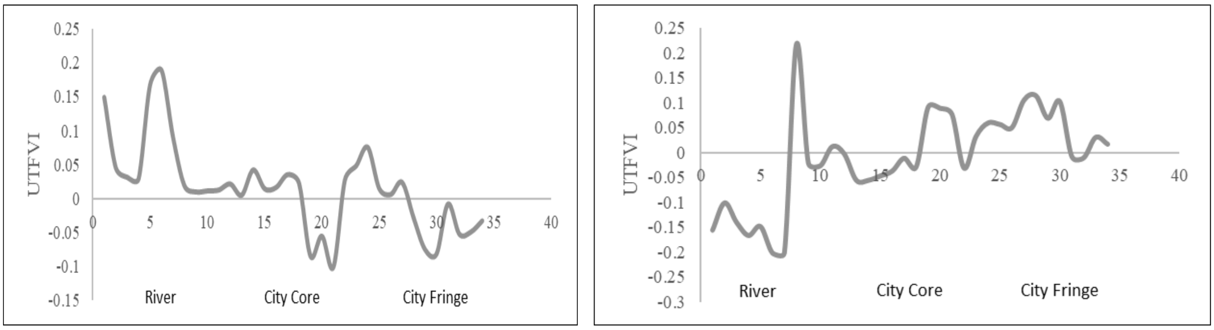


Figure 10: Impacts of UTFVI Changes in 2014-2004 and 2024-2014

4. CONCLUSIONS

The urban heat island effect has become more pronounced in Rajshahi City as indicated by the persistent rise in land surface temperatures (LST) and the urban thermal field variance index (UTFVI) over the years. The central and southern wards, which were majorly inhabited by low and medium-density populations, have been transformed into dense, impervious areas and hence endure higher both day and night temperatures as a result of lack of plants, little evaporative cooling, and poor air movement. The reduction in the number of the cooling plants and open areas has been a cause of prolonged heat and increased public health problems, especially during hot weather. The remaining vegetation in the outskirts still adds to the cooling and thus, the need to preserve the green zones. In order to maintain the city's heat-related risks as low as possible and to boost its resilience against the heat, the integrated urban planning strategies must focus on parks, green roofs, roadside trees, permeable and reflective surfaces, and mixed-use planning that will lead to the desired environmental quality being integrated with density.

ACKNOWLEDGEMENTS

All praises to Almighty Allah, the Most Gracious and Merciful. I would like to acknowledge my profound indebtedness to my teacher, Md. Kamrul Islam, Assistant Professor, Department of Urban and Regional Planning, Chittagong University of Engineering and Technology. Furthermore, I would like to thank my friends and classmates for their valuable discussion and suggestions on conducting the study.

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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