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A GIS-Based Climate-Responsive Urban Planning Framework for Urban Heat Island Mitigation in Rapidly Urbanizing Tier-II Indian Cities: Evidence from Gwalior

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ABSTRACT

Rapid urbanization has intensified the Urban Heat Island (UHI) effect across India's Tier-II cities, where climate-responsive planning is often inadequately integrated into statutory planning frameworks. Although numerous studies have assessed urban thermal patterns using geospatial techniques, limited research has translated these findings into transferable planning frameworks applicable to rapidly urbanizing intermediate cities. This study addresses this gap by developing a GIS-based climate-responsive urban planning framework for UHI mitigation, using Gwalior, Madhya Pradesh, as a representative Tier-II Indian city. Multi-temporal Landsat-8 imagery (2016 and 2026) was analysed to evaluate Land Use/Land Cover (LULC), Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), and Normalized Difference Built-up Index (NDBI). The results reveal a substantial increase in built-up area from 25.36% to 43.36%, accompanied by significant reductions in vegetation, agricultural land, and open spaces, leading to the expansion of high-temperature zones. A moderate negative correlation between NDVI and LST and a positive relationship between NDBI and LST demonstrate that vegetation loss and increasing impervious surfaces are key drivers of thermal intensification. Based on these findings, the study proposes a climate-responsive planning framework integrating green infrastructure, blue-green networks, cool materials, ventilation corridors, and climate-sensitive development regulations into statutory planning processes. While demonstrated through the Gwalior case study, the proposed framework is designed to be transferable to other rapidly urbanizing Tier-II Indian cities experiencing comparable land-use transformations and climate challenges, thereby supporting sustainable, heat-resilient, and climate-responsive urban development.

keywords - Geographic Information System, Urban Heat Island, Land Surface Temperature (LST), Land Use/Land Cover (LULC), Tier-II Indian Cities, Climate-responsive urban planning

Introduction

Urbanization has become one of the most significant drivers of environmental transformation and climate change worldwide. The rapid conversion of natural landscapes into impervious built-up surfaces has substantially altered the thermal characteristics of urban environments, giving rise to the Urban Heat Island (UHI) phenomenon, in which urban areas experience significantly higher temperatures than their surrounding rural regions (Oke, 1982; Voogt & Oke, 2003). Increasing land consumption, vegetation loss, anthropogenic heat emissions, and modifications in urban morphology have intensified surface temperatures, adversely affecting environmental quality, public health, energy consumption, and urban liveability. India is experiencing fast rates of urbanization, with considerable growth occurring in Tier-II and intermediate cities. While metropolitan cities have received substantial attention in Urban Heat Island research, rapidly expanding Tier-II cities remain comparatively underexplored despite exhibiting similar patterns of unplanned urban expansion, increasing impervious surfaces, declining vegetation cover, and growing climate vulnerability (Islam et al., 2024). These cities frequently lack climate-responsive planning mechanisms capable of integrating thermal considerations into statutory planning processes, thereby increasing their susceptibility to heat stress and reducing long-term urban resilience.

Recent advances in remote sensing and Geographic Information Systems (GIS) have enabled accurate assessment of Land Surface Temperature (LST), Land Use/Land Cover (LULC) change, vegetation dynamics through the Normalized Difference Vegetation Index (NDVI), and urban expansion using the Normalized Difference Built-up Index (NDBI). Numerous studies have demonstrated strong relationships between increasing impervious surfaces, declining vegetation

cover, and elevated land surface temperatures (Weng et al., 2004; Jha et al., 2024). However, the majority of existing research primarily focuses on mapping thermal patterns or evaluating environmental impacts, with comparatively limited emphasis on translating geospatial evidence into practical urban planning strategies and statutory development regulations. Consequently, a significant gap remains between scientific assessment and planning implementation, particularly within the context of India's rapidly urbanizing Tier-II cities.

Addressing Urban Heat Island effects requires moving beyond conventional mitigation measures toward climate-responsive urban planning that integrates land-use planning, urban morphology, green infrastructure, blue-green networks, sustainable drainage systems, and climate-sensitive development regulations. Planning interventions such as optimized development density, urban ventilation corridors, Green Plot Ratio standards, permeable surfaces, cool materials, and urban forestry can substantially improve thermal performance while supporting sustainable urban growth. Developing planning frameworks that systematically incorporate geospatial thermal analysis into statutory planning instruments is therefore essential for enhancing climate resilience in emerging Indian cities.

Gwalior, located in the state of Madhya Pradesh, represents a suitable demonstration case for this investigation because it exhibits many characteristics common to rapidly urbanizing Tier-II Indian cities, including accelerated urban expansion, conversion of agricultural land, increasing built-up density, fragmented green spaces, and recurring summer temperatures exceeding 45°C. Rather than treating Gwalior as an isolated case, this study considers it a representative urban laboratory for developing and evaluating a transferable planning framework applicable to cities experiencing comparable climatic conditions, urbanization trajectories, and planning challenges.

Accordingly, this study develops a GIS-based climate-responsive urban planning framework by integrating multi-temporal analysis of Land Use/Land Cover (LULC), Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), and Normalized Difference Built-up Index (NDBI) using Landsat-8 imagery for 2016 and 2026. Spatial correlation and regression analyses are employed to examine the relationships between urban expansion, vegetation dynamics, impervious surfaces, and thermal characteristics. Based on these findings, the study proposes planning interventions that integrate green infrastructure, blue-green systems, climate-sensitive development regulations, and nature-based solutions into statutory planning processes.

The principal contribution of this research lies not only in assessing Urban Heat Island dynamics in Gwalior but also in developing a transferable framework that enables planners and decision-makers to integrate geospatial thermal analysis into Master Plans, Development Plans, Development Control Regulations, and Urban Heat Action Plans across rapidly urbanizing Tier-II Indian cities. By bridging the gap between remote sensing analysis and planning practice, the proposed framework contributes to the advancement of climate-resilient urban planning and supports the achievement of Sustainable Development Goal 11 (Sustainable Cities and Communities) and Sustainable Development Goal 13 (Climate Action).

STUDY AREA

Gwalior is a fast-growing Tier-II city of northern Madhya Pradesh, India with historical importance. The city is situated at 26.20°N latitude and 78.18°E longitude and is in the Gird region of Madhya Pradesh. Gwalior's strategic geographical position makes it an important administrative, educational, commercial, cultural and transportation centre connecting northern and central India.

The city has a hot semi-arid climate with very hot summers, moderate monsoon rainfall and comparatively cool winters. The city is prone to heat stress and UHI intensification during April, May and June when summer temperatures can easily exceed 45 °C. The mean annual rainfall is mainly confined to the southwest monsoon season and long dry spells and sparse vegetation in the summer result in increased thermal stress conditions (Islam et al. 2024).

Fig. 1. Study area location and extent.



Over the last 2 decades, high population growth, infrastructure development, institutional expansion, industrial activities and peri-urban land transformation have led to significant urban growth in Gwalior. As in many other fast-growing Indian cities, urbanisation in Gwalior has been mostly in the form of horizontal sprawl and low-rise, high-ground-coverage development patterns. The development has led to an increase in impervious surfaces, decrease in vegetation cover, fragmentation of open spaces and decline in ecological resilience, all of which contribute significantly to the Surface Urban Heat Island (SUHI) (Oke 1982; Srivastava et al. 2024).

The urban morphology of Gwalior is a combination of:

a. Historic compact city core b. Planned residential colonies
b. Commercial corridors
c. Institutional campuses
d. Industrial areas
e. Peri-Urban Settlements

The historic core area is characterised by a dense built-up fabric, narrow streets, limited ventilation and a high concentration of impervious surfaces, which results in increased thermal accumulation. In contrast, peripheral regions are undergoing rapid conversion of agricultural and open land into residential and commercial built-up zones, intensifying urban expansion and changing the thermal landscape of the city. Gwalior has witnessed a steady decline in its ecological surfaces due to urban encroachment and infrastructure development. Built-up areas have rapidly expanded while vegetation cover, open lands and agricultural surfaces have significantly reduced from 2016 to 2026. The city still has an uneven distribution of existing green-blue infrastructure, including parks, institutional green spaces, water bodies and vegetated patches. Vegetation and water bodies are thought to play a large role in localised cooling through shade and evapotranspiration processes (Jha et al. 2024; Pritipadmaja et al. 2023). The cumulative cooling effectiveness of these has been weakened by fragmentation and reduction of ecological surfaces in Gwalior.

Unlike metropolitan cities where Urban Heat Island research has been extensively carried out, Tier-II cities like Gwalior are comparatively less explored of late despite they are witnessing significant urban growth and environmental stress (Islam et al. 2024). Thus the city of Gwalior serves as an appropriate case to study the interlinkage between Land Use/ Land Cover (LULC) change, urban morphology, vegetation and thermal characteristics in rapidly urbanising Indian cities. The present study aims to analyse the spatial distribution and temporal variation of Land Surface Temperature (LST), Land Use/Land Cover (LULC), vegetation density and built-up intensity in Gwalior in the years 2016 and 2026 by using Remote Sensing and Geographical Information System (GIS) based techniques. Multi-temporal Landsat-8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) datasets, obtained from United States Geological Survey (USGS) Earth Explorer platform, were used to assess Urban Heat Island dynamics and to formulate climate-responsive planning strategies for sustainable urban development.

Rather than considering Gwalior as an isolated case study, this research adopts the city as a representative demonstration case for developing and evaluating a transferable GIS-based climate-responsive planning framework. The city's climatic conditions, urban growth trajectory, planning characteristics, and environmental challenges closely resemble those of many rapidly urbanizing Tier-II Indian cities. Therefore, the methodology and planning framework proposed in this study can be adapted to other intermediate cities with similar physical, climatic, and developmental characteristics, thereby enhancing the broader applicability of the research beyond the specific case of Gwalior.

METHODOLOGY

The present study is based on the spatial analysis techniques of Geographical Information System (GIS) to study the spatial dynamics of Urban Heat Island (UHI) formation in Gwalior city. The methodological framework integrates Land Surface Temperature (LST) analysis, Land Use/Land Cover (LULC) classification, vegetation assessment, built-up analysis and spatial correlation techniques to assess the relationship between urban expansion and thermal variability (Weng et al. 2004; Voogt & Oke 2003). It further examines the influence of changes in urban morphology, decrease in vegetation cover and increase in impervious surfaces in intensifying Surface Urban Heat Island (SUHI) in fast urbanising Tier-II cities.

RESEARCH DESIGN

The study follows a quantitative and spatial analytical approach and makes use of multi-temporal satellite imagery for the years 2016 & 2026. Changes were assessed over time using a comparative analysis of:

a. Land Use/Land Cover (LULC)
b. Land Surface Temperature (LST)
c. Vegetation density
d. Thermal hotspots in urban areas e. Built-up intensity

The approach combines techniques of thermal remote sensing with GIS-based spatial interpretation to link urban growth patterns with thermal behaviour (Weng 2009; Islam et al. 2024).

LAND USE/LAND COVER (LULC) CLASSIFICATION

Land Use/Land Cover classification was conducted to assess urban growth and land-transformation patterns between 2016 and 2026. Supervised classification techniques were employed using training samples generated through image interpretation and reference data (Anderson et al. 1976).

The urban landscape was classified into five major categories:

1. Built-up area
2. Agriculture
3. Vegetation
4. Open/Fallow land
5. Water bodies

Post-classification comparison techniques were used to quantify temporal changes in land-use categories and identify patterns of urban expansion and ecological surface loss.

ACCURACY ASSESSMENT AND VALIDATION

An accuracy assessment was performed to evaluate the reliability of the classified LULC outputs using a confusion matrix approach (Congalton 1991). Random validation points were compared to classified outputs to determine classification performance and minimisation of interpretation errors.

The Kappa value indicates a substantial agreement between the classified outputs and the reference data other than chance (Congalton & Green 2009). The classification accuracy obtained was considered satisfactory for further thermal and spatial analysis

Overall Accuracy (OA) $= \frac{\sum_{j=1}^{k} TP_{jj}}{TP}$ And Kappa Index (KI) $= \frac{N\sum_{j=1}^{k} TP_{jj} - \sum_{j=1}^{k}(TP_{jR} \times TP_{jP})}{TP^2 - \sum_{j=1}^{k}(TP_{jR} \times TP_{jP})}$

ESTIMATION OF LAND SURFACE TEMPERATURE (LST)

The Land Surface Temperature (LST) was obtained from the Landsat-8 Thermal Infrared Sensor (TIRS) Band 10 image using the emissivity corrected single channel algorithm proposed by Avdan and Jovanovska (2016). The procedure consisted of the conversion of Digital Number (DN) values to Top of Atmosphere (TOA) spectral radiance, the derivation of Brightness Temperature (BT), the estimation of Land Surface Emissivity (LSE) using the NDVI threshold method (Sobrino et al. 2004) and the computation of final Land Surface Temperature values.

See "Appendix I" for Equations Used for LST

NDVI ANALYSIS

The Normalised Difference Vegetation Index (NDVI) was calculated to assess the spatial distribution and density of vegetation in the study area. NDVI is a well-known indicator of vegetation that measures photosynthetically active vegetation based on the spectral contrast between the Near Infrared (NIR) and Red reflectance values (Rouse et al. 1974). The index was derived from Landsat-8 Operational Land Imager (OLI) images using Band 5 (NIR) and Band 4 (Red) as:

$NDVI = (NIR - Red)/(NIR + Red)$

NDVI values range from -1 to +1 , with higher positive values indicating dense vegetation cover, values close to zero indicating sparse vegetation or bare surfaces, and negative values generally associated with water bodies . The resulting NDVI maps were used to assess the vegetation distribution and to investigate the relationship between vegetation density and Land Surface Temperature. Finally, correlation and regression analyses were performed to assess the effect of vegetation on urban thermal characteristics and Urban Heat Island intensity.

ANALYSIS OF NDBI

The Normalised Difference Built-up Index (NDBI) was computed for assessing the built-up intensity and distribution of impervious surfaces in Gwalior city. NDBI is a widely used urban index to identify built-up areas and urban expansion using satellite imagery (Zha et al. 2003). The index was calculated using Landsat-8 Shortwave Infrared (SWIR) and Near Infrared (NIR) bands as:

$NDBI = (NIR - SWIR)/(NIR + SWIR)$

The positive NDBI values are associated with dense built-up and impervious surfaces. The lower or negative values are generally associated with vegetation and water bodies. The NDBI maps created were used to assess urban expansion patterns and to investigate the relationship between built-up density and thermal intensity. Subsequently correlation analysis was applied to assess the effect of impervious surfaces on the development of the Urban Heat Island.

CLIMATE RESPONSIVE PLANNING STRATEGIES DEVELOPMENT

Based on the empirical findings of LULC, LST, NDVI and NDBI analysis, climate-responsive planning and development control strategies were developed to mitigate Urban Heat Island in Gwalior city. The proposed framework includes green infrastructure, blue-green systems, cool roofing technologies, permeable surfaces, climate-sensitive development controls,

and sustainable urban planning principles. The framework highlights the urban heat island mitigation can be operationalised through statutory planning instruments and development regulations rather than as stand-alone environmental interventions (Srivastava et al. 2024; Nastar 2020).

METHODOLOGICAL FRAMEWORK

The combination of these approaches allowed a complete assessment of Urban Heat Island dynamics. It assisted in developing evidence-based planning strategies for sustainable and climate-resilient urban development in rapidly urbanising Tier-II Indian cities.

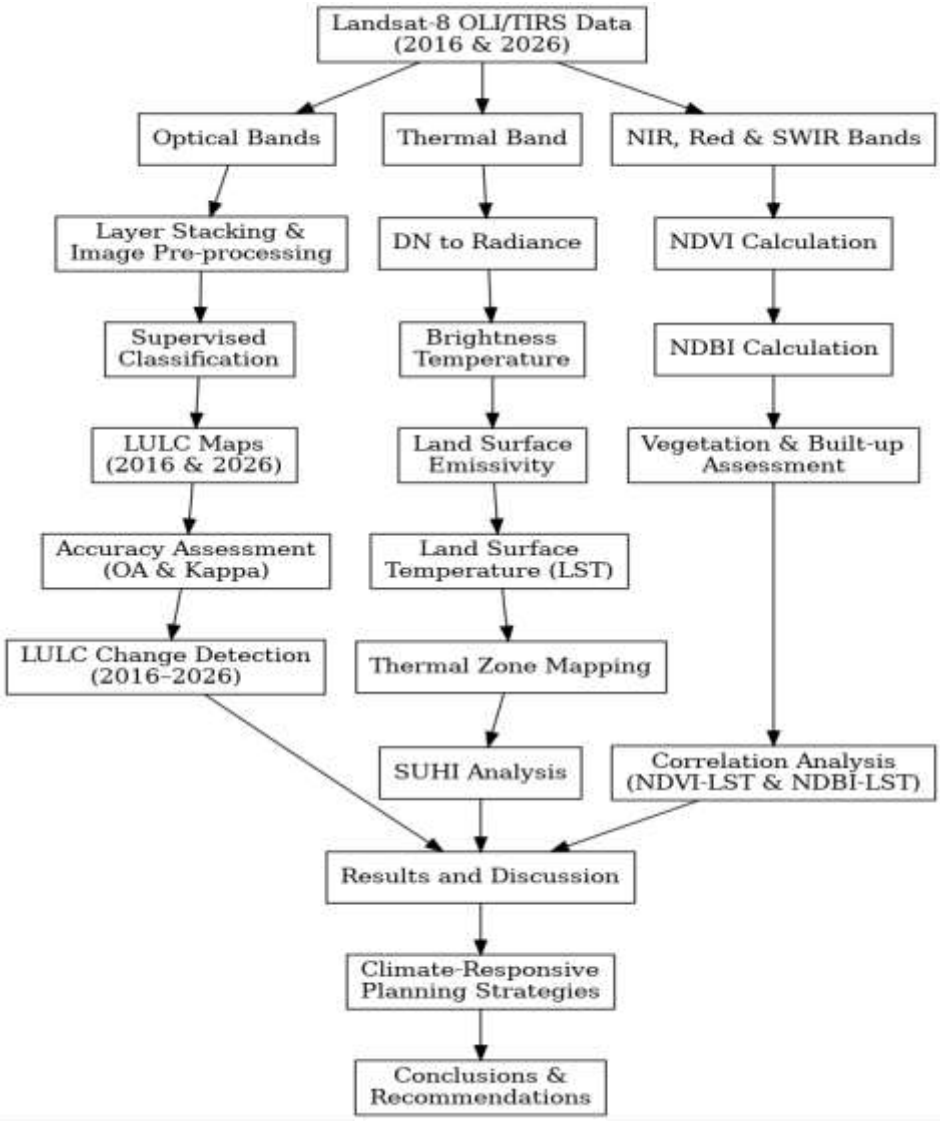


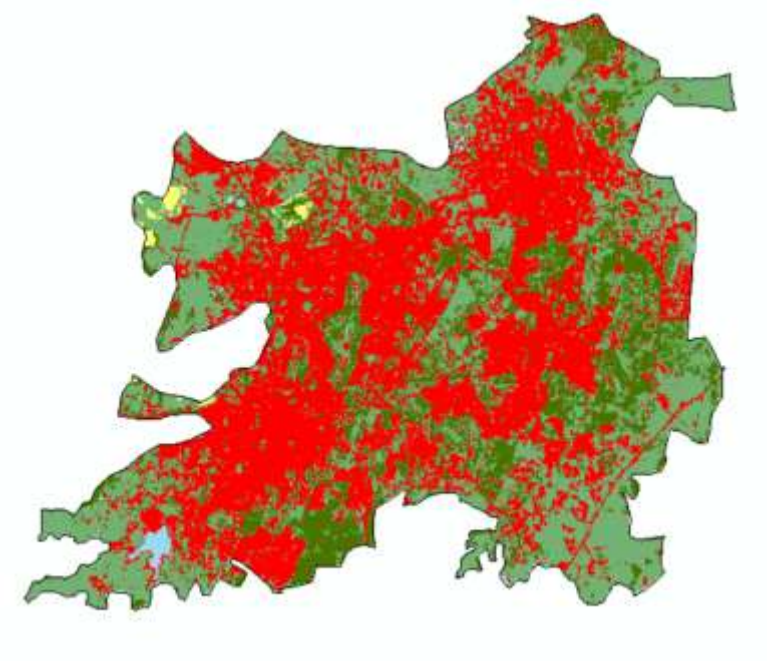
Fig. 2 illustrates the overall methodological framework adopted in this study

Results And Discussion

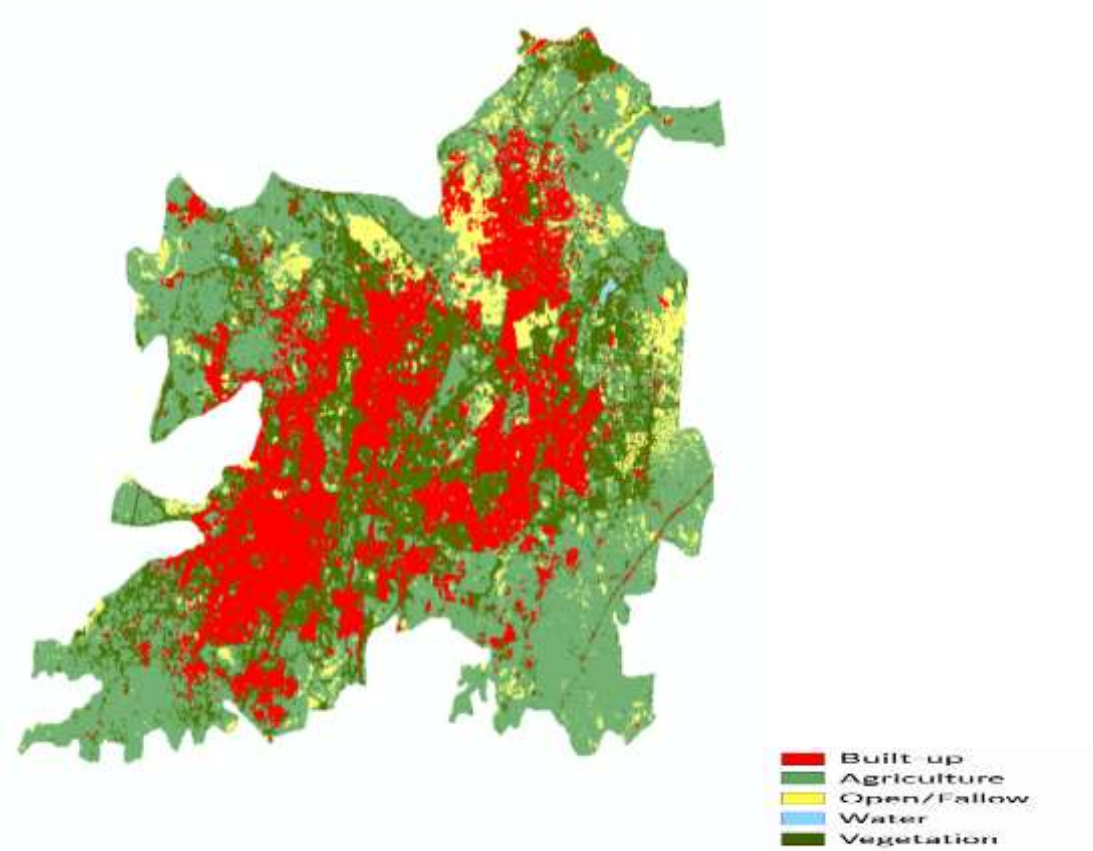
Land Use/Land Cover (LULC) Change Analysis

The Land Use/ Land Cover (LULC) analysis was carried out by using supervised classification of Landsat-8 Operational Land Imager (OLI) images of 2016 and 2026. The classified outputs produced in ArcGIS 10.8 were used for evaluating spatial and temporal changes in urban land transformation in the city of Gwalior. Comparison of classified maps showed significant urban growth and significant changes in ecological surfaces over the decade. The urban landscape was divided into five major land-use classes.

Figures 3 and 4 show the classified LULC maps for 2016 and 2026 respectively.



Figures 3



Figures 4

The LULC results indicate fast urbanisation and growing concentration of impervious surfaces in Gwalior city. The built-up area has risen substantially from 25.36% in 2016 to 43.36% in 2026, an overall increase of approximately 18%. This substantial increase is demonstrative of the urbanisation, infrastructure development, residential construction and peri-urban transformation happening across the city. The observed land transformation reflects the ongoing transition of Gwalior from a medium-sized regional city into a rapidly expanding urban centre. Similar urban growth trajectories have been documented in several Indian Tier-II cities, where increasing population, infrastructure investment, and economic development have accelerated the conversion of natural landscapes into impervious urban surfaces (Islam et al., 2024). These findings indicate that the urbanization process occurring in Gwalior is not unique but forms part of a broader pattern of urban development across emerging Indian cities.

Table 1 summarises the temporal changes in Land Use/Land Cover between 2016 and 2026.

Land Use Category	2016 (%)	2026 (%)	Difference (%)
Built-up	25.36	43.36	+18.00
Agriculture	43.62	37.47	-6.15
Open/Fallow	8.23	0.53	-7.70
Vegetation	22.65	18.05	-4.60
Water	0.14	0.59	+0.45

The increase in built-up area was primarily due to conversion of agricultural land, open/fallow land and vegetated land to urbanised land uses. Similar trends of urban growth have been observed for rapidly growing Indian cities, where unregulated urbanisation has been identified as a major contributor to the intensification of Urban Heat Islands (Islam et al. 2024).

Agricultural land decreased by about 6.15% from 43.62% to 37.47%. In peri-urban areas much of the agricultural land was transformed to residential and commercial development. The largest decline was in Open/Fallow land which declined sharply from 8.23% to 0.53%, indicating intensive encroachment of urban areas and decreasing availability of undeveloped land.

Vegetation cover decreased from 22.65% in 2016 to 18.05% in 2026 i.e. reduction of ~4.60%. The loss of vegetation and ecological surfaces reduced the cooling capacity of the urban environment, and contributed to increasing thermal accumulation. The disappearance of vegetation is directly related to the creation of the Surface Urban Heat Island by decreasing evapotranspiration and shading (Jha et al. 2024; Pritipadmaja et al. 2023). Water bodies increased slightly from 0.14% to 0.59%, but their overall spatial extent remained limited and insufficient to offset increasing thermal stress at the city scale.

The LULC maps obtained from ArcGIS 10.8 vividly illustrate the growth of impervious urban surfaces and the loss of ecological land covers from 2016 to 2026. Such transformations significantly altered the thermal properties of the city and worsened the Surface Urban Heat Island conditions.

Accuracy Assessment & Validation

The accuracy of the classified LULC outputs was evaluated by the confusion matrix approach according to standard Remote Sensing accuracy assessment procedures (Congalton 1991). Random validation points were compared with classified outputs produced from supervised classification in ArcGIS 10.8.

Table 2 Confusion Matrix

OID	Class Value	C_1	C_10	C_35	C_47	C_65	Total	U_Accuracy	Kappa
0	C_1	10	0	0	0	0	10	1	0
1	C_10	0	18	0	0	0	18	1	0
2	C_35	0	10	24	2	1	37	0.648649	0
3	C_47	0	3	0	39	1	43	0.906977	0
4	C_65	0	1	0	0	9	10	0.9	0
5	Total	10	32	24	41	11	118	0	0
6	P_Accuracy	1	0.5625	1	0.95122	0.818182	0	0.847458	0
7	Kappa	0	0	0	0	0	0	0	0.797464

The analysis of the confusion matrix generated the following statistical indicators:

1. Overall Accuracy = 84.75%
2. Kappa Coefficient=0.797

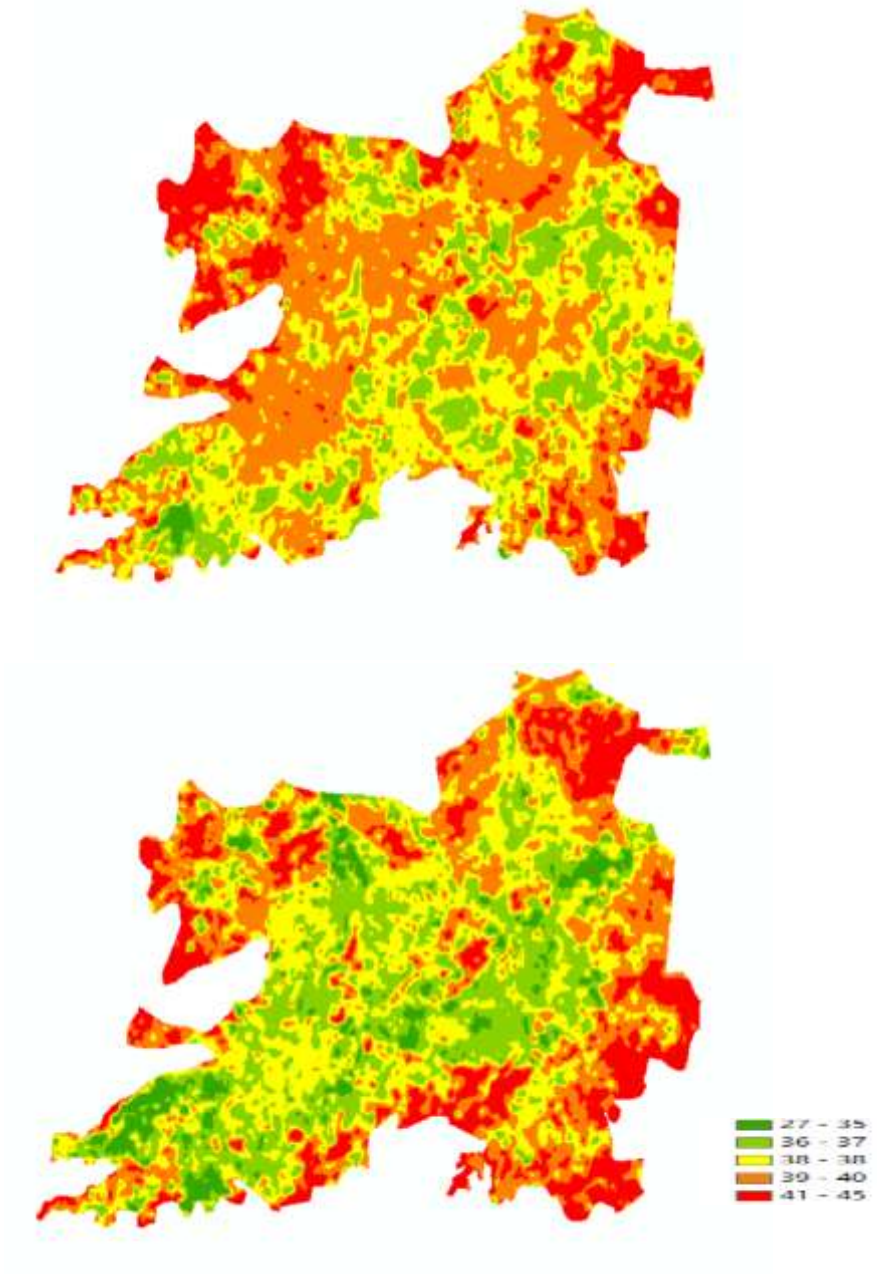
The Overall Accuracy obtained shows that about 85% of the classified pixels were in agreement with the reference data, indicating a satisfactory classification performance for urban spatial analysis.

The Kappa Coefficient of 0.797 shows a substantial agreement between the classified outputs and the reference datasets beyond chance (Congalton & Green 2009). The classification accuracy achieved is above the commonly accepted threshold for Remote Sensing based LULC studies and confirms the reliability of classified outputs for further thermal and spatial analysis.

Analysis of Land Surface Temperature (LST)

Land Surface Temperature (LST) was analysed using Landsat-8 Thermal Infrared Sensor (TIRS) Band 10 imagery for the years 2016 and 2026. Thermal processing was carried out in ArcGIS 10.8 where the Digital Number values were converted to spectral radiance, brightness temperature, emissivity correction and the final temperature extraction in degrees Celsius (Avdan & Jovanovska 2016).

Figures 5 and 6 illustrate the spatial distribution of Land Surface Temperature across Gwalior for 2016 and 2026



Figures 6

Gwalior city exhibits substantial spatial variations in thermal properties as shown by the LST maps. High temperature zones were mostly confined to:

a. Areas densely built up
b. Commercial corridors
c. Industrial areas
d. Compact city fabric
e. rapidly urbanising peri-urban areas

Surface temperatures in these areas were between 41 and 45°C, which is a strong Surface Urban Heat Island intensity. The major causes of the thermal accumulation in these areas are impervious urban materials such as asphalt, concrete and rooftops with high thermal storage capacity and reduced moisture retention (Oke 1982).

Comparison of thermal behaviour between 2016 and 2026 shows expansion of high temperature zones spatially corresponding to built-up growth and land transformation. The peri-urban areas, previously agricultural and open land, were newly urbanised and showed marked increases in Land Surface Temperature by 2026. The emergence of new thermal hotspots was particularly evident along major transportation corridors, newly developed residential colonies, industrial estates, and mixed-use commercial areas. These locations are characterized by high building density, extensive paved surfaces, limited vegetation, and increased anthropogenic heat emissions arising from traffic, commercial activities, and

energy consumption. Such urban characteristics collectively intensify the Surface Urban Heat Island (SUHI) effect by disrupting the natural surface energy balance and reducing opportunities for passive cooling.

The observed relationship between urban expansion and increasing surface temperature is consistent with findings reported in other rapidly urbanizing Indian cities, including Nagpur, Jaipur, Indore, Hyderabad, and Bhubaneswar, where the conversion of vegetated and agricultural land into built-up areas has resulted in significant increases in Land Surface Temperature. These similarities indicate that the thermal processes observed in Gwalior are not unique but reflect broader urbanization trends occurring across many Tier-II cities in India. Consequently, the thermal response identified in this study can reasonably be interpreted as representative of emerging intermediate cities experiencing comparable land transformation and climatic conditions.

lower temperature zones were found in:

a. Parks and green spaces
b. Surfaces of agricultural use
c. Institutional Campuses
d. Areas associated with water
e. Vegetation Areas

These areas showed localised cooling effects due to vegetation-driven evapotranspiration and shading mechanisms (Jha et al. 2024). LST maps clearly show that rapid urbanisation and loss of ecological surface have greatly intensified Surface Urban Heat Island conditions in Gwalior city.

NDVI Analysis and its Relationship with LST

The density of vegetation and its ecological distribution over the study area was assessed by calculating the Normalised Difference Vegetation Index (NDVI) from Landsat-8 multispectral imagery. Higher NDVI values indicate dense vegetation cover whereas low NDVI values indicate built-up surfaces, barren land and sparse vegetation.

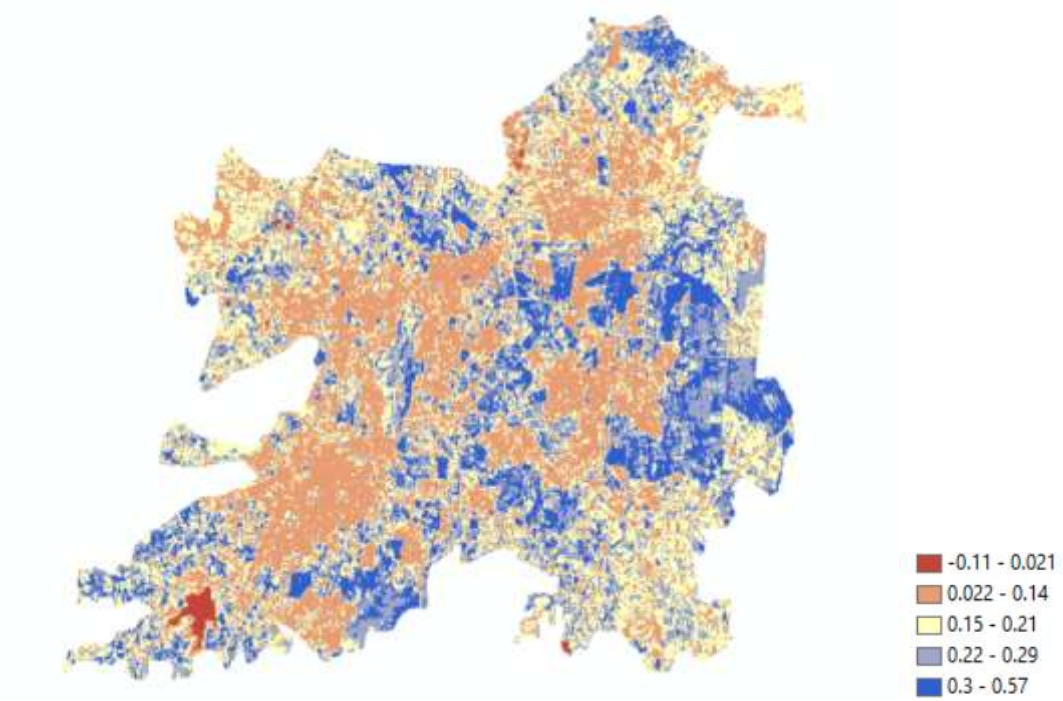


Figure 7 presents the NDVI distribution for 2026

Table 3 summarises the NDVI classification

NDVI Range	Land Cover Interpretation	Vegetation Condition
-0.11 - 0.021	Water bodies, barren land, dense built-up surfaces	No vegetation
0.022 - 0.14	Sparse vegetation, exposed soil, and urbanised areas	Very Low Vegetation
0.15 - 0.21	Grassland, scattered vegetation	Low Vegetation
0.22 - 0.29	Moderate vegetation cover	Moderate Vegetation
0.30 - 0.57	Dense vegetation, parks, forests, and agricultural patches	High Vegetation

Regression analysis between NDVI and Land Surface Temperature for April 2026 generated the following relationship:

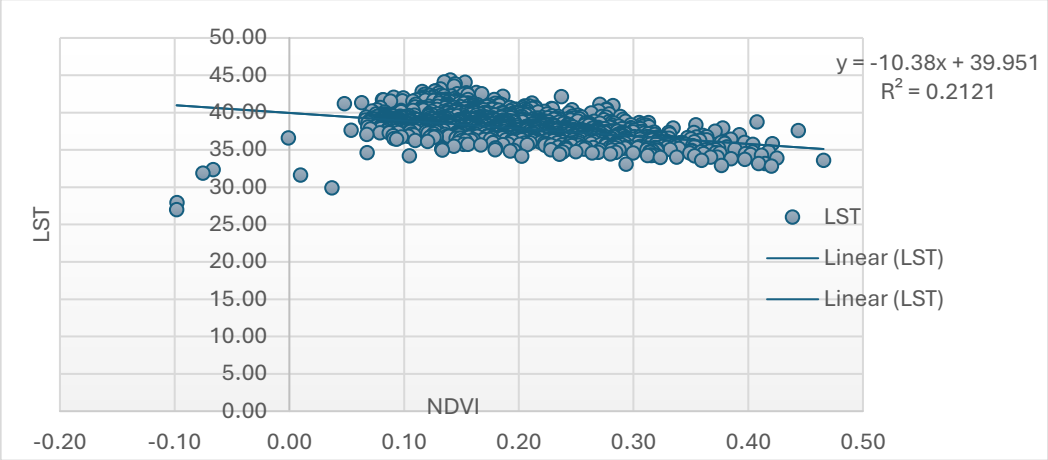


Figure 8 illustrates the relationship between NDVI and LST for April 2026.

The regression analysis of NDVI against Land Surface Temperature (LST) for April 2026 showed a coefficient of determination (R^2) of 0.2121. The corresponding Pearson correlation coefficient (r) was approximately -0.46, indicating a moderate negative correlation between vegetation density and surface temperature. The negative slope of the regression equation implies that the higher NDVI values are mainly related to the lower Land Surface Temperatures, reflecting the cooling effects of vegetation through shading and evapotranspiration.

The R^2 value obtained shows that vegetation cover explains about 21.21% of spatial variation in Land Surface Temperature. In contrast, the other 78.79% are related to other factors, such as built-up density, impervious surface concentration, urban morphology, land-use characteristics and anthropogenic heat emissions. The moderate negative Pearson correlation confirms that vegetation plays a significant role in reducing thermal intensity and mitigating Surface Urban Heat Island (SUHI) effects, although it is not the sole determinant of urban thermal conditions.

Similar inverse relations between NDVI and LST have been reported in studies performed in Delhi, Hyderabad and Bhubaneswar, highlighting the role of urban vegetation in controlling microclimatic conditions and enhancing urban climate resilience (Sharma & Kaur 2019; Jha et al. 2024).

Spatial analysis also revealed that parks, institutional green spaces and vegetated areas served as localised cooling zones, whereas sparsely vegetated and highly urbanised areas experienced higher surface temperatures. It was observed that the reduction in vegetation cover and fragmentation of ecological surfaces has resulted in the increase in Surface Urban Heat Island intensity over Gwalior city. These findings point to the significance of green infrastructure, urban forestry, and ecological conservation in achieving climate-responsive and sustainable urban development.

Table 4 Statistical Summary of NDVI- LST Regression Analysis

Statistical Indicator	**Value**	**Interpretation**
Coefficient of Determination (R^2)	0.2121	21.21% of LST variation explained by NDVI
Pearson Correlation Coefficient (r)	-0.46	Moderate negative correlation
Relationship Type	Inverse	Higher NDVI corresponds to lower LST
Explained Variance	21.21%	Attributable to vegetation density
Unexplained Variance	78.79%	Influenced by other urban and environmental factors that is other than vegetation density

NDBI Analysis

The Normalised Difference Built-up Index (NDBI) was calculated to assess built-up intensity and impervious surface concentration across the city of Gwalior (Zha et al. 2003).

Higher NDBI values indicated dense built-up and impervious surfaces, while lower values indicated vegetation and water bodies.

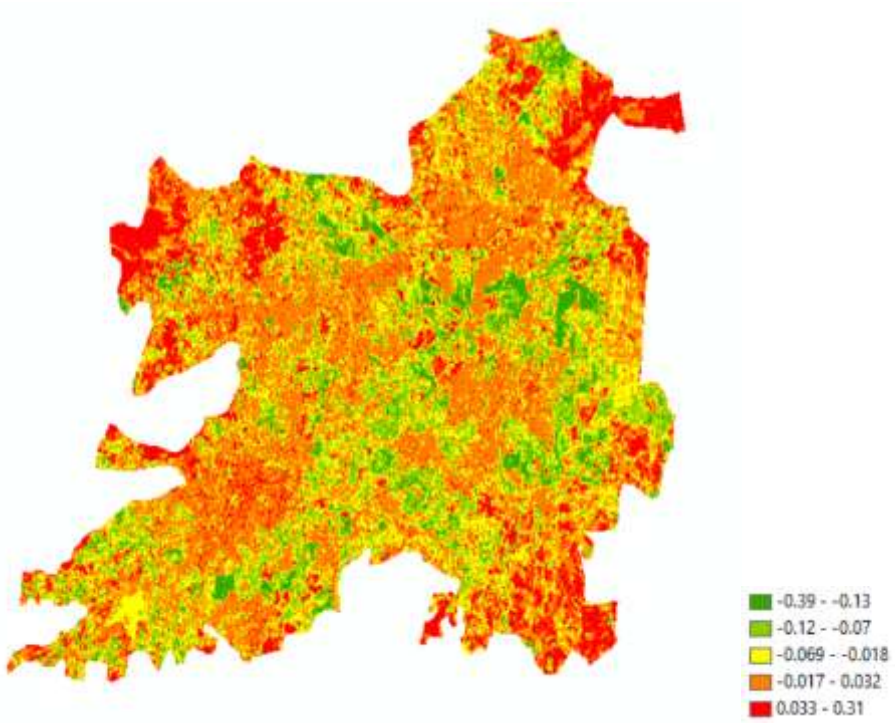


Figure 9 presents the spatial distribution of NDBI values for 2026.

The spatial analysis showed a significant positive correlation between NDBI and Land Surface Temperature. Areas with high NDBI values consistently showed high thermal intensity and stronger Surface Urban Heat Island effects. The highest values of NDBI and LST were found in dense commercial, industrial, transportation corridors and compact urban areas. The increase of built-up concentration contributed to:

a. Enhanced thermal absorption
b. Decreased evapotranspiration
c. Poor urban ventilation
d. More anthropogenic heat build-up
e. Increase in area of thermal hotspot zones

Conversely, the regions with lower NDBI values and higher vegetation cover had a lower thermal intensity.

The positive relationship observed between NDBI and LST validates that the increasing concentration of impervious surfaces significantly enhances the intensity of Surface Urban Heat Island in rapidly urbanising cities (Weng et al. 2004; Islam et al. 2024).

Conclusion

This study investigated the spatial and temporal dynamics of the Urban Heat Island (UHI) phenomenon in Gwalior, a rapidly urbanizing Tier-II city in central India, through the integrated analysis of Land Use/Land Cover (LULC), Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), and Normalized Difference Built-up Index (NDBI) using multi-temporal Landsat-8 imagery for 2016 and 2026. The findings reveal significant urban expansion during the study period, with built-up land increasing from 25.36% to 43.36%, accompanied by substantial reductions in vegetation, agricultural land, and open spaces. These land transformations have intensified the city's thermal environment, resulting in the expansion of surface thermal hotspots and increasing susceptibility to Urban Heat Island effects.

The analysis confirms that urban expansion is the primary driver of thermal intensification in Gwalior. Areas characterized by high built-up intensity consistently exhibited elevated Land Surface Temperatures, whereas vegetated landscapes maintained comparatively lower temperatures through shading and evapotranspiration. These findings highlight the importance of conserving ecological infrastructure while regulating built-up intensity to improve urban climate resilience.

Beyond evaluating thermal patterns, this study contributes by developing a GIS-based climate-responsive urban planning framework that integrates geospatial thermal analysis with planning interventions, including green infrastructure, blue-green networks, climate-sensitive Development Control Regulations, Green Plot Ratio (GnPR), urban forestry, cool materials, and ventilation corridors. The framework provides a practical mechanism for incorporating Urban Heat Island mitigation into Master Plans, Development Plans, and Urban Heat Action Plans, thereby bridging the gap between remote sensing analysis and statutory urban planning.

Although Gwalior served as the demonstration case, the methodological approach and planning framework are intended to be transferable to other rapidly urbanizing Tier-II Indian cities experiencing similar patterns of land transformation, climate vulnerability, and urban growth. The use of freely available satellite imagery, GIS-based spatial analysis, and

standardized thermal indicators enables the framework to be adapted by municipal authorities for monitoring urban expansion, identifying thermal hotspots, prioritizing climate adaptation interventions, and supporting evidence-based decision-making. Consequently, the significance of this study extends beyond the specific case of Gwalior and contributes to the broader discourse on climate-responsive urban planning in emerging Indian cities.

The findings underscore the need for urban planning policies that integrate climate considerations into future development strategies rather than treating Urban Heat Island mitigation solely as an environmental management issue. Embedding thermal assessment within statutory planning instruments can improve urban liveability, reduce heat-related risks, enhance environmental sustainability, and strengthen resilience to climate change.

Future research should extend this framework by incorporating higher-resolution satellite imagery, three-dimensional urban morphology, Local Climate Zone (LCZ) classification, machine learning-based thermal modelling, socio-economic vulnerability indicators, and field-based microclimate observations. Comparative analyses across multiple Tier-II cities would further validate and refine the proposed framework, contributing to the development of nationally applicable climate-responsive planning guidelines for sustainable urban development in India.

Planning interventions are key and include:

a. Urban afforestation, ecological corridors, green belts, and expansion of parks and community green spaces to reinforce urban cooling functions (Jha et al. 2024; Pritipadmaja et al. 2023).

b. Promote green roofs, rooftop gardens, vertical greening systems and green walls (Sharma & Kaur, 2019) in high-density urban areas with limited ground-level open space.

c. Use of cool roofs and high-albedo construction materials to reduce heat absorption, improve indoor thermal comfort and reduce cooling energy demand (Santamouris 2014)

d. Development of permeable pavements, bioswales, rain gardens, infiltration trenches and Sustainable Urban Drainage Systems (SUDS) to optimise the urban hydrology and reduce surface temperatures (Pritipadmaja et al. 2023).

e. Conservation and restoration of lakes, ponds, wetlands and other blue-green infrastructure elements to enhance evaporative cooling, ecological resilience, and water sensitive urban development.

f. Integration of climate-responsive development controls such as Green Plot Ratio standards, mandatory tree plantation requirements, ventilation corridors, open-space provisions, height-to-width ratio controls and FSI ground coverage optimisation (Srivastava et al. 2024).

The study also recommends preparation of an Urban Heat Action Plan at city-level, which shall be integrated with the Master Plans and Development Control Regulations. Such plans should take into account thermal hotspot mapping, heat vulnerability assessment, public cooling infrastructure, early warning systems and climate responsive planning guidelines to reduce heat related risks and improve urban resilience (Nastar 2020).

The results suggest that mitigation of Urban Heat Island should be considered as an important part of sustainable urban development. Future urban growth in Gwalior should be compact, resource-efficient and climate-responsive so as to minimise ecological degradation and improve environmental performance and urban liveability.

Vegetation, ecological corridors, urban forests, parks and blue-green infrastructure should be recognised as essential urban infrastructure for their contribution to thermal regulation, biodiversity conservation, ecosystem service provision and climate adaptation. Likewise, sustainable mobility strategies including shaded pedestrian networks, cycling infrastructure, transit-oriented development and tree-lined transport corridors can reduce thermal stress, improve accessibility and reduce greenhouse gas emissions at the same time (Bowler et al. 2010).

The inclusion of climate responsive planning regulations in Master Plans, Development Plans and Building Bye-laws can ensure that future urban development contributes to long term sustainability, climate resilience, energy efficiency and improved public health. The proposed framework, by correlating thermal analysis with planning regulations and sustainable development goals, offers a reproducible model for fast urbanising Tier-II and Tier-III Indian cities.

Furthermore, the proposed planning framework contributes directly to the achievement of Sustainable Development Goal 11 (Sustainable Cities and Communities) and Sustainable Development Goal 13 (Climate Action) through fostering resilient, inclusive, environmentally sustainable and climate responsive urban development.

APPENDIX

APPENDIX I: Equations used to calculate Land Surface Temperature

The Land Surface Temperature (LST) analysis was performed by using the Landsat-8 Thermal Infrared Sensor (TIRS) Band 10 images based on the emissivity corrected single channel algorithm suggested by Avdan and Jovanovska (2016).

Spectral Radiance ($L\lambda$) $= ML \times Qcal + AL$

Brightness Temperature (BT) $= K2 \times \ln(K1 / L\lambda + 1)$

Vegetation percentage (Pv) $= \left(\frac{NDVI - NDVImin}{NDVImax - NDVImin}\right)^2$

Surface Emissivity of Land (ε) $= 0.004 \times Pv + 0.986$

Land Surface Temperature (LST) $= BT / [1 + (\lambda BT/\rho) \times \ln(\varepsilon)]$

Temperature Conversion (LST) °C $= LST\ (K) - 273.15$

where all variables are defined in the Notation section.

APPENDIX II: Satellite Data used

Parameter	Description
Satellite	Landsat-8
Sensors	OLI and TIRS
Acquisition Years	2016 and 2026
Season	April
Spatial Resolution	30 m
Thermal Band	Band 10
NDVI Bands	Band 5 (NIR), Band 4 (Red)
NDBI Bands	Band 6 (SWIR), Band 5 (NIR)
Processing Software	ArcGIS 10.8
Data Source	USGS Earth Explorer

Availability of Data and Material

For this study, the datasets of Landsat-8 OLI and TIRS are downloaded from the USGS Earth Explorer platform (https://earthexplorer.usgs.gov). The GIS databases used to extract the administrative boundaries data are publicly available. The processed data sets, thematic maps, classification results and analytical results obtained in the course of this study are available from the corresponding author on reasonable request.

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NOTATIONS

In this paper we use the following symbols:

AL = additive scaling factor for radiance
BT = Brightness Temperature (K)
FSI = Floor Space Index
GIS = Geographic Information System
K_1 = thermal calibration constant
K_2 = thermal calibration constant
$L\lambda$ = spectral radiance (W m^{-2} sr^{-1} μm^{-1})
LSE = Land Surface Emissivity;
LST = Land Surface Temperature (°C)
LULC = Land Use/Land Cover
ML = multiplicative scaling factor for radiance
NDBI = Normalised Difference Built-up Index
NDVI = Normalised Difference Vegetation Index
NIR = Near Infrared reflectance
OLI = Operational Land Imagery
Pv = vegetation proportion
Qcal = quantised calibrated pixel value
r = Pearson correlation coefficient
R^2 = coefficient of determination
Red = Red reflectance
SUHI = Surface Urban Heat Island
SUDS = Sustainable Urban Drainage Systems
SWIR = Shortwave Infrared reflectance
TIRS = Thermal Infrared Sensor
TOA = Top-of-Atmosphere radiance
UHI = Urban Heat Island
USGS = United States Geological Survey

ε = surface emissivity
λ = wavelength of emitted radiance
$\rho = hc/\sigma$

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