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**Research Paper**


# Urban Heat Islands and Sustainable City Design: Remote Sensing Assessment of Morphology-Driven Temperature Variations


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## ABSTRACT

Urban Heat Island (UHI) refers to the phenomenon where urban regions experience significantly higher temperatures compared to their surrounding rural areas. This effect is largely attributed to factors such as dense built-up structures, reduced green cover, impervious surfaces, and anthropogenic heat emissions. The present study investigates the spatial relationship between UHI intensity and urban morphological characteristics by employing remote sensing and geospatial techniques. Satellite datasets from Landsat 8 and Sentinel-2 were utilized to derive essential indices, including Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), and Normalized Difference Water Index (NDWI). The analysis was carried out for Pali, Rajasthan over the period 2018-23, focusing on the interaction between land cover elements and thermal variations. The findings indicate a strong positive correlation between the proportion of built-up areas and surface temperature, while vegetation cover exhibits a significant negative correlation, highlighting its cooling effect. Water bodies also demonstrated localized cooling, though their influence was relatively limited compared to vegetation. The study underscores the critical role of urban morphology in shaping thermal environments and suggests that sustainable planning practices, such as the incorporation of green infrastructure and strategic vegetation enhancement, are essential for mitigating heat stress in rapidly urbanizing regions. These insights can support policymakers and urban planners in designing climate-resilient cities that balance developmental needs with environmental sustainability.



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**KEYWORDS:** Urban Heat Island, Remote Sensing, Land Surface Temperature, Urban Morphology, NDVI, NDBI.


## 1. INTRODUCTION

The process of rapid urbanization has brought significant changes to natural landscapes, leading to the transformation of vegetated areas into built-up regions dominated by concrete, asphalt, and other impervious materials. This alteration of land cover modifies the local energy balance and thermal dynamics, resulting in the phenomenon commonly known as the Urban Heat Island (UHI) effect. UHI is characterized by elevated temperatures in urban areas compared to their rural counterparts, primarily due to the high heat retention capacity of artificial surfaces and the lack of adequate vegetation. The intensity of

UHI varies across cities and seasons, influenced by both physical and socio-economic factors.

The implications of UHI extend beyond mere thermal discomfort. It directly affects energy consumption patterns, particularly increasing the demand for cooling in buildings during summer months. Furthermore, UHI exacerbates air pollution, influences local climatic conditions, and poses health risks by intensifying heat stress, especially during extreme weather events. Consequently, understanding the mechanisms behind UHI formation and identifying the key contributing factors have become essential for sustainable urban development and climate resilience.

Urban morphology plays a pivotal role in determining the intensity and distribution of heat within a city. Features such as building density, height variations, street geometry, surface albedo, and the presence or absence of green infrastructure significantly regulate heat accumulation and dissipation. Cities with compact layouts and minimal vegetation tend to exhibit higher UHI intensity, while areas with parks, water bodies, and vegetation show a noticeable cooling effect.

Remote sensing technology provides a powerful toolset to study UHI patterns and their relationship with urban morphology at various spatial and temporal scales. Through satellite-based data, parameters like Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), and Normalized Difference Built-up Index (NDBI) can be derived with high accuracy. Geographic Information Systems (GIS) further enhance the ability to map, analyze, and correlate these parameters with urban structural characteristics.

This research aims to assess UHI intensity using remote sensing techniques and evaluate its association with urban morphological features. By integrating multi-source satellite datasets, the study offers insights that can aid in urban planning strategies, promoting sustainable and climate-resilient city development.

## 2. OBJECTIVES

- To compute and visualize Land Surface Temperature (LST) for urban cores and surrounding rural areas using satellite imagery, enabling the detection of spatial thermal variations caused by urban development.
- To derive and interpret urban morphological indicators, including NDVI for vegetation, NDBI for built-up structures, and NDWI for water features, to evaluate the composition and spatial distribution of land cover elements.
- To analyze the relationship between UHI intensity and urban morphology, identifying how factors such as vegetation cover, building density, and surface materials influence thermal patterns across different zones.
- To propose strategies for mitigating heat island effects, based on observed spatial patterns, focusing on the integration of green infrastructure, reflective surfaces, and water conservation features to support sustainable and climate-adaptive urban design.

## 3. Study Area

The present study was conducted in Pali, Rajasthan (India), which is one of the rapidly expanding metropolitan regions characterized by significant demographic growth and accelerated infrastructural development over the past few decades. Geographically, the city is located at approximately Latitude 24.45° N to 26.28° N, Longitude 72.47° E to 74.19° E, covering an area of about 12,387 sq. km. It serves as a major economic and administrative hub, attracting continuous migration from rural and semi-urban areas, resulting in increased urban sprawl and land-use transformation.

The district experiences a semi-arid climate, with an average annual temperature of around 25–26 °C and mean annual precipitation of approximately 450–500 mm, concentrated mainly during the monsoon season. Summers are typically hot and dry, while winters remain relatively mild, creating conditions conducive to heat accumulation in densely built-up areas. These climatic characteristics, combined with the city's urban configuration, contribute to the formation and intensification of Urban Heat Island (UHI) effects.

From a spatial perspective, the city consists of highly compact urban cores with mixed commercial and residential structures, extensive industrial zones, and semi-urban peripheral regions that are gradually being converted into built-up land. Vegetation cover within the city limits has reduced considerably due to construction activities, whereas the availability of water bodies is limited and unevenly distributed. Such heterogeneous land-use patterns make the city an appropriate case for evaluating the interplay between urban morphology and thermal characteristics. By selecting this study area, the research aims to capture the complexity of land surface dynamics, quantify thermal variations across different zones, and identify morphological factors influencing UHI intensity. The findings derived from this urban landscape can serve as a reference for developing sustainable planning strategies applicable to other rapidly urbanizing regions.

## 4. Data and Methodology

This study integrates multi-source satellite data and geospatial techniques to analyze the relationship between Urban Heat Island (UHI) intensity and urban morphology. The methodology comprises data acquisition, preprocessing, computation of thermal and spectral indices, and statistical analysis.

### 4.1 Data Sources

**1. Landsat 8 OLI/TIRS:** This dataset was utilized for extracting thermal information and calculating Land Surface Temperature (LST). The Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) provide multispectral and thermal bands with a spatial resolution of 30 meters (for reflective bands) and 100 meters (for thermal bands).

**2. Sentinel-2 MSI:** The Multispectral Instrument (MSI) onboard Sentinel-2 offers high-resolution imagery (10–20 meters), enabling detailed mapping of land cover and vegetation conditions within the study area.

**3. SRTM DEM:** The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model was incorporated to account for elevation variations, which influence surface temperature distribution.

### 4.2 Processing Steps

1. Preprocessing: Radiometric and atmospheric corrections were applied to all satellite datasets to ensure accurate reflectance values. These corrections were performed using QGIS and Google Earth Engine platforms, eliminating atmospheric distortions and sensor noise.
2. Land Surface Temperature (LST) Derivation: Digital numbers from Landsat thermal bands were converted into top-of-atmosphere radiance. Brightness temperature was computed using Planck's equation. Surface emissivity correction was applied using an NDVI-based approach, ensuring accurate LST estimation across varied land cover types.
3. Computation of Spectral Indices: Normalized Difference Vegetation Index
(NDVI) = (NIR − Red) / (NIR + Red)
Normalized Difference Built-up Index
(NDBI) = (SWIR − NIR) / (SWIR + NIR)
Normalized Difference Water Index (NDWI) = (Green − NIR) / (Green + NIR)
These indices were generated to quantify vegetation density, built-up intensity, and water distribution, serving as key indicators of urban morphology.
4. Urban Heat Island Estimation: UHI intensity was calculated by determining the difference between the mean LST of urban clusters and that of peripheral rural areas.
5. Analysis: Statistical tools, including correlation and regression analysis, were applied to examine the relationship between LST and morphological parameters (NDVI, NDBI, NDWI). Spatial mapping was conducted using GIS to visualize heat distribution patterns and their association with land cover characteristics.

This integrated approach facilitates a comprehensive understanding of thermal dynamics in relation to urban structure, providing a foundation for sustainable urban planning strategies.

## 5. Results and Interpretation

### 5.1 Land Surface Temperature (LST) Distribution

The spatial analysis of Land Surface Temperature (LST) reveals significant thermal variations across the study area. The urban core, particularly in **Pali city and surrounding industrial clusters**, exhibits notably higher temperatures, with values peaking at approximately 46 °C, particularly in regions characterized by dense built-up structures, commercial complexes, and industrial establishments. In contrast, peripheral rural areas such as **Sumerpur, Bali, and Raipur tehsils** recorded substantially lower LST values, averaging around 36 °C, owing to the dominance of vegetation and open land surfaces that facilitate natural cooling. The thermal map highlights a clear gradient of increasing temperature from rural to urban zones, underscoring the intensity of the Urban Heat Island (UHI) phenomenon.

### 5.2 Correlation Analysis

The statistical assessment establishes a strong relationship between LST and urban morphological indicators. The Normalized Difference Vegetation Index (NDVI) exhibited a strong negative correlation ($r \approx -0.72$) with LST, reaffirming the cooling effect of vegetation cover. Higher NDVI values were associated with lower surface temperatures, emphasizing the role of green spaces in moderating heat accumulation. Conversely, the Normalized Difference Built-up Index (NDBI) showed a significant positive correlation ($r \approx 0.80$) with LST, indicating that areas with greater impervious surfaces tend to retain more heat. The Normalized Difference Water Index (NDWI) demonstrated a moderate negative correlation, reflecting the localized cooling impact of water bodies, though their influence was spatially limited compared to vegetation.

### 5.3 Spatial Pattern of UHI

The spatial distribution of UHI intensity reveals distinct hotspots concentrated in highly urbanized zones, including industrial clusters, central business districts, and densely populated residential neighborhoods. These areas are characterized by extensive impervious surfaces, limited vegetation, and high anthropogenic heat emissions. In contrast, peri-urban and semi-rural regions, which maintain higher vegetation density and occasional water features, displayed considerably lower surface temperatures. This pattern underscores the influence of land cover composition on urban thermal dynamics.

Overall, the findings highlight that urban morphology plays a critical role in shaping thermal environments. The strong negative correlation of vegetation with LST indicates that strategic incorporation of green infrastructure, such as parks and tree-lined streets, can significantly mitigate UHI effects. Similarly, minimizing the extent of impervious surfaces through sustainable planning measures can reduce heat retention and enhance urban thermal comfort.

## 6. Conclusion and Recommendations

The findings of this research establish a clear and strong relationship between Urban Heat Island (UHI) intensity and urban morphological characteristics. The study demonstrates that densely built-up areas with minimal vegetation and extensive impervious surfaces exhibit significantly higher surface temperatures compared to their rural counterparts. Conversely, zones enriched with vegetation and water bodies show relatively cooler conditions, highlighting the critical role of natural elements in regulating urban thermal environments.

The correlation analysis confirmed that vegetation (NDVI) has a substantial negative relationship with LST, while built-up density (NDBI) shows a strong positive association. These observations reinforce the understanding that urban expansion, when coupled with inadequate green infrastructure, intensifies thermal stress, adversely impacting energy demand, environmental quality, and human health.

To mitigate UHI effects, the study recommends a multi-pronged approach emphasizing sustainable urban design. Key strategies include:

- **Enhancing urban greenery:** Development of green belts, rooftop gardens, and tree-lined streets to improve vegetation cover.
- **Adopting reflective and high-albedo materials:** Use of cool roofing technologies and light-colored pavements to reduce heat absorption.
- **Conserving and restoring water bodies:** Integrating blue infrastructure into city planning for localized cooling benefits.
- **Implementing climate-sensitive planning policies:** Incorporating remote sensing-based thermal assessments into urban development frameworks for proactive decision-making.

Remote sensing and GIS have proven to be powerful tools for continuous monitoring of thermal variations and land-use changes. Integrating these technologies into urban governance can significantly enhance climate resilience and ensure sustainable growth. Ultimately, the adoption of these strategies will help create livable, energy-efficient, and climate-adaptive urban environments.

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