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Identification of Key Urban Heat Island Predictors through Multivariate Analysis of Satellite-Derived Environmental Variables

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Abstract:

Rapid urbanisation has intensified the Urban Heat Island (UHI) effect in Indian metropolitan cities, exacerbating environmental and thermal stress. This study investigates the spatiotemporal dynamics and key drivers of UHI in Bengaluru Urban District, India, from 2017 to 2023 using satellite-derived environmental and socio-economic indicators. Land Surface Temperature (LST) was analysed in relation to the Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), Normalized Difference Water Index (NDWI), night-time light intensity, $PM_{2.5}$ concentration, and population density to assess urban–rural thermal contrasts and seasonal variability. Pearson correlation analysis was employed to examine relationships between LST and the explanatory variables, while Principal Component Analysis (PCA) was used to identify the dominant factors influencing UHI patterns. Multiple Linear Regression (MLR) models were developed separately for winter and summer seasons to quantify the relative contribution of selected variables to surface temperature variations. The results reveal a consistently strong negative relationship between LST and both NDVI and NDWI, confirming the cooling influence of vegetation cover and surface moisture. In contrast, NDBI and night-time light intensity exhibit strong positive correlations with LST, underscoring the role of built-up surfaces and urban activity in heat accumulation. Seasonal analysis indicates that these relationships are more pronounced during summer, with a clear intensification of UHI observed in recent years.

Overall, the study demonstrates that land-cover characteristics are the primary determinants of UHI intensity in Bengaluru. The findings highlight the urgent need for climate-sensitive urban planning, including the expansion of green and blue infrastructure and the adoption of nature-based solutions, to mitigate urban heat stress and enhance long-term urban sustainability.

Keywords: Urban Heat Island (UHI); Land Surface Temperature (LST); Principal Component Analysis (PCA); Multiple Linear Regression (MLR); Normalised Difference Vegetation Index (NDVI).

Introduction:

Urban Heat Island (UHI) is a phenomenon in which urban areas experience higher temperatures than their surrounding rural regions due to significant changes in land cover, a decrease in flora and an increase in anthropogenic heat emissions. The impact of UHI has been exacerbated by rapid urbanisation, especially in developing nations, raising the dangers to public health, energy consumption, and thermal stress. Urban warming in Indian metropolitan regions has been made worse by the unchecked growth of built-up areas and the loss of green and blue spaces, which have drastically changed the surface energy balance(Yang et al., 2025)

A dependable measure for evaluating UHI intensity and its spatial variability is LST, which is obtained from satellite-based data. Strong correlations have been demonstrated between LST and LULC in several studies, particularly for indices such as NDVI, NDBI, and NDWI. While impermeable surfaces improve heat absorption and retention, vegetation and water bodies have an important cooling function through evapotranspiration. (Tan et al., 2025)

By combining environmental, demographic, and anthropogenic factors, recent developments in remote sensing and GIS methods have made it possible to analyse UHI patterns over multiple time periods. Urban activity and human-induced heat stress are progressively being correlated by variables including nighttime light intensity, population density, and PM2.5. Though the body of research on UHI is expanding, few studies have concurrently looked at seasonal differences, long-term temporal variability, and multivariate interactions between UHI and its driving variables in rapidly urbanising Indian cities like Bengaluru.

Bengaluru Urban district, once known for its moderate climate and extensive green cover, has undergone rapid urban transformation over the past few decades. The city is now more susceptible to UHI impacts due to the growth of impermeable surfaces, the loss of vegetation and the deterioration of traditional lakes and wetlands. Developing successful climate-sensitive urban planning and mitigation initiatives requires an understanding of the history of UHI and the identification of its major causes in both urban and rural environments.

Objectives:

1. To analyse the temporal analyses (2017-2023) of LST, NDVI, NDBI, NDWI, PM2.5, night light, and population density intensity in urban and rural zones of Bangalore using remote sensing datasets.
2. To examine the relationships between UHI intensity and environmental factors, i.e. areas using Pearson correlation.
3. To identify dominant factors influencing UHI patterns in urban and rural contexts through Principal Component Analysis (PCA).
4. To evaluate predictive relationships between UHI and selected drivers using Multiple Linear Regression (MLR) and diagnostic checks.
5. To generate actionable insights that support climate-sensitive urban planning and guide mitigation strategies for reducing heat stress in rapidly urbanising regions.

Study Area:

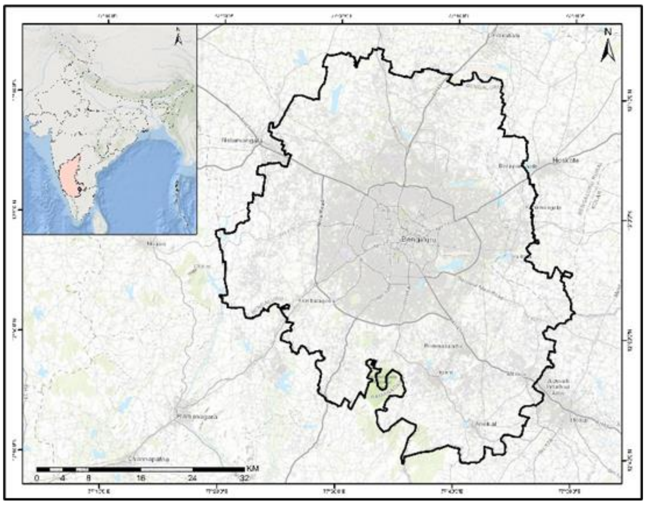

Figure 1: Study area map

Bengaluru Urban district is located in the south-eastern part of Karnataka, India, between 12°39’ - 13°14’N latitude and 77°22’ - 77°52’E longitude. The district lies on the Deccan Plateau with an average elevation of about 900m above mean sea level.

The area has a tropical Savanna climate with distinct summer, monsoon, and winter seasons. Winters are extremely moderate, whereas summers are usually warm with high surface temperatures. Bengaluru was earlier a garden city, but over the past few decades, rapid urbanisation has turned it into a heavily populated metropolitan area. The surface energy balance has been drastically changed by the widespread growth of impermeable surfaces, the decrease in plant cover, and the deterioration of conventional lakes and wetlands. Bengaluru Urban district is particularly susceptible to the UHI effect due to these variations in LULC, making it a perfect place to study the seasonal and spatial dynamics of urban thermal environments.

Methods and Methodologies:

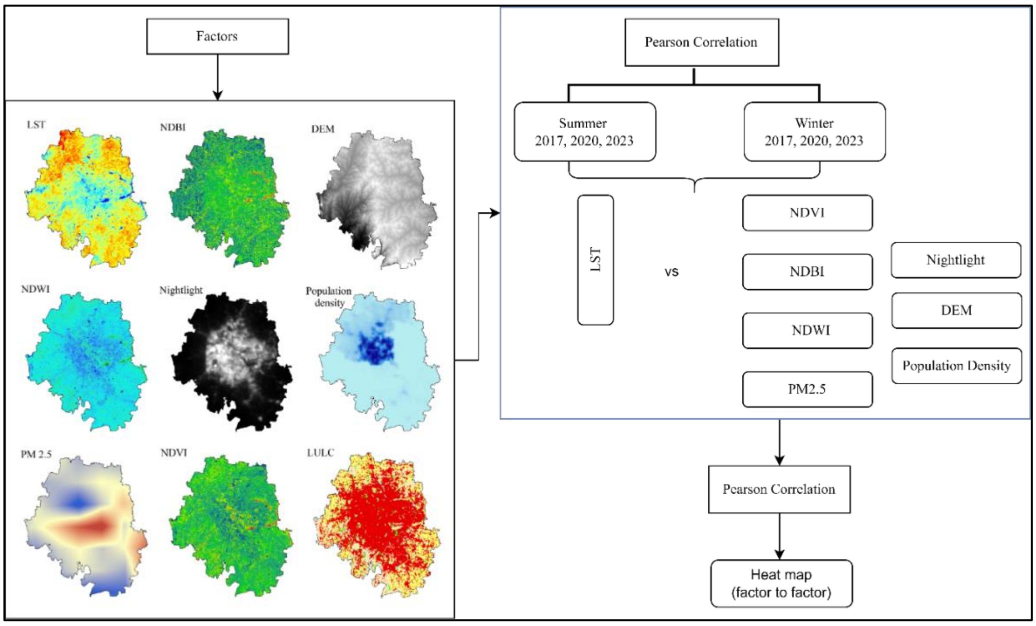

Figure 1: Methodology chart

LST: Land Surface Temperature is derived from thermal infrared satellite data to represent surface thermal conditions. It serves as the primary variable for assessing UHI intensity and spatial-temporal thermal patterns.

NDBI: Normalised Difference Built-up Index identifies the areas of built-up and impervious surfaces. It symbolises the degree of urbanisation and how it raises the temperature of the land surface.

LULC: land use/land cover is used to classify surface characteristics such as built-up, vegetation, waterbodies, barren land, etc. These classes provide essential context for understanding spatial variability in UHI intensity.

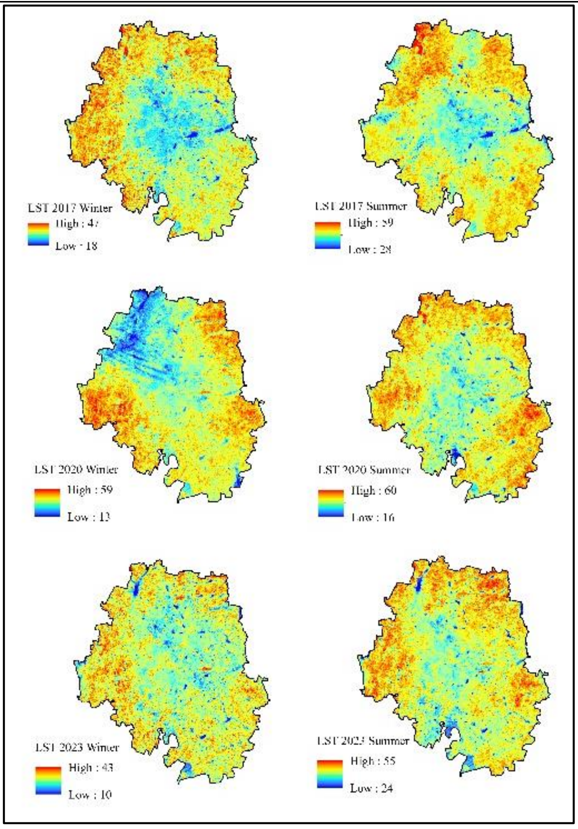

Figure 2: LST variable for winter and summer

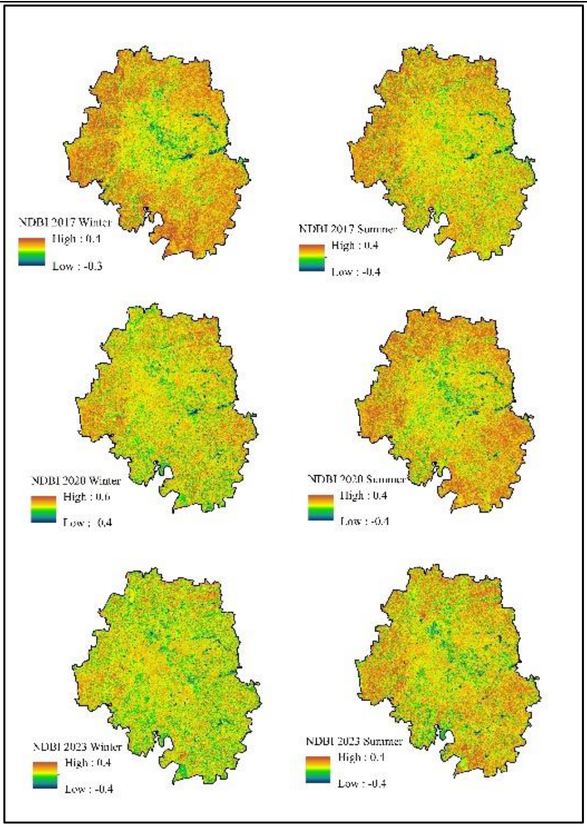

Figure 3: NDBI variable for winter and summer

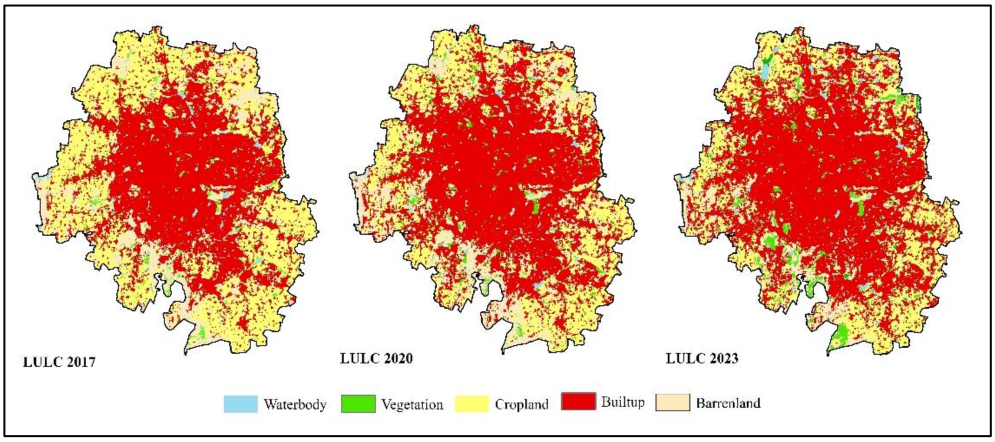

Figure 4: Land use land cover classification

NDWI: Normalised Difference Water Index is used to delineate surface water bodies and moisture conditions. This index helps assess the cooling influence of water features and surface wetness on urban thermal patterns.

NDVI: Normalised Difference Vegetation Index was used to quantify vegetation density and health using red and near-infrared band values from the satellite imagery. It serves as an indicator of vegetation-induced cooling and its role in mitigating surface temperature.

Nightlight: anthropogenic heat sources, infrastructure density and urban activities were all represented by nightlight data. Greater light intensity is a sign of increased energy use and urbanisation.

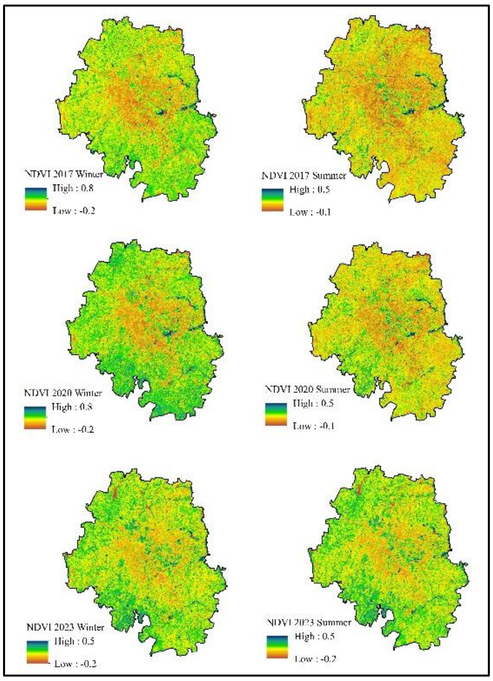

Figure 5: NDWI variable for winter and summer

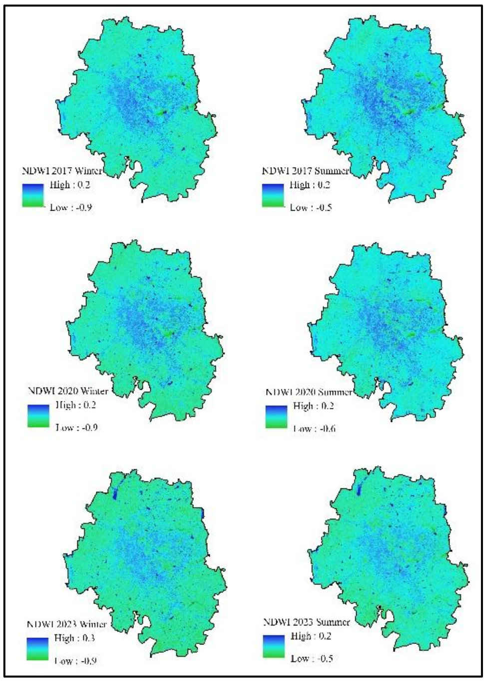

Figure 6: LST variable for winter and summer

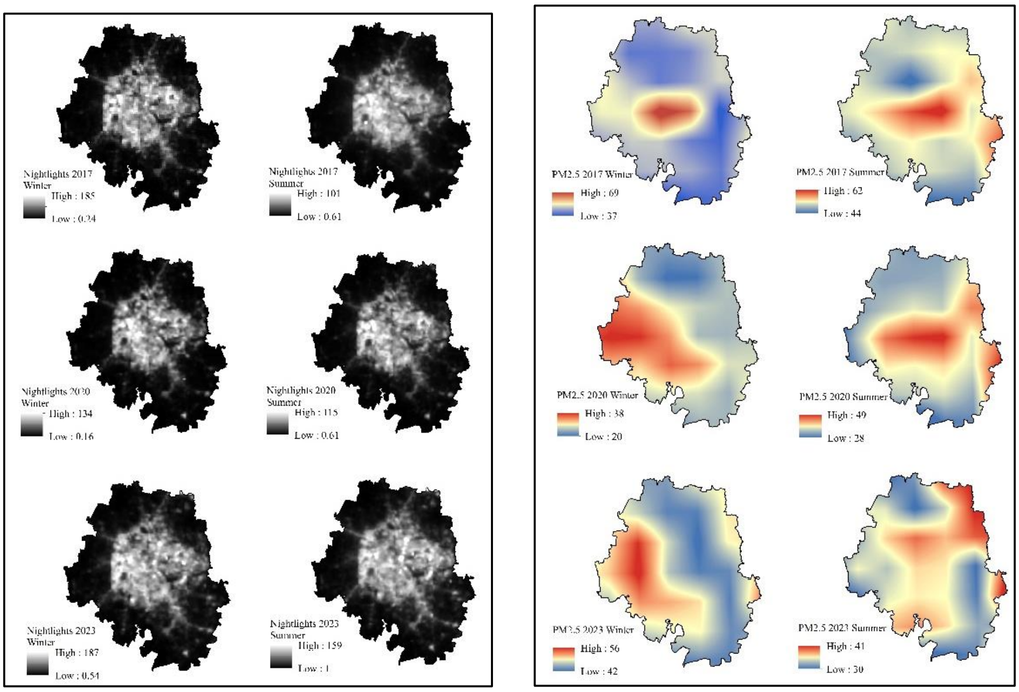

Figure 7: Nightlight and PM2.5 variable for winter and summer

PM2.5: Particulate matter ≤2.5µm is the concentration used as a measure of anthropogenic activity and air pollution. It is a reflection of the stress on the urban environment and its indirect relationship to changes in surface temperature.

Population Density: these were utilised as a substitute for urban intensity and human pressure. Increased infrastructure density and anthropogenic heat emissions are correlated with higher population concentrations.

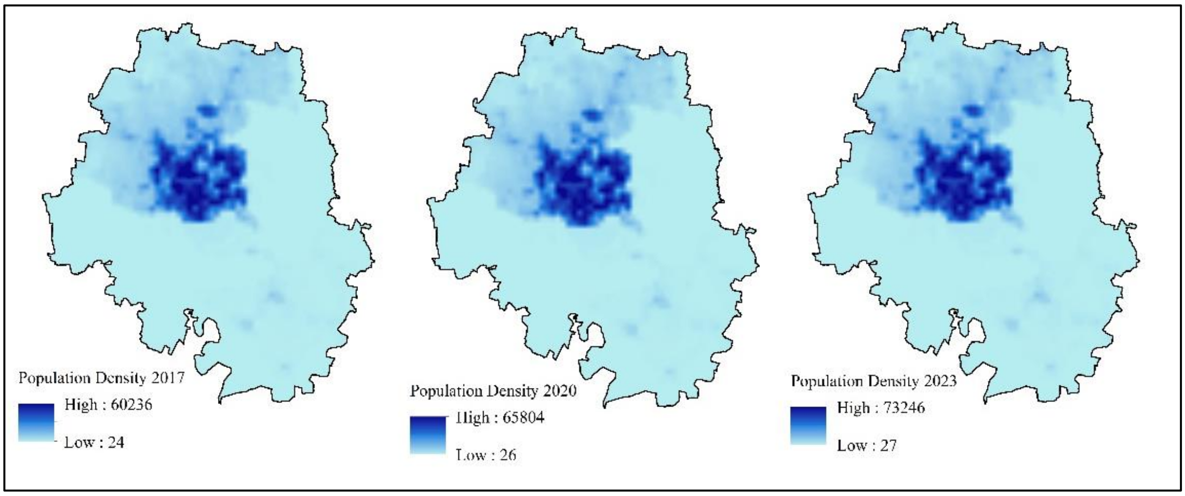

Figure 8: Population density data

Multiple Linear Regression: the combined impact of many human and environmental variables on UHI intensity was investigated using multiple linear regression. Using regression coefficients and diagnostic tests, the model was utilised to analyse predictive associations and determine the proportional contribution of each explanatory variable.

Pearson Correlation: The strength and direction of linear correlation between LST and several environmental variables were measured using Pearson Correlation analysis. This technique aids in determining important factors related to changes in surface temperature.

Result and Discussion:

Relationship between Urban Heat Island intensity and urban environmental variables:

The graphs below show scatter diagrams of the relationship between UHI intensity and urban environmental variables for the Bengaluru urban district. The figures show a linear regression line that depicts the general trend of the relationship between UHI intensity and the variable. The high density of data points is indicative of the high spatial variability of surface thermal properties in the urban environment.

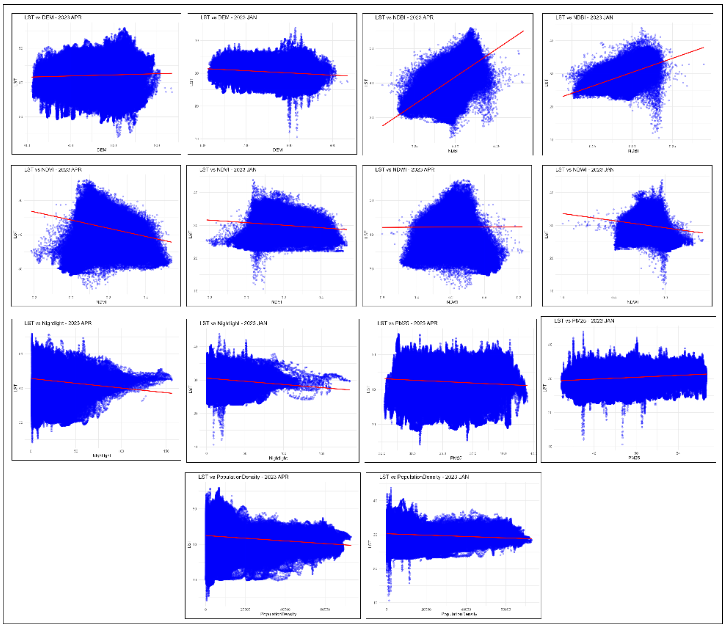

Figure 9: Multi-linear Regression Analysis for 2017 winter and summer

UHI intensity shows strong and meaningful relationships with the important variables of the urban environment. Vegetation related indicators such as NDVI and vegetation fraction generally have a negative relationship with UHI intensity. Areas with higher vegetation cover have relatively lower LST, highlighting the cooling effects of evapotranspiration and shading. Regions with lower vegetation cover have enhanced surface heating which underlines the heat vulnerability of regions with vegetation loss in rapidly urbanizing areas.

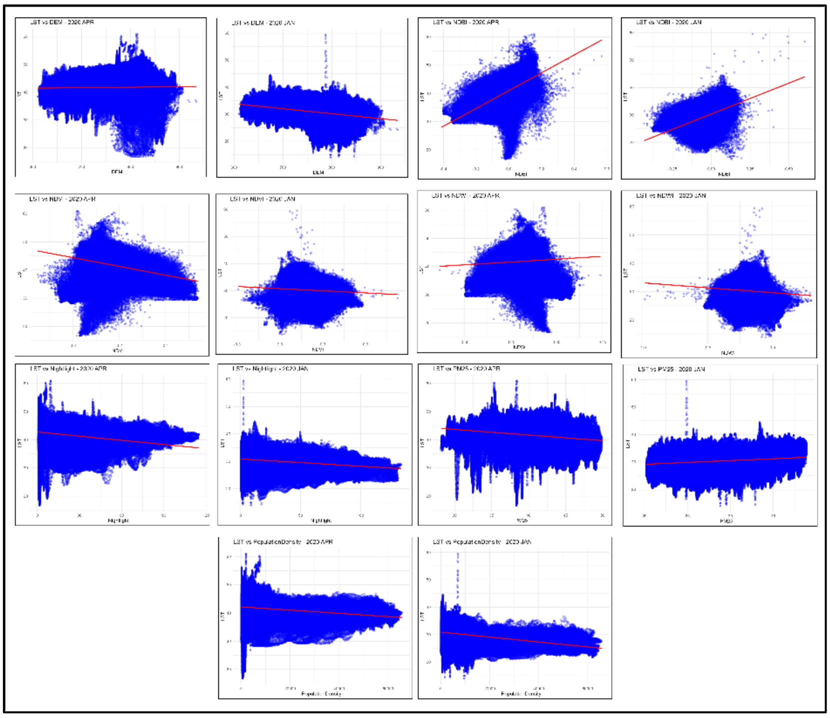

Figure 10: Multi-linear Regression Analysis for 2020 winter and summer

The indicators of built-up i.e., NDBI and impervious surface show a positive correlation with the intensity of UHI in most cases. The positive trend evident in the graphs above the indicate that higher urban density and imperviousness are major factors in the increasing LST. This shows that heat absorbing and heat retaining capacities of construction materials such as asphalt and concrete. The findings are particularly relevant to Bengaluru, which has experienced rapid urbanization, leading to the conversion of natural and semi natural land to built-up land.

Variables that are related to moisture such as NDWI, tend to have a negative or weakly negative correlation with the intensity of UHI. Dry surfaces increase the intensity of thermal stress and regions with relatively higher moisture availability such as areas influenced by water bodies, wetlands or irrigated land that act as localised cooling regions. The weakening of the cooling effect in some plots indicates the reduced effect of the traditional lake and tank system of Bengaluru due to encroachment and degradation.

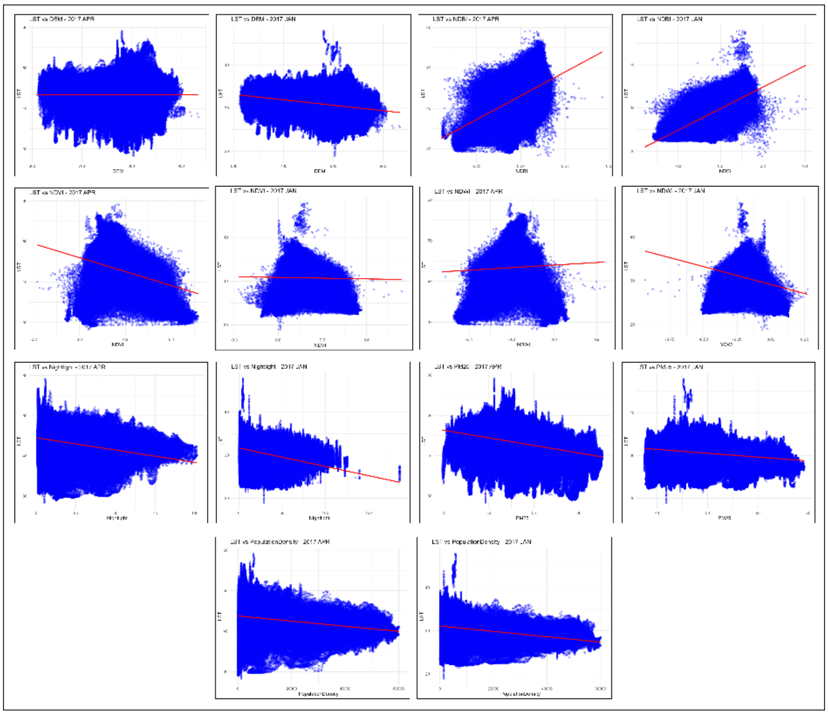

Figure 11: Multi-linear Regression Analysis for 2023 winter and summer

The topographic variables have relatively weaker correlation values with UHI intensity, which indicates that the effect of elevation and terrain is secondary compared to land use and surface characteristics. This implies that, in the moderately undulating terrain of Bengaluru Urban district, human-induced changes are dominant.

The large spread of data points around the regression lines in each of the plots shows that the formation of UHI in Bengaluru is affected by complex nonlinear interactions of various factors. Although each factor has a dominant direction of trend, none of the factors alone can account for the variations in the observed thermal differences. Other factors alone can account for the variations in the observed thermal differences. Other factors like anthropogenic activities may also be important.

Further analysis among the various figures shows that the direction of the relationships is consistent, although the strength of the relationships changes over time. This indicates that although factors, such as the loss of vegetation, expansion of built-up and the decrease in surface moisture, have not changed. In general, the outcome confirms that the UHI effect in Bengaluru Urban district is mainly the need to address green infrastructure, preserve and restore urban water bodies, and adopt climate-resilient urban planning strategies to counter UHI effects in one of India's rapidly developing metropolitan areas.

Pearson Correlation Analysis of LST and Urban Environmental Variables:

The relationship between LST and specific environmental, urban and topographic variables during the summer and winter seasons for the years 2017, 2020 and 2023 in Bengaluru Urban District is shown by Pearson Correlation matrices and graphs.

The connection between vegetation indicators and LST: with correlation coefficients ranging roughly from -0.02 to -0.31, NDVI and LST consistently show a negative relationship throughout all years and seasons. The cooling effect of vegetation through evapotranspiration and shading effects is confirmed by this enduring inverse relationship. This negative correlation is typically stronger in the summer, suggesting that vegetation is more important in reducing surface heating in warmer climates. The contrasting thermal behaviour of vegetated and built-up surfaces is further highlighted by the strong negative correlation between NDVI and NDBI. This inverse relationship highlights one of the main causes of UHI formation: the substitution of impervious urban surface for vegetated areas.

Influence of Built-up and urbanization indicators: there is a moderate to strong positive correlation between LST and NDBI, especially in the summer. Higher LSTs are largely caused by built-up surfaces, as indicated by correlation coefficients that range from roughly 0.48 to 0.65. This relationship holds steady over time, indicating the long-term effects of urban growth and densification on Bengaluru's thermal environment.

Similarly, there is typically a negative correlation between LST and night light data intensity, which serves as a stand-in for infrastructure density and urban activity. This implies that highly urbanised areas have greater thermal loads, supporting the idea that urban morphology and human activity contribute to the increase of UHI effects.

Moisture and Water-related Variables' function: particularly in the summer, there are weak to moderately positive correlations between LST and NDWI. This implies that regions near bodies of water or with surface moisture tend to moderate extreme heat. The comparatively smaller magnitude of these correlations, however, suggests that the cooling effect of water bodies has been reduced, possibly as a result of encroachment, decreased surface area, or seasonal drying of Bengaluru's lakes and wetlands.

Air quality and population density effects: PM2.5 concentrations show generally weak correlations with LST across all seasons and years, indicating an indirect or secondary influence on LST patterns. However, positive correlations between PM2.5 and night light or population density suggest that air pollution is closely associated with urbanised and densely populated areas, which also tend to experience elevated temperatures. Population density consistently shows a weak to moderate correlation with LST, indicating that demographic pressure interacts with land cover, built-up intensity and urban infrastructure rather than directly controlling surface temperatures.

Influence of topography: topographic variation has little effects on LST in Bengaluru Urban district, as evidenced by the weak correlation with

LST across all metrices. This demonstrates how LST and anthropogenic factors predominate over natural terrain controls.

Temporal and seasonal variability: a comparison between 2017, 2020, and 2023 shows that although correlations are generally constant, their strength varies seasonally. Because of increased surface heating brought on by increased solar radiation, summer seasons consistently show stronger correlations between LST and variables related to urbanisation. Winter correlations are relatively weaker, suggesting that there are fewer thermal contrasts in colder climates.

The Pearson correlation analysis clearly shows that the growth of Built-up areas and the loss of vegetation are the main causes of Bengaluru's UHI intensity, with surface moisture, urban activity and air quality having secondary effects. The long term effects of urbanisation on the city's thermal environment are highlighted by the persistence of these relationships over several years, which also emphasises the critical need for vegetation conservation, urban water body restoration, and climate-sensitive urban planning techniques.

Conclusion:

This study highlights how urbanisation has shaped Bengaluru Urban district's UHI features. The results of the integrated analysis of LST, Multi-linear regression and Pearson correlation consistently demonstrate that while built-up expansion significantly raises surface temperatures, vegetation cover has a significant cooling effect. The main cause of UHI formation are vegetation loss and impervious surface growth as evidenced by the ongoing negative correlation between NDVI and LST and the positive correlation with built-up indicators.

Urban water-bodies and moisture-related factors have a relatively smaller cooling effect, suggesting decreased efficacy as a result of deterioration and seasonal fluctuations. While topography has little bearing on thermal stress, anthropogenic factors, such as population density and nightlight intensity. Stronger UHI responses during the summer are revealed by seasonal variations, highlighting increased thermal sensitivity under higher solar radiation.

Overall, the results highlight the necessity of climate-sensitive urban planning, highlighting controlled urban densification, restoration of urban water bodies, and improvement of green infrastructure in order to reduce Bengaluru's increasing thermal stress.

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