

# Spatiotemporal Analysis of Urban Heat Island Effects in Nigerian Cities Using MODIS Data

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Abstract – This study examines the geographical and temporal dynamics of the Urban Heat Island (UHI) effect over ten major Nigerian cities: Lagos, Kano, Ibadan, Benin City, Port Harcourt, Aba, Jos, Ilorin, Abuja, and Kaduna, spanning the period from 2001 to 2023. Ultimately steering urban climate adaptation strategy, the main goal is to assess the intensity and mitigation potential of UHI events through high-resolution remote sensing and climatic indicators. The study is based on three fundamental objectives: (i) to evaluate long-term trends in Land Surface Temperature (LST) and vegetation cover using MODIS satellite data; (ii) to identify and classify UHI hotspots and their vegetation status; and (iii) to quantify the impact of vegetation, albedo, and evapotranspiration in reducing urban heat through the Heat Mitigation Index (HMI). Using MODIS MOD11A1.061 daily LST products at 1 km resolution, MCD43A3 albedo data, and MCD12Q1 land cover datasets, the methodology applied a multiparameter geospatial framework. While trend analysis was conducted using the altered Mann-Kendall test and Sen's slope estimator to identify statistically significant changes in both LST and NDVI, NDVI was created to measure plant health. The HMI model geographically mapped areas with high, moderate, and low heat mitigation capacity under both daytime and nighttime settings by combining plant cover, albedo, and crop coefficient (Kc) data. NDVI and LST trends were studied using Pearson correlation analysis. Results show consistent UHI intensification in urban centers, with daytime LST values hitting 34-38°C and corresponding nighttime values staying high in most cities. As demonstrated by negative NDVI trends and R<sup>2</sup> values over 0.5 in various towns, vegetation decrease, most acute in Lagos, Abuja, and Kano, substantially correlates with increasing surface temperatures. On the other hand, cities like Ibadan and Benin City showed significantly high HMI zones (48-52%), highlighting the cooling capacity of preserved vegetative cover. While Jos and Ibadan exhibited lower albedo (<0.120) in vegetated areas, the albedo study revealed high reflectivity in the urban cores of Lagos, Kano, Ilorin, and Abuja, with values ranging from 0.140 to 0.259, which corresponds to impervious surfaces. The spatial overlap of low vegetation, high albedo, and thermal hotspots highlights even more the combined effect of surface change on UHI intensity. Cities like Kano and Lagos also revealed more than 17% barren or low vegetative Kc areas, which are directly linked to environmental pressure and inadequate cooling capacity. This study emphasises the importance of green infrastructure in reducing urban heat and offers an evidence-based basis for climate-resilient urban development in sub-Saharan Africa. Particularly for fast urbanising areas prone to climate-induced heat stress, the results suggest including vegetation restoration, urban greening programs, and nature-based solutions into long-term UHI mitigation and adaptation plans.

**Keywords** – Urban Heat Island, Land Surface Temperature, NDVI, Heat Mitigation Index, Urban Climate Adaptation, Nigerian Cities

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#### 1.0 Introduction

Urban Heat Island (UHI), a significant meteorological event, makes cities have far higher surface and near-surface temperatures than nearby rural areas. This temperature differential results from human-induced modifications to land surfaces, such as substituting natural vegetation with impermeable materials, including asphalt, concrete, and glass. These changes more effectively absorb, store, and re-radiate heat (Stewart & Oke, 2012; Weng, 2001; Weng et al., 2004; Wu et al., 2024). The urbanisation process magnifies this effect by increasing population density, industrial activity, and land-use/land-cover (LULC) changes, which generate more anthropogenic heat emissions and less evaporative cooling (Peng et al., 2012). Urbanisation is the expansion of urban settlements in terms of population density and land coverage, involving significant land-use change, infrastructure development, and greater human activity (Guo et al., 2022; Uddin, 2021). Since 1950, the global urban population has risen from under 800 million to more than 4.4 billion (UN, 2022). Urbanisation in rapidly developing countries like Nigeria manifests itself through informal settlement growth, loss of vegetation, and high-density urbanization, all of which exacerbate UHI effects (Guo et al., 2022). Urban materials such as asphalt, glass, and concrete retain heat due to their high heat capacity and low albedo (Khan & Shahid, 2024); on the other hand, human heat from automobiles, buildings, and industry increases thermal retention even more (Liu et al., 2021; Luo et al., 2020). Among other things, higher energy needs for cooling, more heat-related health problems, lower thermal comfort, and aggravated urban droughts are some UHI effects. Particularly in tropical cities like Nigeria, these effects endanger human health and environmental sustainability (Abimbola, 2025; Oni & Ibeabuchi, 2023; Santamouris et al., 2015; Simwanda et al., 2019). As Nigerian cities like Lagos, Abuja, Ibadan, and Port Harcourt undergo fast urbanisation at some of the highest rates in Africa, the UHI effect is becoming more apparent (Demographia, 2016; Federal Republic of Nigeria, 2016). Often with minimal planning or environmental control, rapid urban expansion results in the indiscriminate conversion of vegetated areas into built land (Ayanlade, 2016; Salam et al., 2023). Several studies have looked at UHI in Nigerian cities using satellite-based Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) data (Umar & Kumar, 2023; Oni & Ibeabuchi, 2023). These studies, therefore, are sometimes constrained by brief durations, single-city focus, or the absence of statistical integration of urbanization variables. For instance, Landar et al. (2024) examined UHI in Lagos over 11 years but ignored multi-city variance or long-term trends. Existing research

barely addresses diurnal variation in LST or intra-city temperature gradients, especially concerning urban morphology, vegetation dynamics, and climate disparities among cities.

Recent studies have shown varying levels of UHI intensity across Nigerian cities. For instance, in Abuja, LST ranged from 19°C to 39°C, with higher UHI intensity noted in the northern and eastern parts of the city. With high LST values matching regions with limited vegetation cover, Koko et al. (2021) found significant negative relationships between LST and NDVI. UHI reduction is often assessed using the Heat Mitigation Index (HMI). This composite geographic indicator integrates significant biophysical variables, including NDVI (vegetation health), albedo (surface reflection), and evapotranspiration potential (Kc). Usually, sites connected to high HMI values are sites with good land surface characteristics and strong vegetation cover, which promote natural cooling. Conversely, thermally vulnerable locations defined by limited vegetation, high imperviousness, and poor surface reflectivity show low HMI values (Hu et al., 2023; Li et al., 2020a; Zhang, 2019).

This study aims to close significant gaps in UHI research through a long-term, high-resolution, multi-city assessment of UHI intensity and mitigation potential across ten of Nigeria's largest and most rapidly urbanising cities: Lagos, Kano, Ibadan, Benin City, Port Harcourt, Aba, Jos, Ilorin, Abuja, and Kaduna. Using 23 years of MODIS satellite data from 2001 to 2023, this research examines variations in daytime and nighttime Land Surface Temperature (LST), vegetation health (NDVI), surface albedo, and evapotranspiration potential (Kc). These variables are incorporated into a spatially explicit Heat Mitigation Index (HMI), which classifies metropolitan regions as low, moderate, or high mitigation potential. Despite increasing urbanisation and higher land surface temperatures, Sub-Saharan Africa, especially Nigeria, lacks essential, spatially precise, long-term, multi-city research on the urban heat island (UHI) effect. Much of the present research in Nigeria has focused on isolated cities, limited timeframes, or single-variable studies, often overlooking the complex relationship between urban thermal behaviour, land surface characteristics, and plant loss.

Furthermore, only a small number of studies examine the possibility of UHI reduction as a whole, using several biophysical indicators, including NDVI, albedo, and crop coefficient (Kc). The slight inclusion of both daytime and nocturnal thermal dynamics in past UHI assessments further limits knowledge of residual heat risks in urban cores. High-resolution satellite data also reveals a distinct absence of a decision-support system meant for climate adaptation planning. This

research fills in these significant gaps employing a multi-parametric, geospatial analysis across 10 of Nigeria's most populated cities using a two-decade MODIS dataset (2001–2023). By integrating long-term LST trends, vegetation loss, and surface characteristics into a single Heat Mitigation Index (HMI), this work offers a new, data-driven foundation for localized UHI adaptation strategies, therefore bridging a significant knowledge and application gap in urban climate resilience planning for West African cities.

#### 2.0 Study Area

The study area comprises ten of Nigeria's largest cities. More than a million live in the cities of Lagos, Kano, Ibadan, Benin City, Port Harcourt, Aba, Jos, Ilorin, Abuja, and Kaduna. The locations of these cities are demonstrated in Figure 1. The major industrial, cultural, and economic areas of Nigeria are all these cities. It hosts a variety of industries, such as the textile, telephone, oil and gas, tourism, cropping, food processing, and industrial sectors. Cities are also central locations for health care and learning. The rapid urbanization of the 10 study cities is resulting in a host of problems, such as a rise in air pollution, traffic congestion, and shortages of water. The UHI effect is another major issue these locations suffer from. The city has moderate, dry winters from November to January, hot, dry springs from March to May, and monsoon, wet summers from June to August. They range from 5.0 to 1220.0 meters above sea level.

The lower reaches are at Lagos and Port Harcourt, standing at a low of 40.0 meters and a low of 5.0 meters, respectively. At the same time, the northern part comprises the towns of Jos, Kaduna, Abuja, and Kano, standing at a high of 1220.0 meters, 610.0 meters, 477.0 meters, and 462.0 meters, respectively. The largest city, Lagos, covers a size of 1151.1 km², while Ilorin is 149.3 km². There is an extension of cultivated land, especially in the north and central, showing a rise in agricultural cover. Built-up land, especially in major cities such as Lagos, Abuja, and Port Harcourt, has also expanded tremendously, showing significant urbanization, substantial growth, and population increases. On the contrary, vegetation cover in the south and southeast has decreased, likely due to deforestation resulting from agricultural and urban development. Shrublands and grasslands have also reduced somewhat, but wetlands and water are essentially stable. For the most part, the decade illustrates the trend towards more intensified use of land, with increasing pressure placed upon the natural environment.

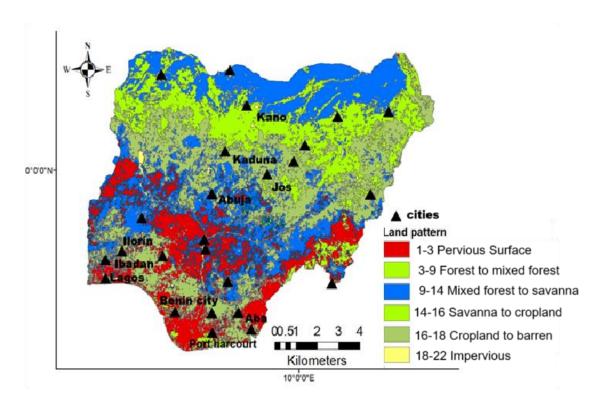


Figure 1: Nigerian map showing the study area

## 3.0 Methodology

#### 3.1 Data Sources and Validation

This study employs daily Land Surface Temperature (LST) data from the MODIS sensors onboard NASA's Terra and Aqua satellites to evaluate urban heat mitigation as part of a broader climate adaptation strategy. Specifically, the MOD11A1.061 product, which provides daily LST at 1 km spatial resolution from the MODIS Terra platform, was used to capture fine-scale spatial and temporal variability in surface temperatures. MOD11A1 data is derived from thermal infrared bands and includes both daytime and nighttime LST values, making it highly suitable for urban heat island (UHI) assessments (Wan, 2007). While MODIS-Terra has been operational since February 2000, MODIS-Aqua began contributing comparable datasets in July 2002 (Khan & Shahid, 2024; Klein et al., 2017). MODIS-Terra was selected for this study due to its more extended temporal coverage and the consistent availability of MOD11A1.061 data. The application of MODIS LST and Land Cover (LC) products are well established in analyzing heat patterns, mitigation efforts, and land use changes (Banerjee & Kumar, 2018). Moreover, the reliability and accuracy of MODIS LST products such as MOD11A1 have been validated in

multiple studies across urban environments (Heck et al., 2019; Huang et al., 2022). Urban land cover classification was derived from the annual MCD12Q1 dataset, which integrates surface reflectance data from both Terra and Aqua sensors (Sulla-Menashe, 2018; Vermote, 2011). This product applies the International Geosphere-Biosphere Programmed (IGBP) classification scheme, which includes 17 distinct land cover types (Belward, 1999). In this study, urban and built-up areas were identified using Class "13" from Land Cover Type 2 of the University of Maryland classification, representing locations with at least 30% impervious surfaces such as buildings, paved roads, and infrastructure (Peng, 2012).

To assess the role of vegetation in mitigating urban heat, the MCD43A3.061 albedo product was used to derive the NDVI. This dataset provides white-sky and black-sky albedo values at a 500-meter resolution, processed from MODIS surface reflectance data. NDVI was calculated using red and near-infrared (NIR) band albedo values to quantify vegetation density and health, essential indicators for urban cooling potential. NDVI has been widely applied in urban climate research to examine the relationship between green infrastructure and temperature regulation (Imhoff et al., 2010; Weng, 2001). Higher NDVI values correspond to areas with more vegetation, which contribute to lower LST through evapotranspiration and shading.

Data reliability was ensured through the use of MODIS Quality Control (QC) flags embedded within both the LST (MOD11A1.061) and albedo products. MODIS LST products typically maintain an uncertainty below  $\pm 1^{\circ}$ C under clear-sky conditions (Wong, 2005), and QC layers help identify potential anomalies (Wan, 2007). Only LST values with uncertainties within  $\pm 2^{\circ}$ C were retained to enhance the robustness of the heat mitigation evaluation. Figure 2 shows a brief description of the methodology flowchart.

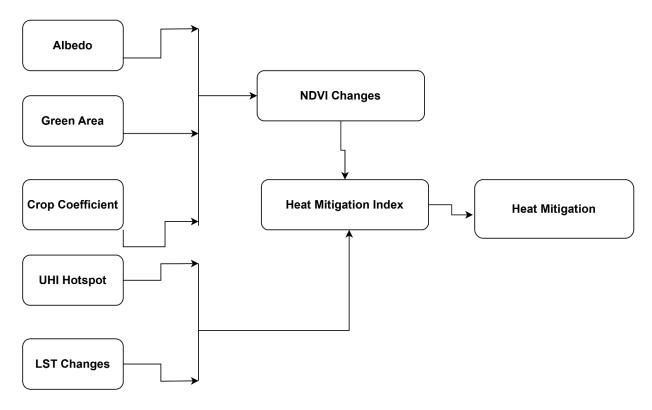


Figure 2: Methodology flow chart of the Heat Mitigation analysis

Table 1 provides a list of satellite data used in the study, detailing the data types, sensors, resolutions, and sources. The data includes Land Surface Temperature (LST) from the MODIS MOD11A1.061 sensor, which has a spatial resolution of 1 km and a daily temporal resolution, sourced from NASA's LP DAAC. The study also uses the NDVI, obtained from the MODIS MOD13A2 sensor with a spatial resolution of 1 km and a 16-day composite temporal resolution, also sourced from NASA LP DAAC. Albedo data is taken from the MODIS MCD43A3 sensor, offering a finer spatial resolution of 500 m with a 16-day composite temporal resolution, and is similarly sourced from NASA LP DAAC. Additionally, the study uses Land Cover Classification data from the MODIS MCD12Q1 sensor, which has a 500 m spatial resolution and a yearly temporal resolution. Finally, the Kc proxy is derived from NDVI data (MOD13A2), with a spatial resolution of 1 km, computed using NDVI-based Kc estimation methods.

**Table 1**: List of satellite data used in the study

Data	Sensors	Resolutions	Sources
Land Surface	MODIS	1 km spatial,	NASA LP DAAC
Temperature	MOD11A1.061	daily temporal	(https://lpdaac.usgs.gov/products/mod11a1v061/)
(LST)			
NDVI	MODIS	1 km spatial,	NASA LP DAAC
(Vegetation	MOD13A2	16-day	(https://lpdaac.usgs.gov/products/mod13a2v061/)
Index)		composite	
A 11 1	MoDia	5001	NACA INDAAC
Albedo	MODIS	500 m spatial,	NASA LP DAAC
	MCD43A3	16-day	(https://lpdaac.usgs.gov/products/mcd43a3v061/)
		composite	
Land Cover	MODIS	500 m spatial,	NASA LP DAAC
Classification	MCD12Q1	yearly	(https://lpdaac.usgs.gov/products/mcd12q1v061/)
		JJ	( <u></u>
Crop	Derived from	1 km spatial	Computed using NDVI-based Kc estimation
Coefficient	NDVI	•	methods (Allen et al., 1998)
(Kc) Proxy	(MOD13A2)		,

This study employed a remote sensing-based approach to evaluate urban heat mitigation as part of climate adaptation strategies. Daily Land Surface Temperature (LST) data were obtained from the MOD11A1.061 product, which provides 1 km spatial resolution LST data from the MODIS sensor aboard NASA's Terra satellite. The dataset includes both daytime and nighttime surface temperatures, and only pixels with quality assurance (QA) flags indicating good retrievals and uncertainty  $\leq \pm 2$ °C were used in the analysis.

#### 3.2 Methods

The study was carried out utilising the following procedures to investigate. The next part offers details on the methods applied. The steps are summarized as follows:

- (a) Data Preparation: For this analysis, MODIS Aqua Land Surface Temperature (LST) data (MOD11A1) from both daytime and nighttime, with a quality flag of no more than 2°C, were chosen (Wong, 2005).
- **(b) Spatial and Temporal Analysis of LST**: The spatial annual average LST from 2001 to 2023 was assessed, considering both daytime and nighttime temperatures. The LST was

- measured across each city, and the Heat Mitigation Index (HMI) was determined for the inner and outer regions of each city.
- **(c) Albedo**: Analyse surface reflectivity to understand how urban areas contribute to heat absorption and assess vegetation cover and its role in reducing urban heat retention.
- (d) UHI Hotspot: Identify areas with the most significant Urban Heat Island effects based on temperature data and track Land Surface Temperature variations to monitor the impact of urbanisation on heat retention.
- **(e) NDVI Changes**: Evaluate changes in vegetation over time to understand the impact of urban growth on green spaces, and calculate vegetation water requirements to understand the relationship between vegetation and heat mitigation.
- **(f) Trend Analysis**: The Mann-Kendall test was used to determine the significance of the NDVI trend over the cities, assessing vegetation changes.
- **(g) Change Analysis**: Changes in several vegetation areas of the cities were identified by analysing LST variations from 2001 to 2023, NDVI, and Albedo.
- (h) Analysis of HMI: The "Urban and Built-up Lands" pixels were derived from MODIS Albedo (MCD43A3.061), MODIS LST (MOD11A1.061), and MODIS NDVI (MOD13A2.061) data to assess heat mitigation potential.
- (i) **Heat Mitigation**: Implement strategies based on the results to reduce the UHI effect and enhance urban heat mitigation, and calculate the potential for heat mitigation based on the distribution of vegetation and heat retention.

## 3.2.1 To apply the modified Sen's slope and the modified Mann-Kendall's

This technique determines the trend analysis of LST, UHI and land use impacts and studies the long-term changes for the Nigerian cities. A modified Mann-Kendall Test (MMK) is used to detect trends in LST and NDVI. The MK test statistic (S) calculates the difference in ranks between later and earlier data Author & Kumar Sen (1968):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sign}(x_i - x_k)$$
 (1)

(Hamed, 2008, 2011) modification removes the effect of autocorrelation on the variance of S. In MMK, the autocorrelation structure is first estimated using an autocorrelation function by the Hurst coefficient (H). H represents the self-similarity of the time series (Koutsoyiannis, 2003) as:

$$C_n(H) = [\rho_{|j-i|}] \text{ for } i = 1:n; j = 1:n$$
 (2)

$$\rho_l = \frac{1}{2} \left( |l+1|^{2H} - 2|l|^{2H} + |l-1|^{2H} \right) \tag{3}$$

where  $\rho_l$  is the autocorrelation function of lag l for a given H. The significance of H is checked against a normal distribution. For significant H, the bias in the variance of S is calculated as:

$$V(S)^{H'} = \sum_{i < j} \sum_{k < l} \frac{2}{\pi} \sin^{-1} \left( \frac{\rho|j - i| - \rho|i - l| - \rho|j - k| + \rho|i - k|}{\sqrt{(2 - 2\rho|i - j|)(2 - 2\rho|k - l|)}} \right)$$
(4)

A correction factor removes this bias before computing the significance test statistic (Z):

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)^H}} & when S > 0\\ 0 & when S = 0\\ \frac{S-1}{\sqrt{V(S)^H}} & when S < 0 \end{cases}$$
 (5)

Z > 1.96 indicates an increasing trend, while Z < -1.96 indicates a decreasing trend at a 0.05 significance level.

The Sen slope estimator (Sen, 1968) is used to quantify change rates ( $Q_m$ ) in the time series. The change rate is estimated from the slopes (C) of all consecutive pairs of data (n).

$$Q_{m} = \begin{cases} \frac{C(n+1)}{2} & \text{if } n \text{ is odd} \\ \frac{C \times n}{2} + C\left(\frac{n+2}{2}\right) \\ \frac{2}{2} & \text{if } n \text{ is even} \end{cases}$$
 (6)

A positive  $Q_{\rm m}$  denotes an upward trend and vice versa.

## 3.2.2 Pearson Correlation Coefficient (r)

To measure the linear relationship between land use changes and LST (Pearson, 1896):

$$r = \frac{\sum_{i=1}^{n} (U_i - U_{mean})(LST_i - LST_{mean})}{\sqrt{\sum_{i=1}^{n} (U_i - U_{mean})^2 * \sum_{i=1}^{n} (LST_i - LST_{mean})^2}}$$
(7)

where;  $U_i = \text{Urbanization metric } at \frac{location}{time} i \; (e.\,g.\,,\% \; built \; -$ 

up);  $LST_i$ =Land  $Surface\ Temperature\ at\ the\ same\ point;\ U_{mean}$  ,  $LST_{mean}$  = their respective means.

# 3.2.3 Vegetation index

Equation 8 uses red and near-infrared wavelengths to calculate the Normalised Differential Vegetation Index (NDVI). The values range from -1 to +1, indicating no vegetation and high vegetation, respectively (Kshetri, 2018).

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{8}$$

where:

Red = Values for digital numbers (DN) derived from band 4.

NIR = values of digital numbers from band 5.

## 3.2.4 Urban hot spots (UHS)

The LST was used to identify hot spots within the research region. These zones, which range in size and are found in the hottest places, are generally regarded as unsuitable for human habitation. These spaces are calculated using the formula below, which is displayed in Equation 9 (Hidalgo-García & Arco-Díaz, 2022).

$$LST > \mu + 2 * \delta \tag{9}$$

where;  $\mu$ = average,  $\delta$ = standard deviation.

#### 3.2.5 Heat mitigation index (HMI)

The urban cooling model computes the HMI on a raster scale by taking into account several variables, including albedo, evapotranspiration, and shadow, as well as proximity to cooling sources like parks. The HMI is determined by using the cooling capability of the neighborhood or its surroundings. When there are no large green patches that affect the pixel, the cooling capacity (CC) index and the HMI are equal. The HMI in this instance is calculated as a distance-weighted average of the green fields and surrounding pixels. According to Hu et al. (2023), the HMI scales from 0 to 1, with 1 representing complete UHI mitigation and 0 representing no cell heat mitigation.

$$GA_i = cell_{area} * CC_{park} = CC_{park} = \sum_{j \in dradius from i} gj$$
 (10)

$$CC_{park} = \sum_{j \in dradius from i} gj. CC_{J}. e(\frac{-d(i,j)}{d_{cool}})$$
(11)

where:

 $GA_i$  = green Area influence at cell i

gj = a binary indicator

d(i, j) = distance between pixels i and j.

dcool = distance over which a green space has a cooling effect

 $cell_{area} =$  area of the cell in ha; gj is 1 if pixel j is a green space or 0 if it is not; and.

 $CC_{park}$  = distance weighted average of the CC values attributable to green spaces.

The HM index is then computed using Equation 12:

$$HM_i = \frac{CC_i if CC_i \ge CC_{parki} or GA_i < 2ha}{CC_{parkiotherwise}}$$
(12)

where;  $HM_i = Heat Mitigation index$ .

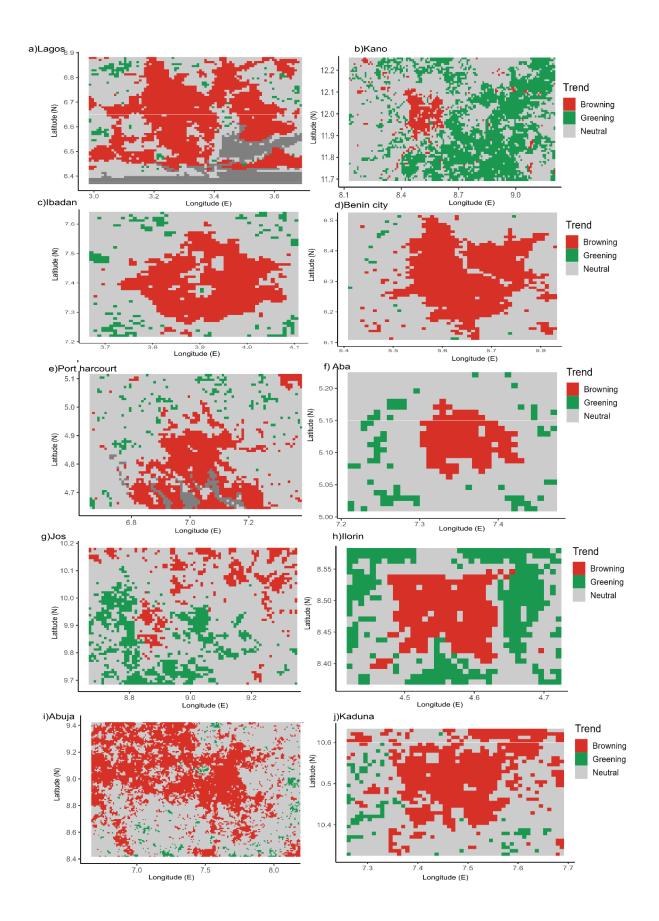
3.2.6 To build the adaptation plan to lessen the UHI impacts concerning the African and Nigerian cities using the LST, land use and NDVI changes.

By analyzing trends, relationships, and the influence of heat and reduced vegetation cover through the vegetation index, urban hot spots (UHS), and the heat mitigation index (HMI), we aim to understand how urbanization shapes land use change patterns in major Nigerian cities. This knowledge will be instrumental in developing strategies to mitigate the risks associated with urban heat, thereby contributing to the creation of more resilient cities in the future.

## 4.0 Results

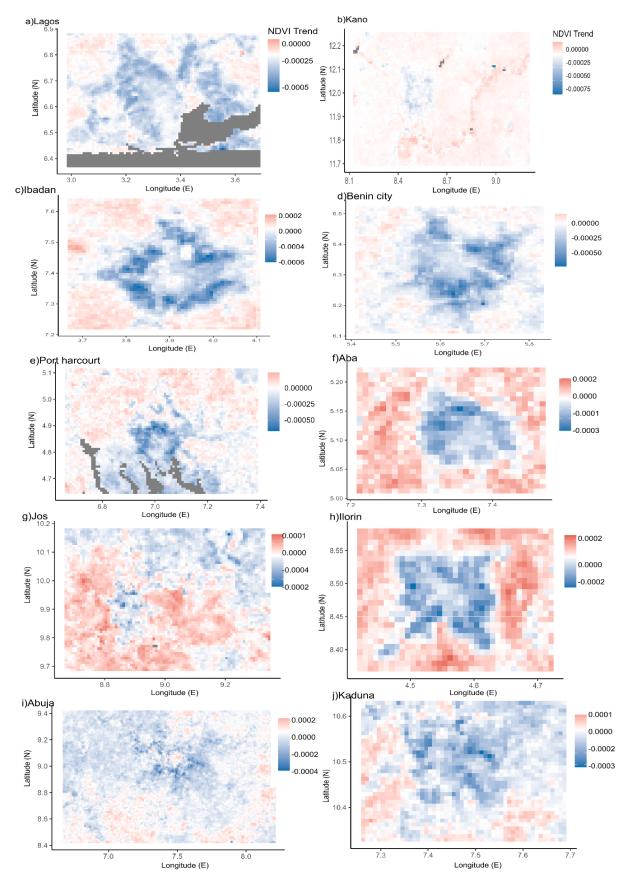
# 4.1 Spatial NDVI Land Use/Land Cover Trend

Figure 3 shows analyses of the NDVI trend degradation in ten prominent Nigerian cities from 2001 to 2023. The study examines the relationship between the nearby surroundings in Nigerian cities, specifically Lagos and Kano, and urbanization, focusing on browning and greening patterns. While Kano's greening tendency is less evident, Lagos's central metropolitan districts are much influenced by urban development. Conversely, Jos indicates more successful urban planning by displaying a better-balanced link between urban growth and adjacent green spaces. Green and neutral zones found in Abuja show a steady balance between urbanisation and protection of the environment. Browning zones in the urban core and greening zones on the periphery indicate Port Harcourt's mixed trend, which suggests that the outside districts might still be connected to nearby natural surroundings. Kaduna's trend is more balanced; some browning occurs, but the vegetation cover remains relatively unaltered. These findings underline the importance of customized urban planning and greening projects, particularly in locations where urban sprawl is surpassing environmental preservation, to minimize the UHI impact and support sustainable urban development.



**Figure 3:** Significant trends in NDVI at a 95% confidence level in ten cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna. Red areas indicate significant vegetation loss (browning) in urban regions, while green areas show vegetation gain (greening), often in rural or less developed zones. Grey areas represent no significant change in vegetation, typically found in stable urban and rural environments.

Figure 4 shows the NDVI Sen's Slope analysis provides a clear view of vegetation change rates across Nigerian cities, complementing the NDVI trend findings. In Lagos (Figure 4a), the study reveals predominantly negative slopes, with values ranging from -0.00025 to -0.0005, indicating significant vegetation loss over time, particularly in the urban core, where rapid development has replaced natural green spaces. This aligns with the browning trend observed in the NDVI analysis. Similarly, Kano (Figure 4b) shows negative slopes between -0.00025 and -0.0005, suggesting moderate vegetation decline in the urban center, but with surrounding areas exhibiting more stable or neutral slopes. In Jos (Figure 4g), a more positive trend is evident, with slopes ranging from 0.0001 to 0.0002, indicating a slight increase or stability in vegetation cover, supporting the greening trend observed in the NDVI analysis. Abuja (Figure 4i) also displays neutral to slightly positive slopes (values around 0.0001), with the surrounding areas showing a slight increase in vegetation, suggesting practical urban greening efforts. Port Harcourt (Figure 4e) and Kaduna (Figure 4j) show a mix of negative and neutral slopes, with values ranging from -0.00025 to 0.0002, indicating both vegetation loss and stability in various areas. Benin City (Figure 4d) exhibits a mixed pattern with slopes ranging from -0.0005 to 0.0002, reflecting areas of vegetation decline as well as stability. These results underscore the varying rates of vegetation change across cities, emphasising the need for targeted interventions in towns like Lagos and Kano, where urbanisation is leading to significant vegetation loss. In contrast, cities like Jos and Abuja show promising trends of recovery and stability.

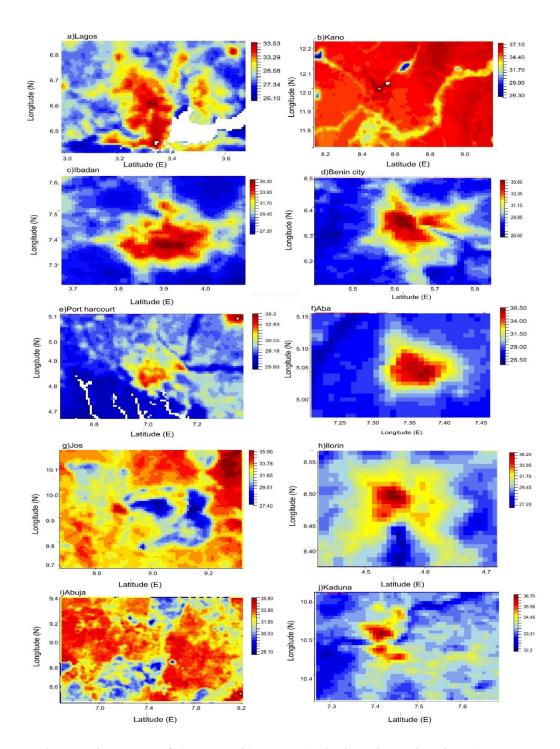


**Figure 4:** Sen's slope in ten cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna. Red areas indicate significant vegetation loss (browning), often in urban areas, while green areas show vegetation gain (greening), typically found in rural or less developed zones. Grey areas represent no significant change in vegetation, seen in both stable urban and rural environments.

# 4.2 Spatial Distribution of LST

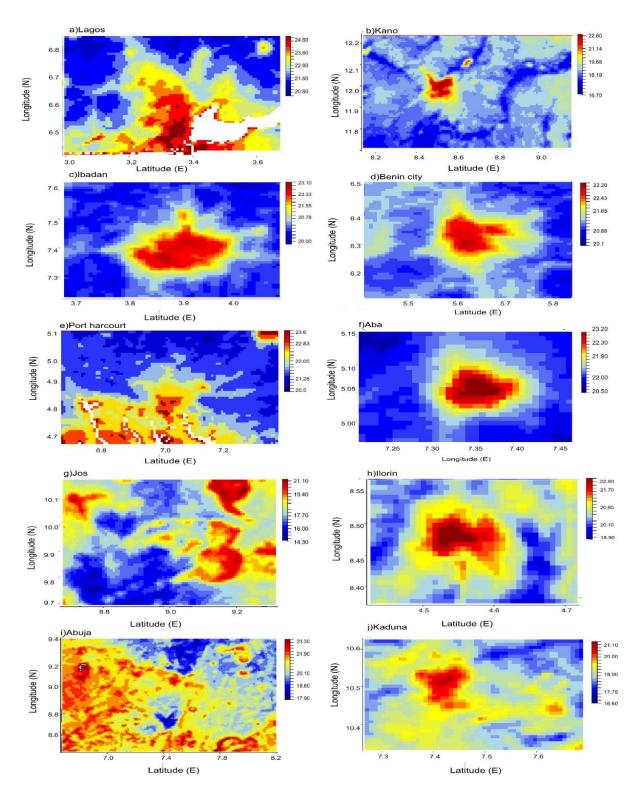
The average annual LST throughout the day in ten Nigerian cities between 2001 and 2023 is shown in Figure 5. The Mean Annual Land Surface Temperature (LST) considering the daytime for the ten cities shows distinct temperature patterns, which are crucial for understanding the relationship between urbanization, vegetation, and the Urban Heat Island (UHI) effect. In towns like Kano (Figure 5b) and Benin City (Figure 5d), the central urban areas exhibit higher LST values (ranging from 30°C to 37°C), indicating the presence of intense heat, likely due to limited vegetation and increased impervious surfaces. Interestingly, Kano, despite having large green areas, still shows temperatures exceeding 34°C. This can be attributed to factors such as the arid or semi-arid climate, the urban heat retention properties of the city's materials (such as concrete or asphalt), and the fact that the green areas may not be distributed in a way that fully mitigates heat in densely populated urban zones.

In contrast, cities like Aba (Figure 5f) and Jos (Figure 5g) show lower LST values (ranging from 27°C to 35°C), especially in the green areas, which correspond to the vegetation gains observed in the NDVI trend analysis. These cooler zones in Aba and Jos align with the greening trends in the NDVI images, suggesting that areas with higher vegetation cover help mitigate temperature rise. Abuja (Figure 5i) and Kaduna (Figure 5j) show mixed temperatures, with some regions experiencing higher LST (up to 36°C), particularly in urbanised areas, while the surrounding rural regions maintain lower temperatures. This supports the observation that green areas, particularly those found in rural or less developed zones, are cooler compared to urban centers, reinforcing the role of vegetation in moderating urban heat and emphasising the need for urban greening strategies to mitigate UHI effects in rapidly developing cities.



**Figure 5:** The Daytime LST of a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna. Urban areas are typically represented by warmer colours (ranging from yellow to red), and the rural regions are shown in cooler colours (ranging from blue to light blue).

Figure 6 shows the nighttime Land Surface Temperature (LST) results for the ten cities, revealing significant temperature patterns that differ from the daytime LST. Daytime and nocturnal Land Surface Temperature (LST) comparisons show that metropolitan areas have notable temperature variations; daytime temperatures are usually substantially higher than nighttime temperatures. Reflecting the heat absorption by urban surfaces like asphalt and concrete, daytime LST values in Lagos (Figure 6a) range from 26.1°C to 33.5°C. Lagos's nighttime LST, though, is between 21.6 and 24.6°C, indicating a cooling impact but still high relative to rural areas. Limited plant cover drives the UHI impact in Lagos, as seen in the NDVI study, which reveals browning loss of vegetation in metropolitan areas. Daytime LST in Kano (Figure 6b) ranges from 26.3°C to 37.1°C; urban areas feel extreme heat from the dry climate (arid climate) and urbanization. Nighttime temperatures in Kano stay high despite some green regions, ranging from 16.7°C to 24.0°C. Reflecting the UHI effect, where urban surfaces retain heat and little vegetation restricts notable temperature reductions, nighttime cooling is quite limited. Cities like Aba (Figure 6f) and Jos (Figure 6g), with more vegetative cover, exhibit more moderate LST levels. Daytime LST in Aba varies from 26.5°C to 35.3°C; nighttime LST values range from 20.0°C to 22.0°C, indicating a notable cooling impact at night supported by greening in both urban and rural areas. In Jos as well, daytime LST varies from 27.4°C to 35.9°C; nocturnal temps range from 18.8°C to 21.0°C, suggesting improved heat moderation during both day and night due to more vegetation.



**Figure 6:** The Nighttime LST of a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna. Urban areas are typically represented by warmer colors (ranging from yellow to red), and the rural regions are shown in cooler colors (ranging from blue to light blue).

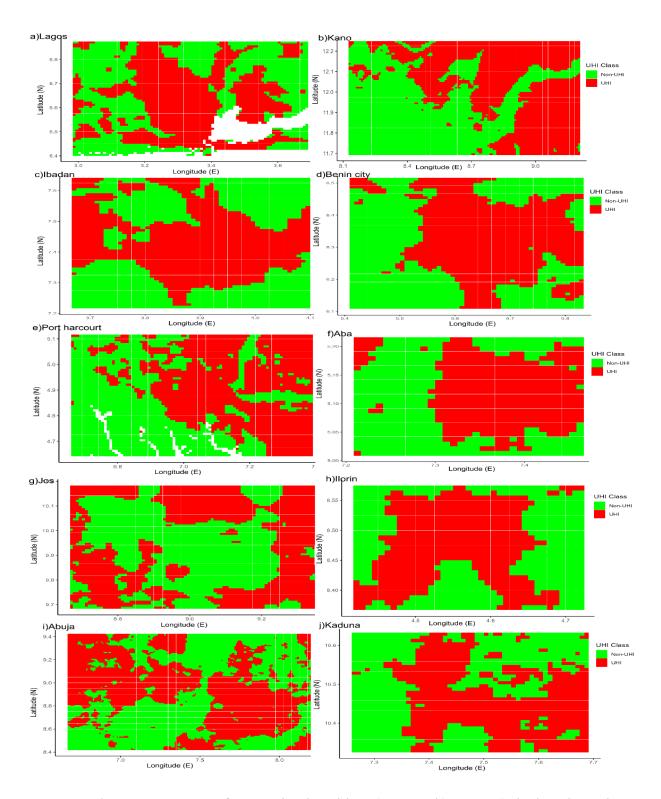
## 4.3 UHI Variations Analysis

Figure 7 shows a UHI classification map and corresponding quantitative analysis across ten major Nigerian cities, providing a detailed understanding of spatial heat stress and its intensity. The classification distinguishes between UHI zones (in red) and non-UHI zones (in green). It is further supported by hotspot statistics in terms of area and percentage coverage, as in Table 2. Across all cities, the average UHI coverage accounts for approximately 45-46% of the total area, while thermal hotspots, the most intense UHI zones, make up around 5%, leaving about 50% as non-UHI zones. For instance, Abuja has the most significant mapped extent with 45% UHI coverage (7.83 km<sup>2</sup>) and 5% thermal hotspots (0.87 km<sup>2</sup>), confirming the city's rapid urban expansion and impervious surface growth. Similarly, Lagos and Ibadan show significant UHI dominance, with Ibadan's UHI zones covering 45.19% (0.94 km<sup>2</sup>) and hotspots reaching 4.81% (0.10 km<sup>2</sup>). Benin City, Aba, and Ilorin reflect similar trends, with UHI zones averaging between 44.5% and 45.3%, and thermal hotspots slightly exceeding 5% in Ilorin (5.41%) and Kaduna (5.37%). Kano and Jos, despite having more scattered UHI patterns visually, also demonstrate substantial thermal buildup, with Kano's UHI zones covering 45.03% (3.08 km²) and hotspots contributing 4.97% (0.34 km²). In comparison, Jos reflects 45% UHI area (1.71 km<sup>2</sup>) and 5% hotspot concentration (0.19 km<sup>2</sup>). These values collectively highlight that while UHI effects are widespread, the thermal hotspots, even more minor in spatial extent (average 0.03-0.34 km<sup>2</sup>), represent critical areas of concern for heat-related health and infrastructure risk.

**Table 2:** The UHI Hotspot Area With Percentage

City	UHI	Hotspot	Count	Area km <sup>2</sup>	Percentage Cover
Aba	Non-UHI	Normal	416	0.32	50
Aba	UHI	Normal	374	0.29	45.31
Aba	UHI	Thermal Hotspot	42	0.03	4.69
Abuja	Non-UHI	Normal	11253	8.7	50
Abuja	UHI	Normal	10127	7.83	45
Abuja	UHI	Thermal Hotspot	1126	0.87	5
Benin_City	Non-UHI	Normal	1275	0.99	50
Benin_City	UHI	Normal	1147	0.89	44.95
Benin_City	UHI	Thermal Hotspot	128	0.1	5.05
Ibadan	Non-UHI	Normal	1352	1.04	50
Ibadan	UHI	Normal	1215	0.94	45.19
Ibadan	UHI	Thermal Hotspot	136	0.1	4.81
Ilorin	Non-UHI	Normal	481	0.37	50
Ilorin	UHI	Normal	432	0.33	44.59

Ilorin	UHI	Thermal Hotspot	49	0.04	5.41	
Jos	Non-UHI	Normal	2461	1.9	50	
Jos	UHI	Normal	2213	1.71	45	
Jos	UHI	Thermal Hotspot	246	0.19	5	
Kaduna	Non-UHI	Normal	962	0.74	49.66	
Kaduna	UHI	Normal	865	0.67	44.97	
Kaduna	UHI	Thermal Hotspot	97	0.08	5.37	
Kano	Non-UHI	Normal	4420	3.42	50	
Kano	UHI	Normal	3978	3.08	45.03	
Kano	UHI	Thermal Hotspot	442	0.34	4.97	



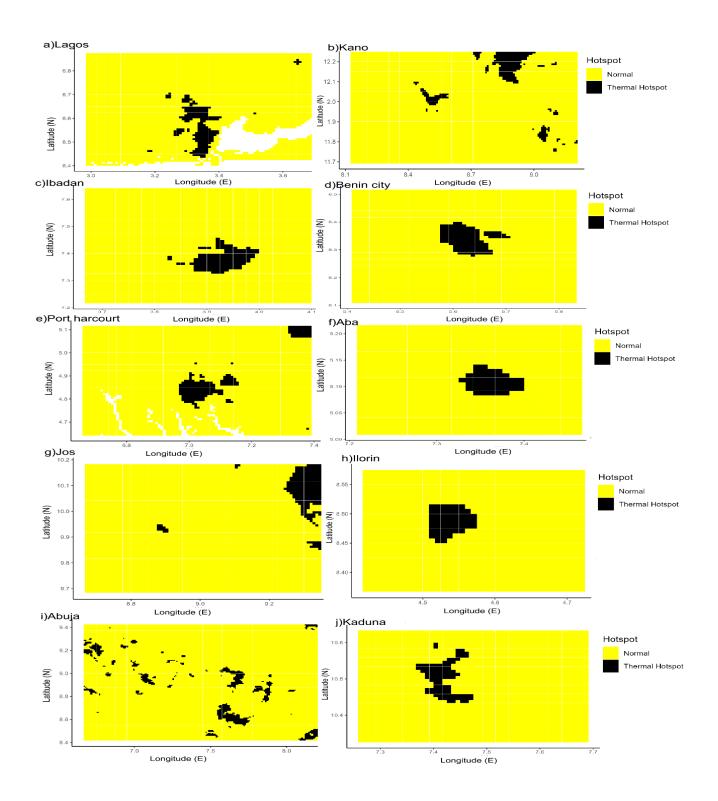
**Figure 7:** The UHI zones map for ten Nigerian cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna. Urban areas are typically represented by warmer colors (red) and rural areas, shown in cooler colours (green).

Figure 8 shows that the UHI hotspots identified in the thermal hotspot analysis correspond to areas of high temperature retention in urban centers, primarily in the black regions on the maps. These hotspots are associated with dense urbanization, where surfaces like asphalt and concrete absorb significant amounts of heat, contributing to the UHI effect, with percentages covered as shown in Table 3. Lagos exhibits one of the most extensive thermal hotspots, with 0.12 km<sup>2</sup> (70.59%) of these areas dominated by low vegetation, and only 29.41% retaining moderate NDVI, confirming a strong correlation between vegetation loss and hotspot emergence. Similarly, Aba shows a balanced split, with 50% of hotspots under low vegetation and 50% under moderate vegetation, suggesting a compact but intense heat buildup within a highly urbanized zone. Ibadan's hotspots, totaling 0.11 km<sup>2</sup>, are primarily surrounded by moderate vegetation (81.82%), which may offer limited buffer capacity but still highlights vulnerability in urban cores. In Benin City, Abuja, Ilorin, Jos, and Kano, the hotspots are predominantly in moderate vegetation zones, covering 100% of the hotspot area in cities like Abuja (0.87 km<sup>2</sup>), Benin City (0.10 km<sup>2</sup>), Ilorin (0.03 km<sup>2</sup>), and Jos (0.19 km<sup>2</sup>). This implies that even moderately vegetated areas can become thermal stress zones under intense land use pressure or poor ecological conditions. However, cities like Kaduna, Kano, and Port Harcourt display mixed conditions. Kaduna's hotspots are 87.5% moderate vegetation and 12.5% low, while Port Harcourt, with 0.19 km<sup>2</sup> of hotspot area, includes 84.21% moderate vegetation and 15.79% low vegetation, showing the encroachment of thermal stress into partially vegetated zones.

**Table 3**: Hotspot area with percentage cover

City	NDVI Class	Count	Area_km <sup>2</sup>	Percentage Cover (%)	
Aba	Low Vegetation	20	0.02	50	
Aba	Moderate Vegetation	22	0.02	50	
Abuja	Low Vegetation	1	0	0	
Abuja	Moderate Vegetation	1125	0.87	100	
Benin City	Low Vegetation	3	0	0	
Benin City	Moderate Vegetation	125	0.1	100	
Ibadan	Low Vegetation	22	0.02	18.18	
Ibadan	Moderate Vegetation	114	0.09	81.82	
Ilorin	Low Vegetation	7	0	0	
Ilorin	Moderate Vegetation	42	0.03		100
Jos	Low Vegetation	6	0		0
Jos	Moderate Vegetation	240	0.19		100
Kaduna	Low Vegetation	9	0.01		12.5

Kaduna	Moderate Vegetation	88	0.07	87.5
Kano	Low Vegetation	44	0.03	8.82
Kano	Moderate Vegetation	398	0.31	91.18
Lagos	Low Vegetation	152	0.12	70.59
Lagos	Moderate Vegetation	70	0.05	29.41
Port Harcourt	Low Vegetation	38	0.03	15.79
Port Harcourt	Moderate Vegetation	207	0.16	84.21



**Figure 8:** Thermal Hotspot map for ten Nigerian cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna. Urban areas are typically represented by warmer colors (black) and the rural regions, shown in cooler colors (yellow).

# 4.4 Vegetation Cover at the Thermal Hotspot

Figure 9 shows the spread of low and moderate vegetation cover inside UHI thermal hotspot areas throughout ten Nigerian cities. The image shows that, on the whole, thermal hotspots are mostly linked to low vegetation cover (shown in red), hence verifying the importance of vegetation loss in raising urban surface temperatures. Thermal hotspots in Lagos, Aba, and Ibadan are mostly made up of low vegetation regions, suggesting significant environmental deterioration in urban centers. Aba's hotspot area, for instance, is mainly covered with sparse vegetation, which indicates a high-priority area for urban greening projects. Especially in central and northern zones, Port Harcourt, Ilorin, and Abuja show significant concentrations of sparse vegetation inside hotspot areas as well. By contrast, places like Jos, Benin City, and Kano display hotspots ruled by moderate vegetation, implying transitional landscapes where urban pressure is rising but some natural buffers still exist. Particularly in more urbanized or fast-expanding cities, these geographical patterns imply that thermal hotspot generation is mainly driven by plant loss. Low vegetation lowers albedo and evapotranspiration, hence increasing heat absorption and storage in urban materials. Conversely, regions with moderate vegetation cover in hotspot areas suggest possibilities for climate adaptation, where urban forestry, green infrastructure, and ecological restoration can help to reduce UHI effects. This data highlights the urgent need to prioritise vegetation restoration and safeguard remaining green areas within and around hotspot zones to improve thermal comfort, urban resilience, and human health outcomes in Nigerian cities.

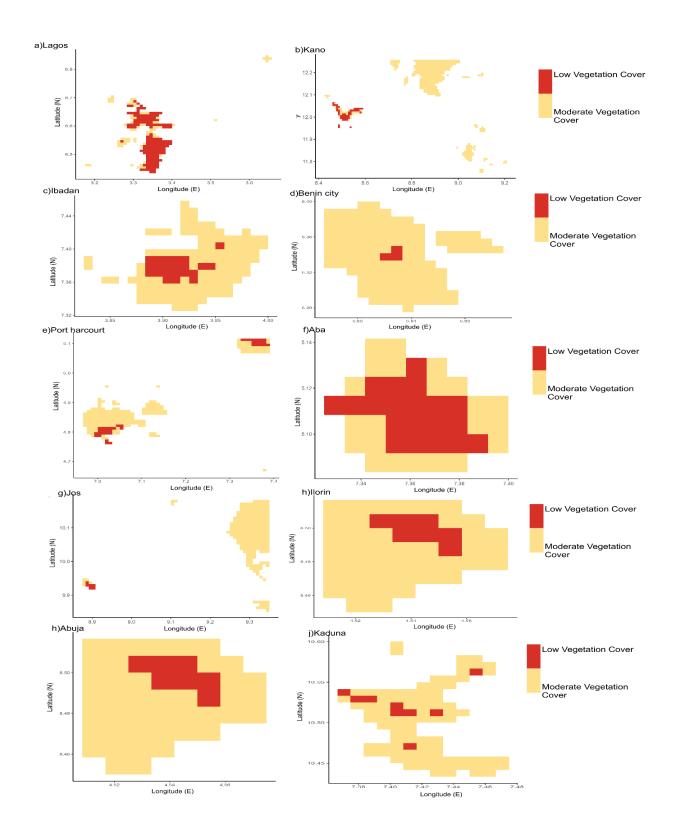
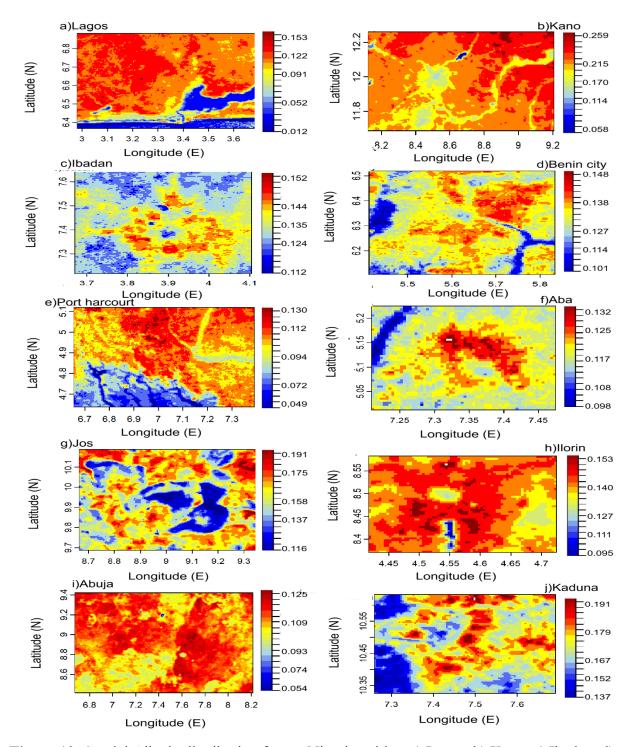


Figure 9: Vegetation effect at the Hotspot for ten Nigerian cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna.

## 4.5 Spatial distribution of Albedo

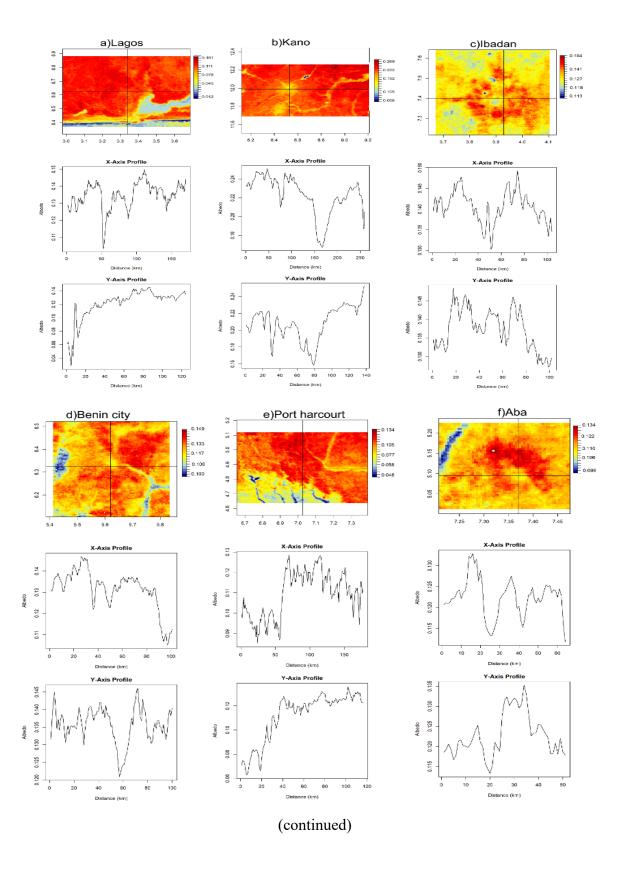
Figure 10 shows the surface albedo spatial distribution over ten major Nigerian cities. A key physical factor in nature, albedo is the reflectivity of the Earth's surface; higher values (shown in red) suggest more reflective surfaces (e.g., bare soil, concrete, and rooftops), while lower values (blue) correspond to darker, absorptive surfaces like vegetation, water bodies, and asphalt, which retain more heat. Particularly in urban centers, the maps show that Lagos, Kano, Ilorin, and Abuja have large regions of high albedo (0.140-0.259). Built-up areas with common impermeable surfaces show this, which helps to keep surface heat during the day. Cities like Jos, Kaduna, and Ibadan, on the other hand, show more varied albedo patterns with lower albedo patches (<0.120, seen in blue and dark blue), suggesting the existence of wetlands, vegetation, or water bodies. Port Harcourt, Benin City, and Aba have varied albedo patterns; urban cores usually have moderately high albedo areas (0.125-0.140) surrounded by lower albedo vegetative belts. Interestingly, Jos and Kaduna have different low-albedo valleys encircled by more reflective hills that could relate to urban-forest transitions or vegetation-rich basins. The link between albedo and UHI is vital: low albedo surfaces absorb more solar radiation, hence amplifying the Urban Heat Island effect, particularly where vegetation is limited. On the other hand, extremely high albedo areas might reflect heat but might cause thermal discomfort owing to radiative feedback, particularly in highly populated built-up areas lacking sufficient shading.

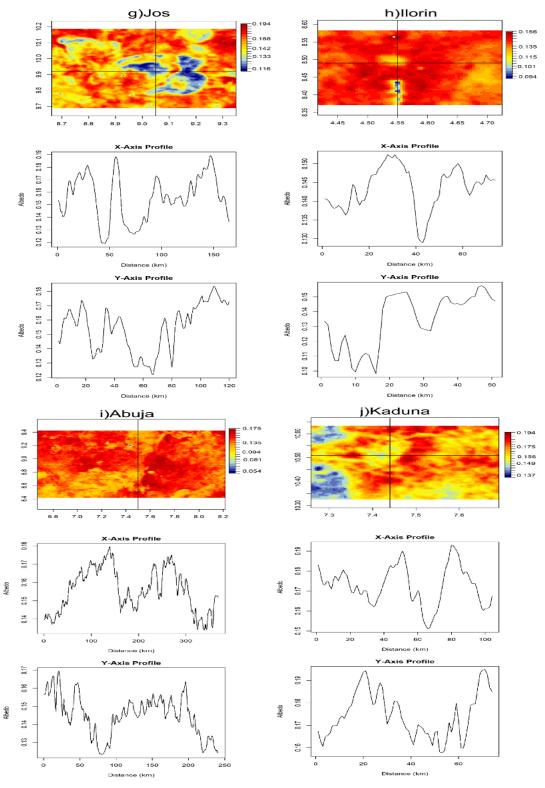


**Figure 10:** Spatial Albedo distribution for ten Nigerian cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna. Urban areas are typically represented by warmer colors (ranging from yellow to red), and the rural regions are shown in cooler colors (ranging from blue to light blue).

## 4.6 Albedo Spatial Profile

Figure 11 presents the Albedo profile for the ten cities, highlighting differences in surface reflectivity across various areas in each town. By showing the albedo values over particular distances, the X-axis and Y-axis profiles help us to understand better how reflectivity varies between urban and rural locations. In cities like Lagos (Figure 11a) and Kano (Figure 11b), the albedo profiles reveal a notable difference in reflectivity, with higher albedo values (indicated in red) concentrated in urban areas, suggesting that these places are made up of materials like concrete or asphalt that reflect a great deal of sunlight. Their high temperatures during the daytime LST and nighttime LST support this, which helps to create the Urban Heat Island (UHI) effect. With urbanized areas exhibiting greater albedo (0.12 to 0.16) relative to adjacent rural zones, the X-axis and Y-axis profiles reveal significant albedo variation. The albedo profiles in cities like Aba (Figure 11f) and Jos (Figure 11g) reveal more consistent reflectivity with relatively lower albedo values (about 0.12 to 0.14). Typically, natural, vegetated surfaces absorb more sunlight in areas with higher vegetation cover. This lower albedo indicates that these rural or less urbanized areas have a natural cooling impact corresponding with the milder temperatures seen in both the daytime and nighttime LST profiles. With a combination of high and low albedo, cities like Abuja (Figure i) and Kaduna (Figure 11j) show moderate differences. Urban locations have greater albedo (0.15 to 0.18) in the X-axis and Y-axis profiles; rural areas tend to have lower albedo (0.12 to 0.15). Especially during the daytime, this implies a balance between built-up surfaces and greenery in these cities, hence affecting the heat mitigation potential and urban heat retention.





**Figure 11:** Spatial Albedo distribution for ten Nigerian cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna. Urban areas are typically represented by warmer colors (ranging from yellow to red), and the rural regions are shown in cooler colors (ranging from blue to light blue).

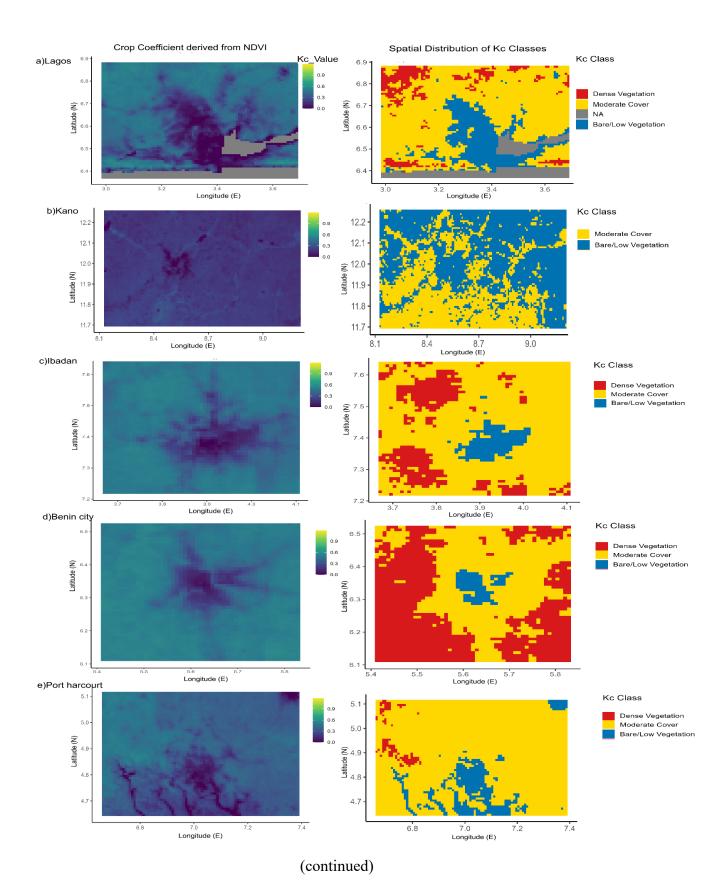
# 4.7 Crop Coefficient Index Analysis

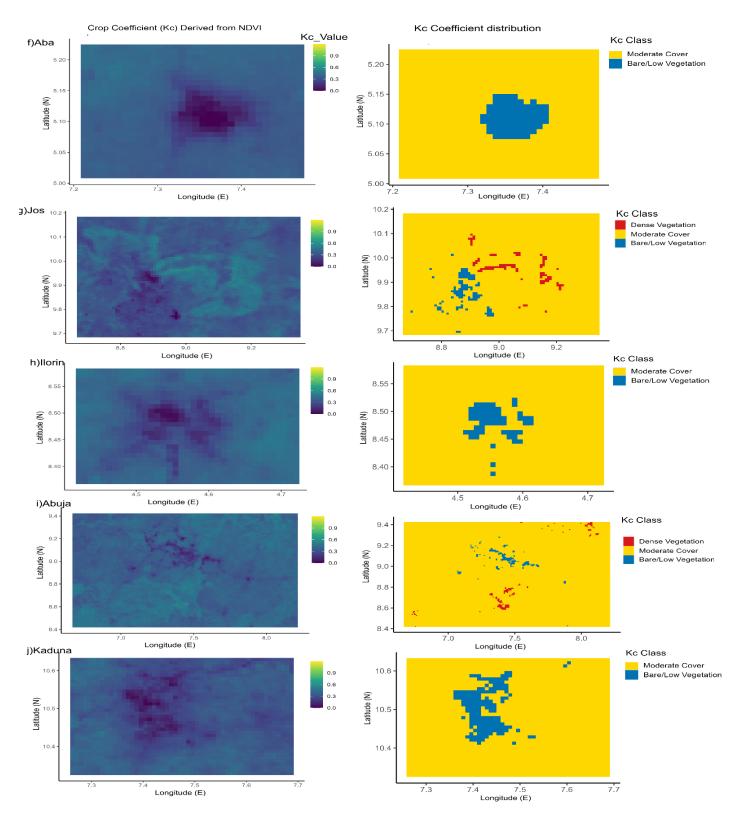
Figure 12 shows the crop coefficient index derived from NDVI in this study, with Table 4 showing the percentages covered. The crop coefficient (Kc) is a proxy for plant density and its related evapotranspiration potential, both of which are vital for controlling urban surface temperature and reducing the Urban Heat Island (UHI) effect. While lower Kc values (approaching 0.0) correspond to bare or impervious surfaces that retain heat, higher Kc values (approaching 0.9) suggest dense, transpiring flora that cools the surrounding environment. With percentages varying from 75.6% in Ibadan to as high as 98.2% in Abuja, the spatial distribution maps and classification data show that most cities are dominated by moderate vegetation cover. Though they can become vulnerable without continuous greening efforts, cities like Ilorin (94.6%) and Jos (95.8%) also show a significant prevalence of moderately vegetated areas, suggesting typically stable vegetative conditions. While Lagos (17.94%), Kaduna (8.72%), and Port Harcourt (11.37%) also show significant exposure to bare or sparsely vegetated surface zones very prone to heat accumulation and urban heat island intensification, Kano stands out with 57.98% of its land area under bare/low vegetation, making it the most ecologically stressed city. With most other cities reporting under 10%, dense vegetation, which is essential for managing local microclimates via evapotranspiration, is mainly limited to Benin City (49.5%) and Ibadan (17.7%). For instance, in Abuja, dense vegetation makes up just 0.8% of the city's vast land area; Kano, Ilorin, Jos, and Kaduna have no notable dense vegetation areas. This disparity implies that while intermediate cover is common, really thick plants with substantial cooling impact are uncommon, and when they are there, they are only found in scattered areas. These trends show that low Kc locations (0.0–0.3), linked with built-up or degraded surfaces, are spatially in line with formerly found UHI hotspots, hence supporting the connection between plant loss and thermal danger.

Table 4: Crop Coefficient distribution with percentage cover

City	K <sub>c</sub> Class	Count	Area_km <sup>2</sup>	Percentage Cover (%)
Abuja	Bare/Low Vegetation	221	0.17	0.98
Abuja	Dense Vegetation	174	0.14	0.8
Abuja	Moderate Cover	22111	17.09	98.22
Benin City	Bare/Low Vegetation	99	0.08	4.04
Benin City	Dense Vegetation	1261	0.98	49.49
Benin City	Moderate Cover	1190	0.92	46.46
Ibadan	Bare/Low Vegetation	180	0.14	6.7
Ibadan	Dense Vegetation	481	0.37	17.7
Ibadan	Moderate Cover	2042	1.58	75.6

Ilorin	Bare/Low Vegetation	55	0.04	5.41
Ilorin	Moderate Cover	907	0.7	94.59
Jos	Bare/Low Vegetation	114	0.09	2.37
Jos	Dense Vegetation	90	0.07	1.84
Jos	Moderate Cover	4716	3.64	95.79
Kaduna	Bare/Low Vegetation	165	0.13	8.72
Kaduna	Moderate Cover	1759	1.36	91.28
Kano	Bare/Low Vegetation	5123	3.96	57.98
Kano	Moderate Cover	3717	2.87	42.02
Lagos	Bare/Low Vegetation	940	0.73	17.94
Lagos	Dense Vegetation	490	0.38	9.34
Lagos	Moderate Cover	3264	2.52	61.92
Lagos		576	0.44	10.81
Port Harcourt	Bare/Low Vegetation	576	0.44	11.37
Port Harcourt	Dense Vegetation	114	0.09	2.33
Port Harcourt	Moderate Cover	4326	3.34	86.3





**Figure 12:** Spatial distribution of Kc and its values derived from NDVI for ten Nigerian cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna.

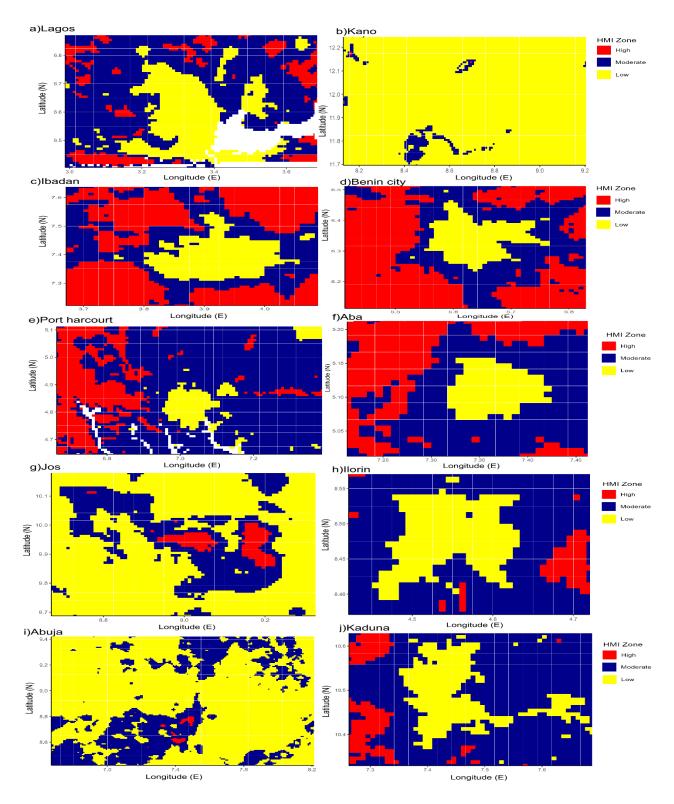
## 4.8 Urban Heat Mitigation

Figure 13 presents a spatial classification of zones with low, moderate, and high potential, along with percentage cover, as detailed in Table 5. The Urban Heat Mitigation Index (HMI) values, based on daytime Land Surface Temperature (LST), are used to mitigate the effects of UHI across ten Nigerian cities. This classification incorporates biophysical parameters, including vegetation cover, albedo, and crop coefficient, to identify areas that are ecologically suited to mitigate urban heat or are susceptible to thermal stress and necessitate intervention. Cities like Benin City (51.78%) and Ibadan (48.30%) exhibit the highest percentages of high HMI zones, suggesting that almost half of their urban land cover possesses considerable mitigation potential attributed to dense vegetation and advantageous surface characteristics. Kano (0.03%) and Abuja (0.46%) demonstrate minimal high-mitigation zones, with the majority of their landscapes categorized as low HMI classes (Kano: 96.74%, Abuja: 73.07%), indicating their ecological vulnerability and restricted vegetative cover. Jos (4.19%), Ilorin (6.92%), and Kaduna (9.67%) exhibit low proportions of high HMI zones. However, moderate HMI zones are notably prevalent in Ilorin (66.70%) and Kaduna (69.59%), indicating the presence of baseline vegetation that has potential for enhancement. Lagos, a highly urbanized city, exhibits a high HMI of 13%, a moderate HMI of 60.64%, and a low HMI of 26.36%. This distribution suggests fragmented yet significant opportunities for mitigating urban heat islands in its peri-urban and mixed-use areas. Port Harcourt exhibits a high HMI of 21.30% and a moderate HMI of 71.30%, indicating the impact of its natural wetlands and remaining vegetation, which can be utilized for climate adaptation strategies.

**Table 5**: Heat Mitigation Index considering daytime temperature for the ten Nigerian cities

City	HMI Class	n	Percentage (%)
Aba	High	265	34.19
Aba	Low	101	13.03
Aba	Moderate	409	52.77
Abuja	High	104	0.46
Abuja	Low	16445	73.07
Abuja	Moderate	5957	26.47
Benin city	High	1294	51.78
Benin city	Low	334	13.37
Benin city	Moderate	871	34.85

Ibadan	High	1281	48.3
Ibadan	Low	445	16.78
Ibadan	Moderate	926	34.92
Ilorin	High	64	6.92
Ilorin	Low	244	26.38
Ilorin	Moderate	617	66.7
Jos	High	206	4.19
Jos	Low	3442	69.96
Jos	Moderate	1272	25.85
Kaduna	High	186	9.67
Kaduna	Low	399	20.74
Kaduna	Moderate	1339	69.59
Kano	High	3	0.03
Kano	Low	8426	96.74
Kano	Moderate	281	3.23
Lagos	High	565	13
Lagos	Low	1146	26.36
Lagos	Moderate	2636	60.64
Port Harcourt	High	1043	21.3
Port Harcourt	Low	362	7.39
Port Harcourt	Moderate	3491	71.3



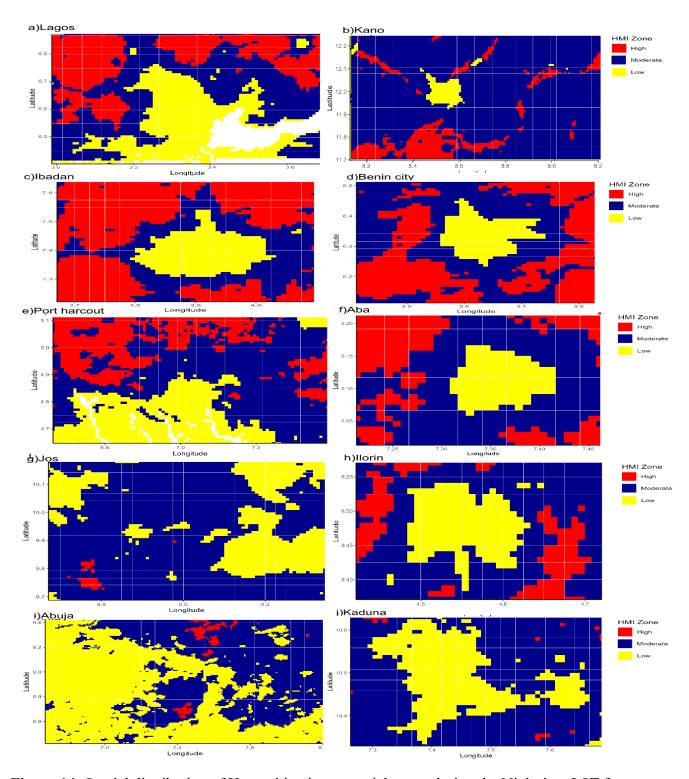
**Figure 13:** Spatial distribution of Heat mitigation potential zones during the daytime LST for ten Nigerian cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna.

Figure 14 shows the nighttime Heat Mitigation Index (HMI). When compared to daylight settings, the nighttime Heat Mitigation Index (HMI) with percentages is shown in Table 6 With 52.75% of high HMI zones, Ibadan stands out for its excellent evening cooling capability, thanks to its rich vegetation. Benin City (41.06%) and Lagos (28.66%) have significantly high HMI zones as well, suggesting these cities still benefit from surface cooling and vegetation overnight. By contrast, Abuja (1.77%), Kaduna (0.94%), and Jos (0.87%) show little high HMI coverage at night despite excellent daytime performance, implying ongoing heat retention and little nighttime evapotranspiration. Aba maintains a moderate presence, with a 29.03% high HMI, whereas Kano, which had almost no high HMI during the day, shows a slight improvement to 11.25% at night. Reflecting a cooling plateau rather than notable heat loss, most cities, including Abuja (43.77%), Kaduna (68.09%), Jos (73.50%), and Ilorin (60.43%), shift towards moderate HMI dominance.

Table 6: Heat Mitigation Index considering Nighttime temperature for the ten Nigerian cities

City	HMI Class	n	Percentage (%)
Aba	High	225	29.03
Aba	Low	114	14.71
Aba	Moderate	436	56.26
Abuja	High	399	1.77
Abuja	Low	12257	54.46
Abuja	Moderate	9850	43.77
Benin city	High	1026	41.06
Benin city	Low	290	11.6
Benin city	Moderate	1183	47.34
Ibadan	High	1399	52.75
Ibadan	Low	429	16.18
Ibadan	Moderate	824	31.07
Ilorin	High	164	17.73
Ilorin	Low	202	21.84
Ilorin	Moderate	559	60.43
Jos	High	43	0.87
Jos	Low	1261	25.63
Jos	Moderate	3616	73.5
Kaduna	High	18	0.94
Kaduna	Low	596	30.98
Kaduna	Moderate	1310	68.09
Kano	High	980	11.25
Kano	Low	252	2.89

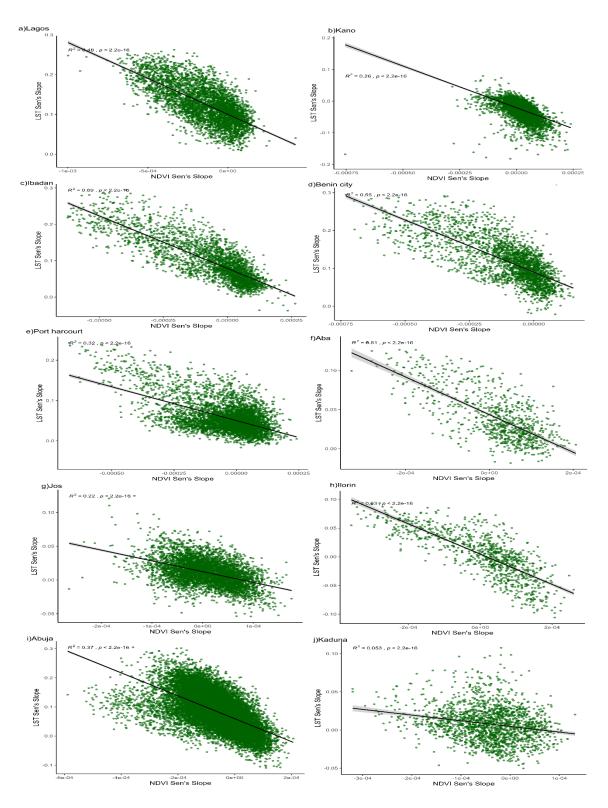
Kano	Moderate	7478	85.86
Lagos	High	1246	28.66
Lagos	Low	1241	28.55
Lagos	Moderate	1860	42.79
Port Harcourt	High	1149	23.47
Port Harcourt	Low	1248	25.49
Port Harcourt	Moderate	2499	51.04



**Figure 14:** Spatial distribution of Heat mitigation potential zones during the Nighttime LST for ten Nigerian cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna.

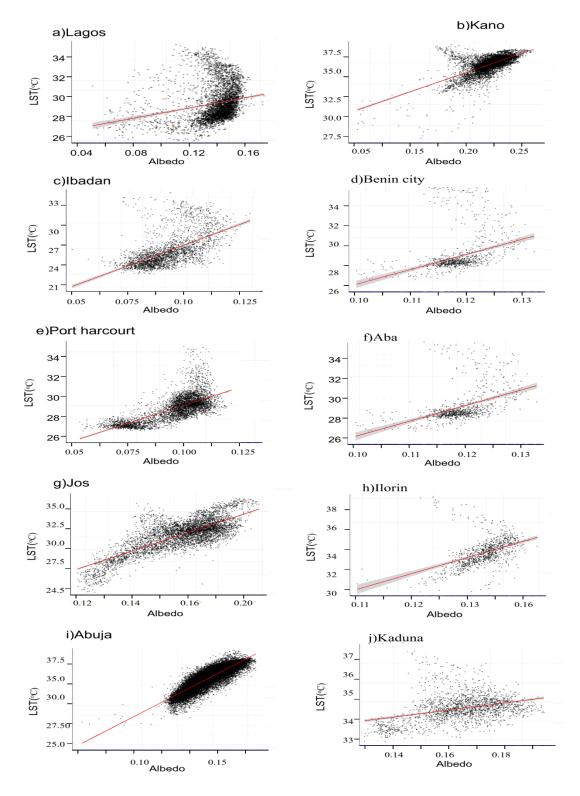
# 4.9 Correlation Analysis

Figure 15 presents the correlation analysis between NDVI and Land Surface Temperature (LST) trends across ten major Nigerian cities, revealing a consistent negative relationship. This confirms that areas with declining vegetation are also experiencing an increase in surface temperatures, a characteristic of Urban Heat Island (UHI) intensification. Particularly high negative associations are seen in cities like Lagos ( $R^2 = 0.48$ ), Ibadan ( $R^2 = 0.59$ ), Benin City ( $R^2 = 0.55$ ), Aba ( $R^2 = 0.51$ ), and Ilorin ( $R^2 = 0.63$ ), which imply that LST rises are significantly driven by vegetation loss in these cities. This suggests that in these cities, greening policies might significantly reduce UHI effects. By contrast, cities like Jos ( $R^2 = 0.22$ ), Kano ( $R^2 = 0.25$ ), and Kaduna ( $R^2 = 0.05$ ) exhibit weaker correlations, suggesting that topography, altitude, or non-vegetative land use changes could also affect LST variability in these locations. With  $R^2$ s of 0.37 for Abuja and 0.32 for Port Harcourt, both lie in the mid-range, implying a moderate but significant connection between thermal behaviour and vegetation trends. This study confirms the importance of vegetation in urban thermal control. It helps by giving NDVI-driven UHI reduction strategies top priority, particularly in places where vegetative loss is most closely related to increasing surface temperatures.



**Figure 15:** The correlation analysis between NDVI and LST trends for ten Nigerian cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna.

Figure 16 shows the correlation analysis between Albedo and Land Surface Temperature (LST) across Nigerian cities, revealing distinct spatial patterns in how surface reflectivity influences urban heat dynamics. Cities like Kano (albedo ~0.05-0.25, LST ~30-37.5°C), Abuja  $(\sim 0.10-0.17, \sim 27-37^{\circ}\text{C})$ , Ilorin  $(\sim 0.10-0.16, \sim 30-38^{\circ}\text{C})$ , and Kaduna  $(\sim 0.14-0.19, \sim 33-37^{\circ}\text{C})$ show robust positive correlations, where low albedo surfaces drive sharp increases in LST, making them clear priorities for aggressive interventions like cool roofs, reflective pavements, and urban greening to cut heat absorption. Moderate correlations in Lagos (~0.04–0.16, ~26–32°C), Ibadan  $(\sim 0.05-0.13, \sim 27-33$ °C), Benin City  $(\sim 0.10-0.13, \sim 28-34$ °C), Port Harcourt  $(\sim 0.05-0.12, \sim 26-0.12, \sim$ 33°C), and Jos (~0.12–0.20, ~27.5–35°C) suggest that increasing albedo can moderately reduce temperatures. Still, interventions should be paired with urban vegetation and water-sensitive design to maximise cooling. Aba (~0.10–0.13, ~26–32°C), with its weak correlation and stable LST near 30°C, in contrast, Aba's weak correlation indicates that factors beyond albedo, like vegetation cover and humidity, dominate temperature dynamics there, pointing to a need for hybrid cooling interventions like green roofs and water-sensitive design. Overall, boosting urban albedo remains a core adaptation tool most impactful where correlation is strong, but should be integrated with localised strategies based on each city's specific urban and climatic context.



**Figure 16:** The correlation analysis between LST and Albedo for ten Nigerian cities. a) Lagos, b) Kano, c) Ibadan, d) Benin City, e) Port Harcourt, f) Aba, g) Jos, h) Ilorin, i) Abuja, j) Kaduna.

#### 5.0 Discussion

## 5.1 Current UHI Mitigation Strategies

The decrease of Urban Heat Island (UHI) effects in Nigeria is reactive primarily and has little incorporation into official urban planning processes. Often haphazard, current mitigation strategies depend on informal greening projects surrounding residential areas, peri-urban vegetation buffers, and single tree-planting campaigns. Evidence in cities like Lagos, Ibadan, and Benin City reveals that regions with thick vegetation correspond with high Heat Mitigation Index (HMI) zones, therefore highlighting the critical part these vegetated areas play in lowering temperatures both during the day and at night. Cities like Kano and Abuja, on the other hand, show extremely low proportions of high HMI zones (daytime <1% and nighttime <2%), hence stressing the critical requirement of proactive, policy-driven strategies to UHI reduction integrated into urban development rules. Around the world, UHI reduction plans are becoming more data-driven and tightly integrated into urban design. For instance, green space-building integration systems in Beijing are being employed to improve UHI resilience (Wu et al., 2024). Likewise, California has popularised urban design rules and reflected surface technologies to control urban thermal loads properly (Gilbert et al., 2016). By contrast, UHI reduction initiatives in Nigeria are still in their early stages, highlighting the importance of evidence-based approaches customised to fit particular local circumstances and needs.

### 5.2 Role of Green Infrastructure in UHI Mitigation

In urban settings, vegetation remains the most effective and reliable method for reducing surface temperature rise. Strong negative relationships (R<sup>2</sup> = 0.48 to 0.63) in places like Lagos, Ibadan, Ilorin, and Benin City, as shown by the NDVI-LST trend study, support the conclusion that more vegetation causes significant LST drops. Local research in Lafia and Enugu supports these results by underlining the vital importance of tree planting and green corridors in urban thermal comfort (Apeh et al., 2023; Ebuga et al., 2023). Green infrastructure is internationally crucial to UHI mitigation, not just for its biophysical cooling impacts but also for its ecosystem services, including air purification and psychological well-being (Parmeggiani et al., 2024). High-density plants in towns like Benin and Ibadan, where more than 40% of the area is designated as high mitigation zones, demonstrate the effectiveness of vegetation in mitigating UHI severity. So, Nigeria's

climate adaptation plan should focus on green infrastructure, backed by satellite-based monitoring and focused urban forestry initiatives.

## 5.3 Challenges and Barriers in UHI Mitigation

Though green infrastructure has clear advantages, various obstacles limit its use in Nigerian cities. First, land-use pressure and rapid urbanisation continue to displace vegetated areas, particularly in Abuja and Kano, where NDVI values are low, and vegetation loss is closely linked to increasing LST. Institutional fragmentation and poor policy enforcement are the following key factors in preventing the mainstreaming of climate-resilient infrastructure. Martinez et al. (2019) underlined that even in affluent settings, well-defined government and cross-sectoral cooperation determine the effectiveness of heat-health action plans. Lack of financing, public knowledge, and technical capacity are still key obstacles in Nigeria. Urban heat is also made more noticeable by socioeconomic elements, including informal settlements and limited access to green areas. International examples imply UHI management's inclusion with building standards, zoning laws, and public health policies (Khare et al., 2021; Levermore et al., 2018). Overcoming these obstacles requires a comprehensive policy framework that prioritises data-driven planning, public involvement, and long-term investment in nature-based solutions.

### 5.4 Long-Term Effectiveness and Sustainability

The long-term efficacy of Urban Heat Island (UHI) mitigation techniques depends on their adaptability, upkeep, and integration into larger urban planning systems. Projects like urban tree planting and the creation of green areas have demonstrated promise in Nigerian cities like Enugu and Lafia, where community involvement has been essential in maintaining these activities (Ebuga et al., 2023). Still, there are problems, including financial limitations, land-use pressures, and insufficient institutional capacity, that could compromise the durability of these projects. Green infrastructure, including green roofs, urban trees, and reflective materials, has been incorporated into several countries, showing great promise in lowering UHI impacts. For example, in Beijing, the inclusion of green areas inside city buildings has reduced heat buildup (Daramola et al., 2018; N et al., 2009). Likewise, in California, the use of cool roofs and pavements has helped to reduce urban temperatures and improve energy efficiency (Gilbert et al., 2016). These instances highlight

the need to include UHI-reducing techniques in long-term urban development projects to guarantee their durability and efficacy.

## 5.5 Impact of Indices on Heat Mitigation

A growing body of research highlights the strong negative correlations between the Normalised Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) in various urban areas, particularly in Nigerian cities such as Lagos, Ibadan, Ilorin, and Benin City, where R² values have been reported to range from 0.48 to 0.63 (Oguntunde, 2018; Sinsel et al., 2021). These correlations underscore the fundamental role of increased vegetation cover in cooling urban environments. Additional studies in Lafia and Enugu further support these findings, illustrating the significant impact of tree planting initiatives and the creation of green corridors in enhancing urban thermal comfort and reducing heat stress (De Cian et al., 2020). Globally, green infrastructure is lauded not only for its direct biophysical cooling effects but also for providing essential ecosystem services such as air purification, noise reduction, and promoting psychological well-being (Davies, 2017; Tzoulas et al., 2007). Cities such as Benin and Ibadan, where over 40% of the area is designated as high mitigation zones, exemplify the effectiveness of dense vegetation in alleviating the intensity of urban heat islands (UHI), a phenomenon commonly observed in rapidly urbanizing regions (Szota et al., 2019).

Recent investigations into the relationship between Albedo and LST across Nigerian cities have revealed significant variation in their associations, emphasising the influence of surface reflectivity on urban thermal dynamics. Cities like Kano, Abuja, Ilorin, and Kaduna exhibit strong positive correlations between Albedo and LST, with Albedo values ranging from 0.05 to 0.25 and corresponding LSTs reaching up to 38°C (Cheng, 2020). These findings suggest that areas with lower albedo, often characterised by darker surfaces like asphalt and concrete, absorb more heat, thereby contributing to higher LSTs. Consequently, the introduction of reflective materials, alongside urban greening efforts, could substantially reduce heat absorption and mitigate the UHI effect in these regions (Santamouris, 2014). In contrast, cities such as Lagos, Ibadan, Benin City, Port Harcourt, and Jos demonstrate more moderate correlations, indicating that albedo is just one of several factors influencing LST. Other contributing factors include the characteristics of urban infrastructure, the geographic location, and the extent of vegetation cover (Gilkeson et al., 2013). For example, Aba, with its weak correlation between albedo and LST, may be more strongly

influenced by local factors such as vegetation density or humidity, which may exert a more substantial impact on thermal variation (Rizwan et al., 2008).

The crop coefficient (Kc), derived from NDVI data, provides further insights into the role of vegetation in moderating LST. Cities like Lagos (17.94%), Kaduna (8.72%), and Port Harcourt (11.37%) exhibit low Kc values, indicating significant exposure to bare or sparsely vegetated surfaces. These areas are more susceptible to heat accumulation and intensified UHI effects due to the reduced cooling potential provided by vegetation (Zhao et al., 2014). Conversely, cities like Abuja (with a Kc of 0.8%) and Jos (95.8%) demonstrate higher Kc values, reflecting more stable vegetative conditions capable of mitigating heat accumulation through evapotranspiration (Li et al., 2020). Notably, Kano stands out as one of the most ecologically stressed cities, with 57.98% of its area covered by bare or low vegetation, exacerbating the intensity of the (Kotharkar et al., 2018).

For cities such as Ilorin (94.6%) and Jos (95.8%), which feature considerable vegetation cover, the Kc values suggest that their vegetative conditions play a significant role in cooling the urban environment through the process of evapotranspiration (Elvidge, 2017). However, cities with more moderate vegetation cover, like Ibadan (75.6%), remain vulnerable to UHI effects in the absence of continuous greening efforts. These trends strongly reinforce the relationship between urban vegetation cover and surface temperature regulation. Cities with low Kc values tend to coincide with known UHI hotspots. In contrast, those with high Kc values (close to 0.9) show a mitigating effect on LST, highlighting the importance of plant density, evapotranspiration, and the reduction of thermal risks in urban areas (Pataki, 2011).

Given the mounting evidence, it is clear that Nigeria's climate adaptation strategies must prioritise green infrastructure development. This can be achieved through satellite-based monitoring and targeted urban forestry initiatives aimed at expanding vegetation cover in cities (Liu et al., 2021). Integrating green infrastructure into urban planning not only helps to reduce the UHI effect but also provides co-benefits, including improved air quality, enhanced biodiversity, and better mental health outcomes for residents (Satish et al., 2012). Furthermore, incorporating reflective materials in urban design can complement these efforts, particularly in cities where albedo is a significant driver of LST. A comprehensive approach, combining vegetation enhancement with increased surface reflectivity, will be essential in developing resilient and sustainable urban environments across Nigeria. By fostering urban spaces that are cooler, greener,

and more adaptable, cities can better navigate the challenges posed by climate change and ensure a higher quality of life for their inhabitants.

Implementing reflective materials and promoting urban greening in these cities could significantly reduce heat absorption and mitigate the UHI effect (Li et al., 2020). The crop coefficient (Kc) values derived from NDVI data provide a crucial insight into the role of vegetation in moderating LST. Cities such as Lagos, Kaduna, and Port Harcourt exhibit low Kc values, indicating significant exposure to bare or sparsely vegetated surfaces, making them more prone to heat accumulation and intensified UHI effects.

Recent analyses of the correlation between Albedo and Land Surface Temperature (LST) across Nigerian cities have revealed varying degrees of association, emphasising the importance of surface reflectivity in urban thermal dynamics. Studies have shown that urban heat islands (UHI) are influenced by both albedo and LST, with lower albedo areas (e.g., darker surfaces like asphalt) absorbing more heat and leading to higher LSTs (Oke, 1982). In cities such as Kano, Abuja, Ilorin, and Kaduna, there is a strong positive correlation between Albedo and LST, with Albedo values ranging from 0.05 to 0.25 and LSTs reaching up to 38°C. This suggests that cities with lower albedo values tend to have higher LSTs, supporting the theory that darker surfaces absorb more solar radiation (Bounoua et al., 2002).

Implementing reflective materials and promoting urban greening in these cities could significantly reduce heat absorption and mitigate the UHI effect (Li et al., 2019). In contrast, cities like Lagos, Ibadan, Benin City, Port Harcourt, and Jos exhibit moderate correlations, implying that while albedo is an essential factor influencing LST, other variables such as urban infrastructure, building materials, and geographic location also play a significant role (Akbari et al., 2001). For example, cities located near coastal areas, such as Lagos, might experience cooling effects from the sea. Aba, with its weak correlation between Albedo and LST, further highlights that other factors, such as vegetation and humidity, may have a more significant impact on LST variations than albedo alone. This suggests that while albedo and Kc are critical in influencing LST, the spatial distribution and density of vegetation also play pivotal roles in shaping urban thermal dynamics. Breezes, thereby moderating the impact of albedo on LST (Patz, 2005).

#### 6.0 Conclusion

This study provides a thorough evaluation of Urban Heat Island (UHI) dynamics across ten major Nigerian cities, combining multi-dimensional indicators including Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), albedo, crop coefficient (Kc), and Heat Mitigation Index (HMI) across both daytime and nighttime hours. Particularly in fast urbanizing areas like Lagos, Abuja, Kano, and Aba, the spatial and statistical studies verify that plant loss, evidenced by notable NDVI browning trends, is a leading cause of rising urban surface temperatures. Consistently lower daytime and nighttime LSTs and greater HMI zones were found in cities with dense vegetation cover, such as Ibadan and Benin City, hence confirming the temperature control function of green infrastructure. Strong inverse correlations were observed in several cities, e.g., Ilorin ( $R^2 = 0.63$ ) and Ibadan ( $R^2 = 0.59$ ), between NDVI and LST trends, suggesting a direct relationship between UHI severity and the deterioration of vegetative cover. The spatial patterns of thermal hotspots further demonstrate that low Kc values, particularly in low vegetation areas, are the most heat-stressed, often coinciding with built-up and impervious surfaces. Moreover, the HMI comparisons between day and night show that whereas certain cities at night have considerable cooling capacity, many metropolitan areas, especially Kano and Jos, lack vegetation-driven nocturnal cooling, which puts their population at risk of extended heat exposure. The research highlights significant challenges in achieving long-term UHI reduction in Nigeria, despite current urban greening initiatives. These consist of insufficient policy integration, land-use disputes, poor enforcement, and low public knowledge. Lessons from overseas cities such as Beijing's green space-building integration (Wu et al., 2024), California's remarkable community developments (Gilbert et al., 2016), and Miami's institutional responses emphasize the efficacy of proactive, coordinated, and well-governed approaches.

Addressing UHI in Nigerian cities thus calls for a multi-scale, multi-sectoral approach that gives green infrastructure priority, uses remote sensing technologies for monitoring, and includes UHI reduction into climate resilience planning. Reducing temperature extremes, safeguarding public health, and fostering sustainable urban life depend on improving the density and quality of vegetative cover supported by policy, public involvement, and adaptable urban design. This work emphasises the need to translate results into practical plans for various Nigerian urban settings, providing a data-driven basis for such interventions.

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#### **Conflicts of Interest**

The author declares that there is no conflict of interest regarding the publication of this paper.

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#### **Data Availability Declaration**

The data and codes supporting the findings of this study are available from the corresponding author upon request.

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