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Geospatial Analysis of LST and UHI Variability in Relation to Land Use/Land Cover Changes in Anambra State, Nigeria

Okechukwu Ebuka Agbasi[1], Jude Steven Ejepu[2], Sunday Edet Etuk[3] and Ubong Williams Robert[4]

[1]Department of Physics, School of Pure and Applied Science, Federal University of Technology Ikot Abasi (FUTIA), Ikot Abasi, Akwa Ibom State, Nigeria
[2]Department of Geology, School of Physical Sciences, Federal University of Technology, Minna, P.M.B. 65, Minna, Niger State, Nigeria
[3]Department of Physics, University of Uyo, P.M.B. 1017, Uyo, Akwa Ibom State, Nigeria.
[4]Department of Physics (Geophysics Research Group), Akwa Ibom State University, Mkpat Enin, P.M.B. 1162, Uyo, Akwa Ibom State, Nigeria

Corresponding author: okechukwuagbasi@futia.edu.ng
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Abstract - Rapid urbanization and land use/land cover (LULC) changes have significantly altered land surface temperature (LST) patterns and intensified urban heat island (UHI) effects, particularly in rapidly developing regions of sub-Saharan Africa. This study aims to analyze the spatial variability of LST and UHI in relation to LULC changes across urban and rural areas of Anambra State, Nigeria. The study integrates Landsat 8 satellite imagery (2019 and 2024), Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), and geospatial analysis techniques. We classified LULC using a Support Vector Machine (SVM) algorithm and derived LST from thermal infrared bands using the Multi-Window Algorithm (MWA) with NDVI-based emissivity correction. UHI intensity was estimated using statistical threshold methods based on mean LST and standard deviation. Results indicate a 15.1% expansion of built-up areas, particularly in urban centres such as Onitsha, Nnewi, and Awka, leading to LST values exceeding 35.68°C and UHI intensities up to 30.59°C. In contrast, rural areas such as Ayamelum, Ogbaru, and Anambra West exhibited lower temperatures (below 31.37°C), attributed to higher vegetation cover and proximity to water bodies. However, ongoing deforestation and agricultural expansion have contributed to moderate temperature increases in rural regions. The study concludes that LULC changes are a primary driver of thermal variability in Anambra State. Sustainable land-use planning, afforestation, and climate-responsive urban design are essential for mitigating UHI effects and enhancing environmental resilience.

Keywords: climate adaptation, environmental sustainability, remote sensing, thermal anomalies, urban

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Introduction

Land Surface Temperature (LST), Urban Heat Island (UHI), slope characteristics, and Land Use and Land Cover (LULC) changes are interconnected factors that influence environmental dynamics, climate variability, and land-use planning. These elements collectively impact ecological stability, human settlements, and sustainable development (Khan *et al*., 2020; Tian *et al*., 2023). With rapid urbanization and increasing anthropogenic activities, modifications

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in land cover have altered temperature patterns, affected landscape stability, and influenced ecosystem services (Akaolisa *et al*., 2023; Adewumi and Agbasi, 2024). Understanding these relationships is fundamental for climate adaptation, heat mitigation, and sustainable land-use planning.

LST represents the radiative temperature of the earth surface, primarily determined by solar radiation, land cover type, and surface moisture content. It is a crucial parameter in energy balance studies, climate modeling, and urban heat assessments (Oliveira *et al*., 2021). The UHI phenomenon primarily drives higher temperatures in metropolitan areas compared to their rural surroundings, due to land cover transformations, vegetation loss, and artificial surface expansion (Guo et al., 2024). Slope features affect land stability, water drainage, and erosion susceptibility, playing a crucial role in urban development, agriculture, and infrastructure planning (Okoli *et al*., 2024). LULC changes, which include built-up expansion, deforestation, agricultural shifts, and land reclamation, alter thermal properties, hydrological cycles, and biodiversity (Khachoo *et al*., 2023). As urban expansion continues, understanding the complex interactions between LST, UHI, slope, and LULC is essential for environmental sustainability and effective land management.

The UHI effect is a significant consequence of urbanization, wherein urban areas record higher temperatures compared to rural surroundings due to land cover modifications. The conversion of vegetated areas into built-up environments reduces natural cooling mechanisms such as shade, soil moisture, and evapotranspiration (Manoli *et al*., 2019). Impervious surfaces absorb heat during the day and release it slowly at night, causing persistent temperature elevation in urban centers. LST directly impacts UHI intensity, as different land cover types exhibit varied thermal properties affecting heat retention and dissipation rates (Ren *et al*., 2021). Urban areas with high LST values experience more intense UHI effects, while rural and vegetated regions exhibit lower temperatures due to higher moisture levels and greater evapotranspiration.

Slope variations also influence UHI formation by affecting wind circulation, drainage capacity, and solar radiation absorption. Steeper slopes promote air circulation and cooling, whereas low-lying urban areas tend to retain heat for longer durations (Koko *et al*., 2021). The expansion of built-up areas at the expense of natural landscapes further exacerbates UHI effects, reducing natural cooling mechanisms and increasing heat accumulation. To mitigate UHI effects, strategies such as urban greening, improved land-use planning, and sustainable infrastructure design are essential (Han *et al*., 2022). Slope plays a fundamental role in land temperature regulation, soil erosion, and water retention, significantly influencing land stability and development potential. Steep slopes tend to have lower LST values due to increased runoff, lower heat absorption, and higher wind exposure, facilitating heat dissipation. In contrast, flatter terrains, especially in urban areas, accumulate higher heat levels due to reduced air circulation and high impervious cover (Taripanah and Ranjbar, 2021). LULC changes interact with slope characteristics by shaping land stability, erosion risks, and land conversion patterns. Deforestation and agricultural expansion on steep slopes lead to increased soil erosion and reduced land productivity, while urban expansion on flat terrains intensifies heat accumulation and disrupts natural drainage systems (Okeke *et al*., 2020; Umoh *et al.,* 2024). Implementing sustainable slope management practices such as afforestation, terracing, and erosion control is essential for maintaining ecological balance and mitigating temperature extremes. LULC changes significantly influence environmental conditions, shaping land temperature distribution, urban heat retention, and slope stability. Rapid urbanization, deforestation, agricultural expansion, and land reclamation alter the natural balance of ecosystems, impacting climate conditions and land productivity (Das and Angadi, 2020). The impact of LULC changes on slope stability is evident in areas experiencing deforestation and unsustainable land development. Vegetation loss on steep slopes leads to accelerated soil erosion,

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landslides, and increased runoff, resulting in land degradation. In urban settings, poor land-use planning exacerbates flood risks, infrastructure damage, and environmental deterioration.

Recent studies have extensively examined the relationship between LST, UHI effects, and LULC dynamics using geospatial and remote sensing techniques. Globally, remote sensing-based approaches using Landsat, MODIS, and Sentinel datasets have been widely adopted for LST retrieval and UHI characterization due to their temporal consistency and spatial coverage (Guo *et al*., 2024; Manoli *et al*., 2019). Several studies have established strong correlations between urban expansion and increasing surface temperatures. Khan *et al*. (2020) and Harmay *et al*. (2021) demonstrated that the replacement of vegetated surfaces with impervious materials significantly increased LST and intensified UHI effects in rapidly urbanizing regions. Similarly, Das and Angadi (2020) highlighted that LULC transitions, particularly deforestation and built-up expansion, were primary drivers of thermal anomalies in developing regions. In the African context, geospatial analyses have increasingly focused on urban climate dynamics. Studies conducted in Nigerian cities such as Abuja and Port Harcourt have shown that vegetation loss and increased infrastructure density contribute significantly to elevated urban temperatures (Awuh *et al*., 2021; Ekwe *et al*., 2020). Koko *et al*. (2021) further emphasized the importance of integrating LULC classification with thermal indices to better understand spatial heat distribution.

Methodologically, most existing studies rely on single-variable analysis, focusing primarily on LST-LULC relationships using indices such as NDVI and NDBI, often without incorporating terrain variables such as slope or conducting comparative urban-rural assessments. While some recent works have begun integrating machine learning and advanced modelling techniques (Khachoo *et al*., 2023), there remains a gap in studies that combine topographic influence (slope), LULC dynamics, and UHI intensity within a unified geospatial framework, particularly in the rapidly developing regions of southeastern Nigeria. Furthermore, limited studies have conducted comparative analyses between rural and urban thermal landscapes while simultaneously quantifying LULC transitions over time. This gap restricts a comprehensive understanding of how urbanization gradients influence thermal behaviour across different land systems.

Therefore, this study advances the state-of-the-art by integrating LST, UHI intensity, slope characteristics, and multitemporal LULC analysis (2019-2024) within a single geospatial framework. Unlike previous studies, this work provides a comparative rural-urban thermal assessment while explicitly linking terrain variability to land surface temperature distribution. This integrated approach improves understanding of spatial heat dynamics and supports more informed climate adaptation and land-use planning strategies. Urbanization, climate variability, and land degradation require a comprehensive understanding of LST, UHI, slope, and LULC dynamics. This study analyzes LST and UHI distribution, assesses slope impact on temperature and land stability, and examines LULC changes on surface temperature regulation. The findings provide data-driven recommendations for mitigating UHI, promoting sustainable land management, and enhancing climate resilience. Insights will aid policymakers in urban greening, climate adaptation, and ecological conservation strategies.

Geospatial and Environmental Characteristics of The Researched Area

Researched Area

Anambra State is located in southeastern Nigeria, positioned between latitude 5°42′N and 6°47′N and longitude 6°36′E and 7°21′E (Figure 1a). The state shares boundaries with Delta State to the west, Imo and Rivers States to the south, Enugu State to the east, and Kogi State to the north. Covering an area of approximately 4,844 km², Anambra is recognized as one of Nigeria's most densely populated states (Figure 1b). The state consists of both urbanized and rural areas, with distinct variations in population distribu-

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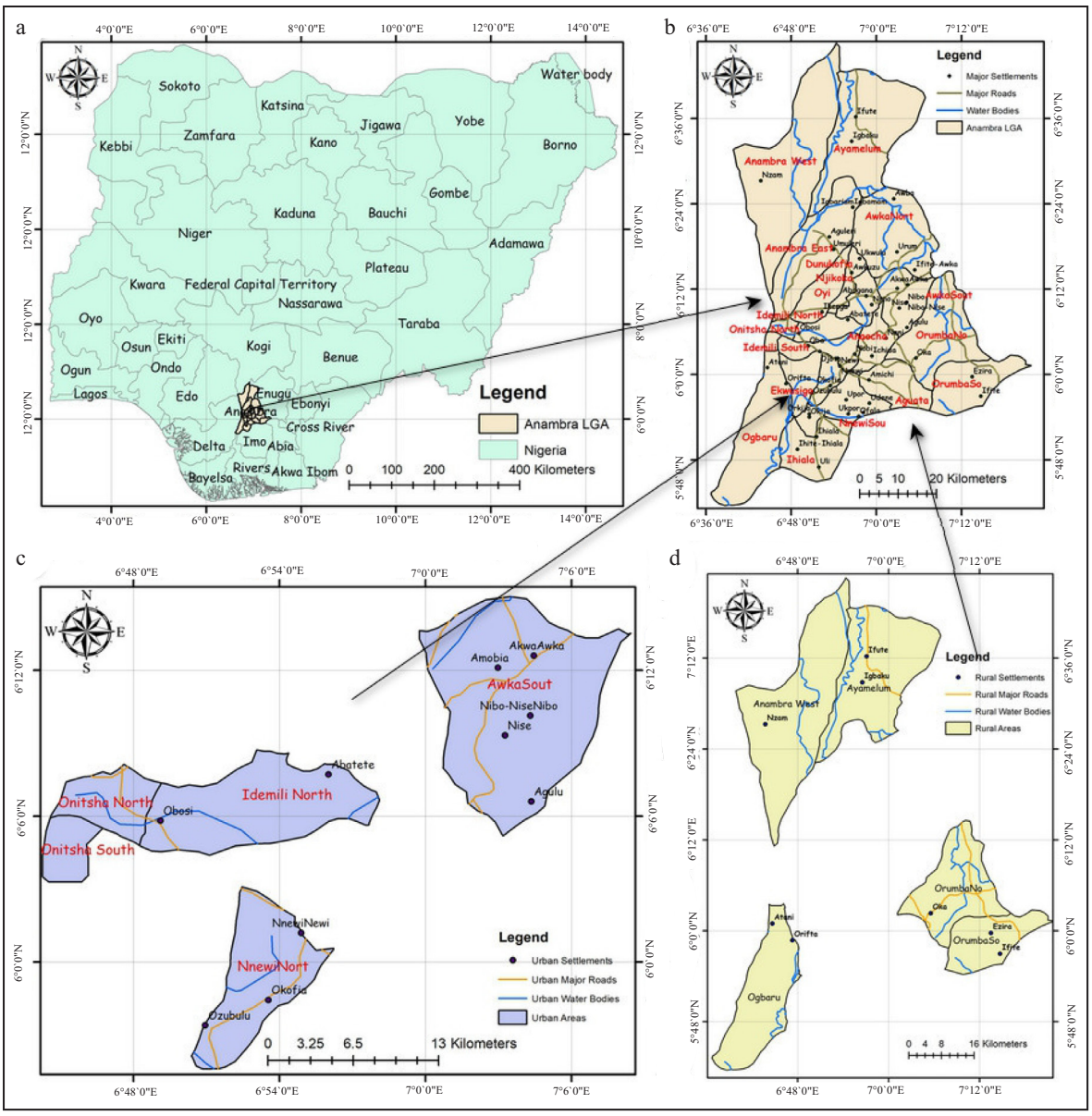


Figure 1. (a) Nigeria map, (b) Anambra State with LGAs, roads, and water bodies, (c) Urban areas with roads and water bodies, (d) Rural areas with roads and water bodies.

tion and land use (Ifeanyichukwu *et al*., 2021). Urban settlements, which collectively span approximately 367.78 km², are concentrated in the Onitsha North, Onitsha South, Awka South, Idemili North, and Nnewi North Local Government Areas (LGAs) (Figure 1c). Onitsha, a prominent commercial centre in West Africa, has an estimated population exceeding 1.5 million people and functions as a critical trade and transportation hub. Awka, the capital of Anambra State, has a population of approximately 500,000 people and serves as the administrative center (Ifeanyichukwu *et al*., 2021). Similarly, Nnewi, an industrial hub, has a population of around 900,000 people and plays a crucial role in the state's automobile and manufacturing sectors.

The rural areas of Anambra State, covering 2,300.00 km², span Anambra West, Ayamelum, Orumba North, Orumba South, Ogbaru, and Anambra East. These regions have lower population densities and economies reliant on agriculture, fishing, and subsistence farming. Ayamelum, a central rice farming hub, has approximately 200,000 residents. Anambra West,

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a predominantly riverine area, houses around 150,000 people, with most engaged in fishing and small-scale farming. Ogbaru, along the Niger River, has 300,000 residents but faces frequent flooding due to its low-lying terrain. Anambra State has a well-developed road network connecting urban and rural regions, promoting trade and transportation. Water bodies play a crucial role in Anambra geography and economy. The Niger River supports transportation and fishing, while the Omambala and Idemili Rivers provide irrigation and influence settlement patterns, contributing to livelihoods and environmental sustainability (Ayadiuno and Ndulue, 2024).

Topography of the Studied Area

Anambra State exhibits diverse topographic characteristics, with elevations ranging from -2 m to 388 m above sea level, as shown in Figure 2. The high-altitude areas, predominantly found in Aguata, Orumba North, Orumba South, and parts of Awka South, have elevations exceeding 320 m. Aguata LGA has one of the highest points in the state, reaching approximately 388 m. In contrast, Awka South, which includes the state capital Awka, is situated at an elevation of around 240 m. These elevated regions are characterized by hilly terrain and steep slopes, influencing land use and settlement patterns.

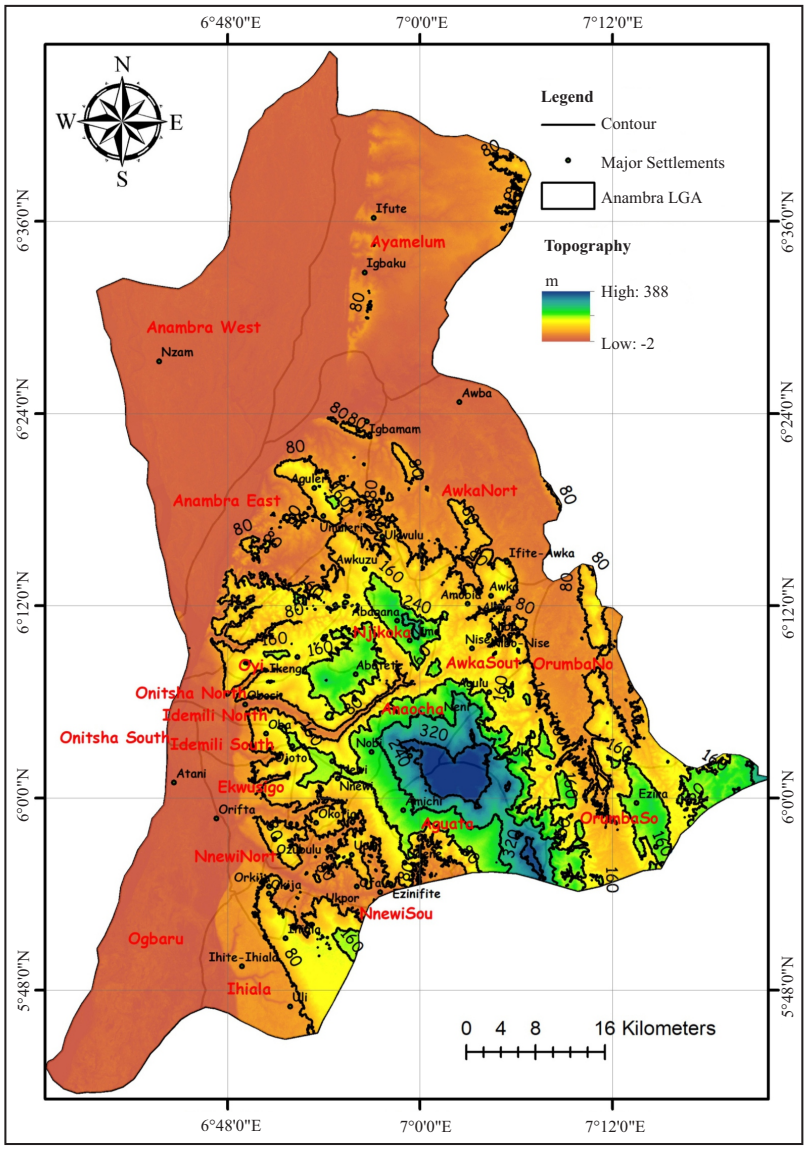


Figure 2. Topography of Anambra State, Nigeria.

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The lowland areas are concentrated in Anambra West, Ogbaru, Ayamelum, and Anambra East, where elevations drop to as low as -2 m. Onitsha North and Onitsha South, which are major commercial hubs, lie within low-lying regions along the Niger River at approximately 40-80 m elevation (Ifeanyichukwu *et al*., 2021). Ogbaru LGA, with settlements such as Atani and Ossomala, represents one of the lowest-lying regions, making it highly prone to seasonal flooding. The spatial distribution of topography significantly influences settlement development, agricultural activities, and flood risks across Anambra State. The highland regions support residential and agricultural expansion, while the lowlands remain vulnerable to water-related challenges.

Geology of The Studied Area

The geology of Anambra State is characterized by diverse lithological formations, which significantly influence its geomorphology, soil composition, and hydrogeological properties. The principal geological formations present in the studied area include the Ameki Group, the Ogwashi-Asaba Formation, the Upper Coal Measures, Clay and Shale with Limestone Intercalations, sands, gravels and clay, and the Sombreiro Warri Deltaic Plain (Figure 3).

The Ameki Group, which occupies the central part of the state, consists mainly of sandstone, clay, and shale, providing an important foundation for groundwater storage and agricultural activities. To the west, the Ogwashi-Asaba Formation

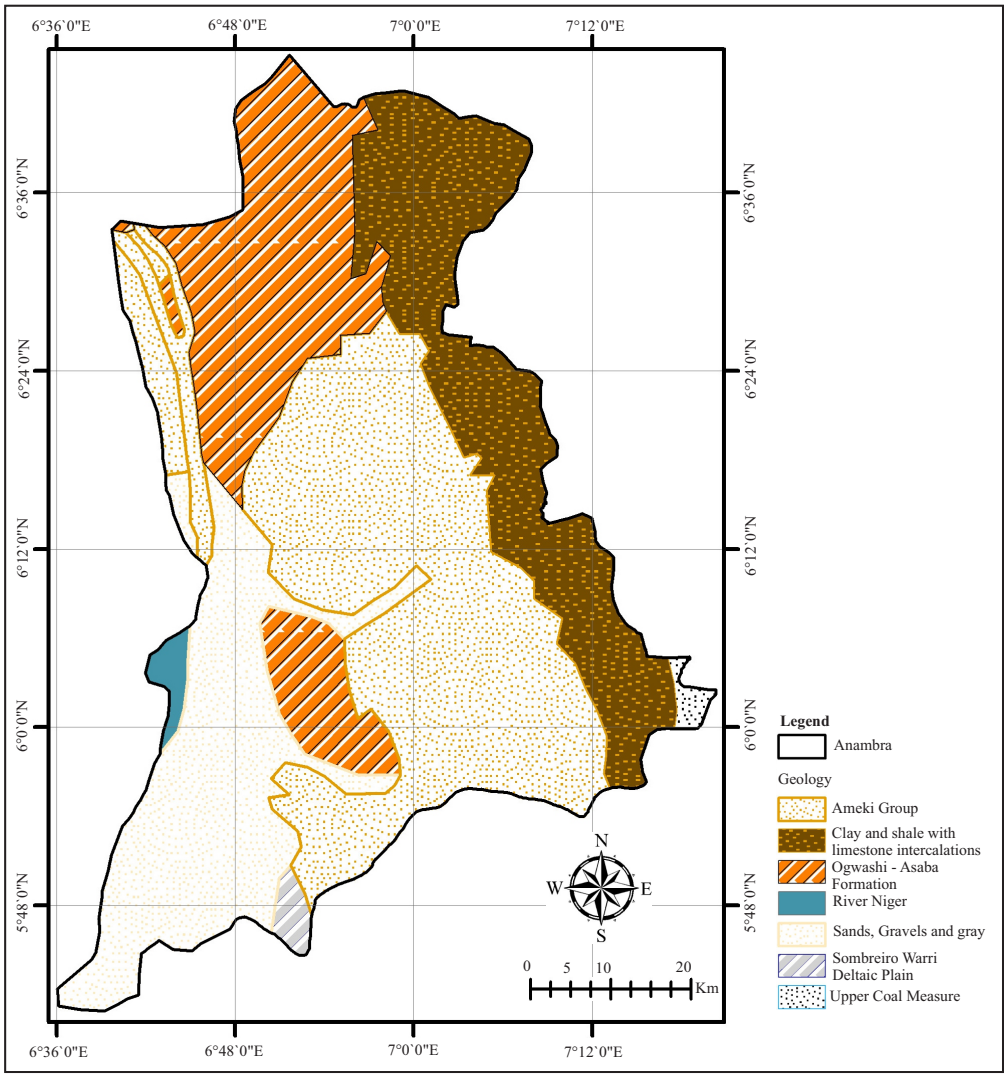


Figure 3. Geological formations of Anambra State and their spatial distribution.

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is dominant, consisting of alternating layers of sandstone, lignite, and clays (Ifeanyichukwu *et al*., 2021). This formation plays a crucial role in determining soil fertility and vegetation patterns in the region.

In the northern and eastern parts of the state, clay and shale with limestone intercalations are prevalent. These formations influence land stability and are commonly associated with limestone deposits, which are important for construction and industrial applications. The Upper Coal Measures, found in some southeastern regions, contain significant coal deposits, historically contributing to Nigeria's coal industry (Ifeanyichukwu *et al*., 2021). The Niger River, forming the western boundary of the state, has significantly influenced the deposition of sands, gravels, and clay, which are essential for construction and infrastructure development. The Sombreiro Warri Deltaic Plain, present in the southwestern section, consists of alluvial deposits, making the area highly susceptible to flooding.

Methodology

Data Acquisition

This study utilized SRTM DEM data for slope analysis, classifying terrain into flat, gentle, moderate, and steep slopes. Landsat eight imagery (30 m resolution) was used for LULC classification, processed in ArcGIS with SVM classification. LST was derived from Landsat 8 thermal bands using the Multi-Window Algorithm (MWA) and corrected with Normalized Difference Vegetation Index (NDVI)-based emissivity. UHI intensity was analyzed using standard deviation thresholds and mapping urban heat zones. ArcGIS was used for data processing, spatial analysis, and visualization.

Slope Analysis

The slope data derived from the DEM was analyzed to understand the terrain characteristics of the studied area (Ejepu *et al*., 2021). The slope (S) was calculated using the following equation:

$$S = \arctan\left(\frac{\Delta z}{d}\right) x \frac{180}{\pi} \quad \text{..... (1)}$$

where:
Δz Is the change in elevation, and
d Is the horizontal distance.

The slope data were classified (*e.g.* flat, gentle, moderate, steep) to assess the distribution of different slope classes across the studied area.

Quantitative Analysis of Slope-Temperature Relationship

To quantitatively assess the relationship between terrain slope and thermal characteristics, a statistical correlation analysis was performed between slope values and both LST and UHI intensity. Raster layers of slope, LST, and UHI were resampled to a common spatial resolution and aligned using ArcGIS. A pixel-wise extraction approach was applied, whereby slope values were paired with corresponding LST and UHI values across the studied area. The strength and direction of the relationship were evaluated using the Pearson correlation coefficient (r), defined in equation 2:

$$r = \frac{\sum (Si - \bar{S})(Ti - \bar{T})}{\sqrt{\sum \left(Si - \bar{S}\right)^2 \sum \left(Ti - \bar{T}\right)^2}} \quad \text{..... (2)}$$

where:
S_i represents slope values,
T_i represents LST or UHI values, and
$\bar{S}$, $\bar{T}$ are their respective means.

In addition, a simple linear regression model was developed to evaluate the predictive influence of slope on temperature variables:

$$T = \alpha + BS + \varepsilon \quad \text{..... (3)}$$

where:
TTT is LST or UHI,
SSS is slope,
β\betaβ represents the slope coefficient, and
ε\epsilonε is the error term.

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The coefficient of determination (R2R^2R2) was used to assess explanatory power. The analysis was conducted using ArcGIS and statistical processing tools to ensure robust spatial-statistical integration.

LULC Classification Evaluation

Landsat 8 satellite imagery was utilized to create a composite image with a 30 m resolution, providing a detailed aerial view of the earth's surface. To ensure spatial accuracy, the image was projected onto the UTM/WGS 84 coordinate system using ArcGIS (Abdulmalik *et al*., 2021). The LULC classification aimed to generate pixel-level representations of human activities and natural vegetation. Various classifiers were used to categorize land cover types such as water bodies, forests, croplands, and urban areas. The LULC change analysis quantified variations in land cover types between 2019 and 2024. The extent of these changes was evaluated using the following equation:

$$\Delta LULC = LULC_{2024} - LULC_{2019} \quad \text{.....(4)}$$

Accuracy Assessment of LULC Classification

To ensure the reliability and robustness of the LULC classification, an accuracy assessment was conducted using a confusion matrix approach. Reference data were obtained from high-resolution Google Earth imagery and supported by field knowledge of the studied area to provide reliable ground truth information. A set of randomly distributed validation points was generated across all land cover classes, including water bodies, trees, flooded vegetation, croplands, built-up areas, bare ground, and rangelands. Each classified pixel was compared with its corresponding reference data to evaluate classification performance and minimize misclassification errors.

The classification accuracy was quantified using standard statistical indicators, including Overall Accuracy (OA), Producer's Accuracy (PA), User's Accuracy (UA), and the Kappa Coefficient (K). Overall accuracy represents the proportion of correctly classified pixels relative to the total number of validation samples and is expressed as:

$$OA = \frac{\sum Correctly\ classified\ pixels}{Total\ number\ of\ validation\ pixels} x100 \quad \text{.....(5)}$$

The Kappa coefficient was used to measure the level of agreement between the classified results and reference data while accounting for agreement occurring by chance:

$$K = \frac{P_o - P_e}{1 - P_e} \quad \text{.....(6)}$$

where:
P_o represents the observed agreement and
P_e represents the expected agreement by chance.

The results of the accuracy assessment (Table 1) indicate that the classification achieved an overall accuracy of 88.9% and a Kappa Coefficient of 0.85, demonstrating a strong level of agreement between the classified map and reference data. According to established classification standards, a Kappa value greater than 0.80 indicates excellent classification performance.

Class-wise accuracy analysis further revealed high classification reliability across all land cover categories, with producer's accuracy ranging from 82.1% to 94.2% and user's accuracy ranging from 80.6% to 92.8%. The highest accuracies were observed for water bodies and built-up areas, while slightly lower accuracies in bare ground and cropland classes reflect typical spectral confusion in heterogeneous landscapes.

The accuracy assessment confirms that the LULC classification is reliable and suitable for

Table 1: Accuracy Assessment of LULC Classification

LULC Class	Producer's Accuracy (%)	User's Accuracy (%)
Water	94.2	92.8
Trees	88.6	86.9
Cropland	85.3	83.7
Built-up	91.5	89.4
Bare Ground	82.1	80.6
Rangeland	86.7	84.9

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analyzing spatial and temporal land cover changes in Anambra State.

Land Surface Analysis Using RS Indices

NDVI is a key metric for monitoring vegetation cover, assessing plant health, and detecting environmental changes. It analyzes visible and near-infrared reflections to quantify vegetation density, aiding in the identification of desert formation, deforestation, and agricultural productivity (De La Iglesia Martinez and Labib, 2022). NDVI is calculated using equation 7:

$$NDVI = \frac{Landsat\ Band\ 5 - Landsat\ Band\ 4}{Landsat\ Band\ 5 + Landsat\ Band\ 4} \quad \text{..... (7)}$$

NDVI measures near-infrared (NIR) and red reflectance, providing a ratio-based index to assess vegetation health and coverage across ecosystems. Its ability to monitor vegetative cycles and resilience makes it essential for environmental management, land monitoring, and climate studies. It offers a reliable tool for detecting ecological changes on a global scale.

LST Determination

In this study, the MWA was applied to Landsat satellite data to estimate LST efficiently. This method simplifies UHI analysis, enabling a better understanding of urbanization effects on local climates. Landsat 8 utilizes thermal band 10 (10.6-11.19 µm) to calculate surface temperature variations, helping detect ground temperature fluctuations. Converting digital numbers (DNs) to radiance ensures data accuracy and consistency. LST data reveal information about heat distribution, land cover changes, and regional temperature trends, which are essential for climate adaptation, urban planning, and environmental sustainability (Darettamarlan *et al*., 2021).

$$L\lambda = \left(\frac{L_{\max\lambda} - L_{\min\lambda}}{QCal_{\max} - QCal_{\min}}\right) * (QCal - QCal_{\min}) + L_{\min\lambda} \quad \text{..... (8)}$$

In sensor measurements, $^{QCal_{min}}$ represents the measured radiance, while $_{max\lambda}$ and $L_{min\lambda}$, denote the highest and lowest radiance values recorded in Band 8, respectively. QCal refers to the quantized and calibrated pixel values measured in digital numbers (DN), with $QCal_{max}$ and $QCal_{min}$ indicating the maximum and minimum DN values. These parameters facilitate sensor data calibration, ensuring accurate interpretation of RS imagery, particularly for Landsat data analysis.

$$L\lambda = M_l * QCal + A_l \quad \text{..... (9)}$$

L_λ which stands for the multiplicative scaling factor for radiance for band 10, and A_t, for the additive scaling factor.

Equation 10 corrects differences in local sun elevation angles, ensuring the accuracy and uniformity of radiometric values across different spectral bands. LST is estimated using thermal data from Landsat 8, specifically within the 10.6-11.19 µm spectral range. Adjusting for sun elevation angles and thermal variations enhances LST precision, providing reliable temperature assessments.

$$LL'_\lambda = \frac{L\lambda}{\sin\theta_s} \quad \text{..... (10)}$$

The solar elevation angle ($\sin\theta_s$) at the image centre significantly influences brightness temperature (BT) estimation. Equation 7 calculates BT in degrees Celsius after post-DN processing. BT measures the radiation emitted by an object at a specific wavelength, indicating the temperature a blackbody would need to match its intensity. BT is essential for accurate surface temperature assessments, aiding in heat dynamics analysis, UHI studies, and land-atmosphere interactions (Saleem *et al*., 2020).

$$BT = \left(\frac{K_2}{in\left(\frac{K_1}{L_\lambda} + 1\right)}\right) - 273.15 \quad \text{..... (11)}$$

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k refers to the bandwidth of the radiation centre wavelength in BT, and ε is the emissivity as defined in equation 12:

$$\varepsilon = 0.004\,pv + 0.986 \quad \text{..... (12)}$$

Emissivity is the ability of a surface to radiate heat energy, including both visible and infrared radiation. It plays a crucial role in predicting air temperatures and thermal dynamics, particularly for LST monitoring and environmental assessments (Zhong *et al*., 2021). The percentage of vegetation (ρv) is determined by Equation 13:

$$pv = \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \right)^2 \quad \text{..... (13)}$$

After LST was derived using NDVI, its geographical distribution was mapped, categorizing temperature ranges into comfort levels with distinct colours. Reflectivity constants K_1 and K_2 Specific to thermal bands, these were incorporated to ensure accurate temperature estimation and enhance the precision of thermal analysis for environmental assessments.

$$LST = \left(\frac{BT}{1 + \left(\frac{\lambda (BT)}{\rho} \right)} \right) XIn(\varepsilon) \quad \text{..... (14)}$$

Urban Heat Island (UHI)

UHI refers to metropolitan areas experiencing higher temperatures than surrounding rural regions due to human activity, dense urbanization, construction materials, air quality, and global warming (Simwanda *et al*., 2019). UHI zones in this study were identified using mean LST ($^{\sigma}$) and standard deviation ($^{\sigma}$), representing LST variability. Areas with LST values exceeding the mean plus half of the standard deviation were classified as UHI regions, highlighting the warmest geographic locations influenced by urban infrastructure and land-use patterns.

$$LST > \mu + 0.5 * \sigma \quad \text{..... (15)}$$

$$0 < LST \leq \mu + 0.5 * \sigma \quad \text{..... (16)}$$

Regions not categorized as UHI zones were detected by LST values falling below a predetermined threshold. The UHI index is computed using the formula:

$$UHI = LST - LST_{mean} / LST_{std} \quad \text{..... (17)}$$

Validation and Reliability Assessment

Although this study primarily relies on satellite-derived datasets, several validation strategies were employed to ensure the reliability and scientific robustness of the results. Due to logistical and temporal constraints, direct field-based measurements such as in situ temperature monitoring and vegetation sampling were not conducted. However, indirect validation approaches commonly adopted in remote sensing studies were applied.

Landsat 8-derived LST values were validated against established temperature ranges reported in previous studies conducted in similar tropical urban environments in Nigeria and other developing regions. The observed LST range of 25.92° C to 45.49° C is consistent with findings from prior studies (Ahmed *et al*., 2020; Awuh *et al*., 2021), confirming the reliability of the thermal outputs. NDVI was used as a proxy indicator for vegetation cover and surface cooling effects. The inverse relationship observed between NDVI and LST aligns with well-established ecological principles, where higher vegetation density leads to reduced surface temperatures due to evapotranspiration effects. This relationship provides an internal consistency check for the dataset.

Spatial patterns of UHI intensity correspond strongly with known urban centres such as Onitsha, Nnewi, and Awka, which are characterized by dense built-up infrastructure and reduced vegetation. Conversely, lower temperature zones were observed in riverine and vegetated regions such as Ogbaru and Anambra West. These spatial

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correspondences with known land-use characteristics serve as a form of spatial validation. LULC classification was carried out using supervised classification techniques and cross-checked with high-resolution imagery and existing land-use maps to ensure classification accuracy. The consistency of LULC trends (*e.g.* urban expansion and deforestation) with documented regional development patterns further supports the reliability of the results.

While in-situ field validation was not conducted, the integration of literature comparison, index-based validation (NDVI-LST relationship), and spatial consistency analysis provides a robust framework for validating the study outcomes.

Result and Discussion

Slope Distribution and Terrain Variations

The slope characteristics of Anambra State vary significantly across different LGAs, influencing land use, erosion susceptibility, and agricultural suitability. As illustrated in Figure 4, the slope values across the studied area range from 0° to 43.15°, with the lowest slopes found in the riverine and lowland regions. In contrast,

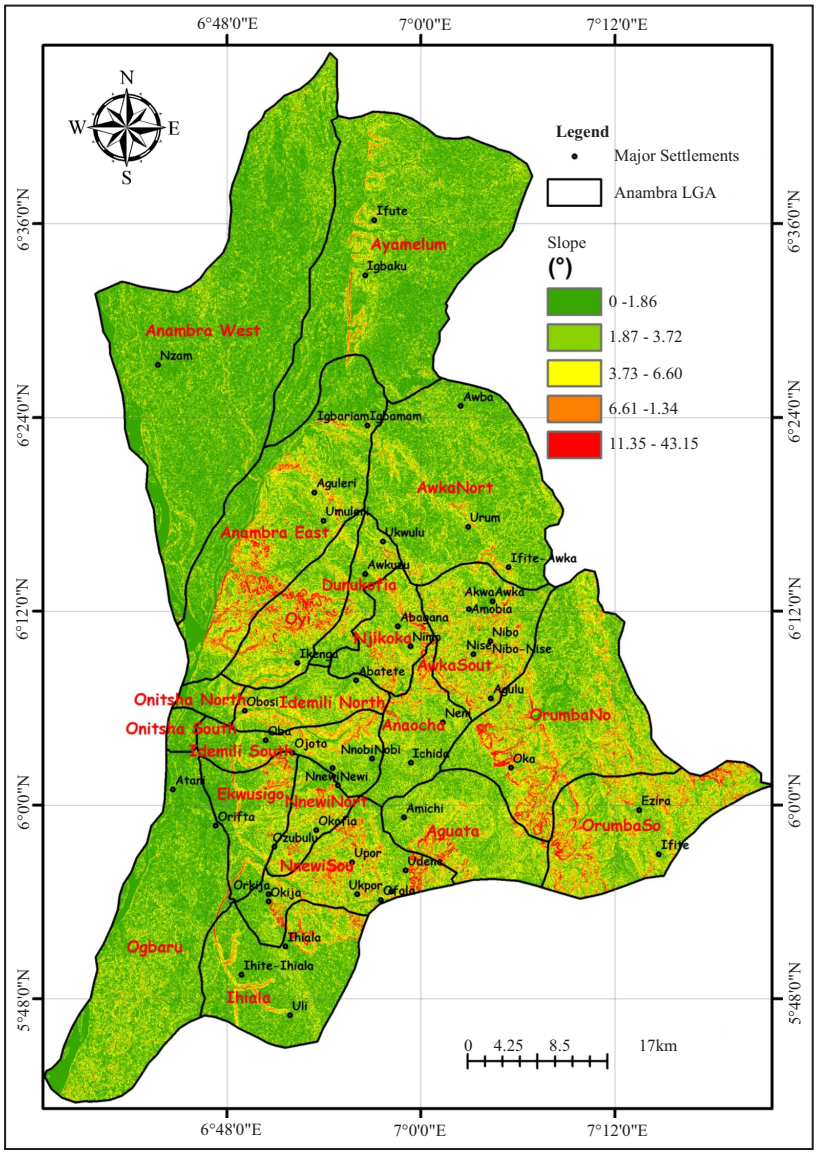


Figure 4. Slope analysis and its implications on land use in Anambra State.

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the highest slopes are concentrated in the southeastern highlands.

The low-slope regions (0°-1.86°), predominantly found in Ogbaru, Anambra West, Ayamelum, and parts of Onitsha North and South, account for the flat floodplain areas along The Niger River and Omambala River. These areas are more susceptible to flooding, particularly in Ogbaru and Anambra West, where settlements like Atani, Ossomala, and Nzam are prone to seasonal inundation. Moderate slopes, ranging from 1.87° to 6.60°, are widespread across Awka North, Idemili North, Idemili South, and parts of Oyi and Njikoka. These regions feature undulating terrain, making them suitable for urban expansion and moderate agricultural activities, as also reported by Mansour *et al*. (2022). Awka, the state capital, falls within this range, which supports its urban development and infrastructure expansion.

Steeper slopes, 6.61°–11.34°, are concentrated in the central and southeastern LGAs, including Aguata, Orumba North, Orumba South, and parts of Awka South. Highland regions, such as Ekwulobia, Umunze, and Oko, are home to settlements where land stability is crucial for construction and farming activities. The highest slope values, exceeding 11.35°, are predominantly located in the Aguata-Orumba axis, particularly around Umunze, Ajalli, and Ezira, where elevation peaks exceed 300 m above sea level. These areas are prone to gully erosion, which poses a significant threat to infrastructure and farmland (Yazie *et al*., 2020).

Approximately 60 % of the studied area has a slope below 3.72°, supporting agricultural and urban activities. However, about 15% of the land, mainly in the southeastern LGAs, has steep slopes exceeding 6.6°, necessitating soil conservation measures to mitigate erosion risks.

LULC Transformation

LULC Dynamics

LULC analysis of Anambra State between 2019 and 2024 reveals significant changes in the spatial distribution of different land cover types, as illustrated in Figure 5 and Table 2. The LULC classification results were validated using a confusion matrix, yielding an overall accuracy of 88.9% and a Kappa coefficient of 0.85, indicating strong agreement and high classification reliability.

The built-up area has increased from 1,154.96 km² in 2019 to 1,329.77 km² in 2024, reflecting rapid urbanization in cities such as Onitsha North, Onitsha South, Awka South, and Nnewi North. This urban expansion is primarily driven by population growth and economic activities, particularly in major commercial hubs such as Onitsha and Nnewi, where real estate development has intensified. Similarly, Awka, the state capital, has witnessed infrastructure growth, with increasing residential and commercial developments (Ifeanyichukwu *et al*., 2021).

The tree cover area has significantly declined from 1,644.81 km² in 2019 to 1,345.35 km² in 2024, indicating widespread deforestation. This trend is particularly noticeable in LGAs such as Orumba North, Orumba South, Aguata, and Ayamelum, where forested lands have been converted for agricultural and settlement purposes. The reduction in tree cover poses ecological concerns, including biodiversity loss and increased vulnerability to climate change impacts. The agricultural land (crops category) has expanded from 245.63 km² in 2019 to 437.04 km² in 2024, reflecting an increase in farming activities. This growth is predominantly observed in Ayamelum, Anambra East, and Ogbaru, where rice farming and other agricultural activities have intensified to meet food demand. However, this increase in farmland has contributed to deforestation and landscape modification (Nnadi *et al*., 2019).

Flooded vegetation has seen a slight increase from 21.42 km² to 22.07 km², which could be attributed to seasonal variations and water management practices in riverine communities such as Anambra West and Ogbaru. Meanwhile, the water body area has remained relatively stable, with a minor increase from 95.79 km² in 2019 to 96.15 km² in 2024, indicating consistency in river and lake extents within the state. The bare ground area has slightly decreased from 19.22 km² in 2019 to 16.63 km² in 2024, suggesting land reclamation for agricultural or urban development.

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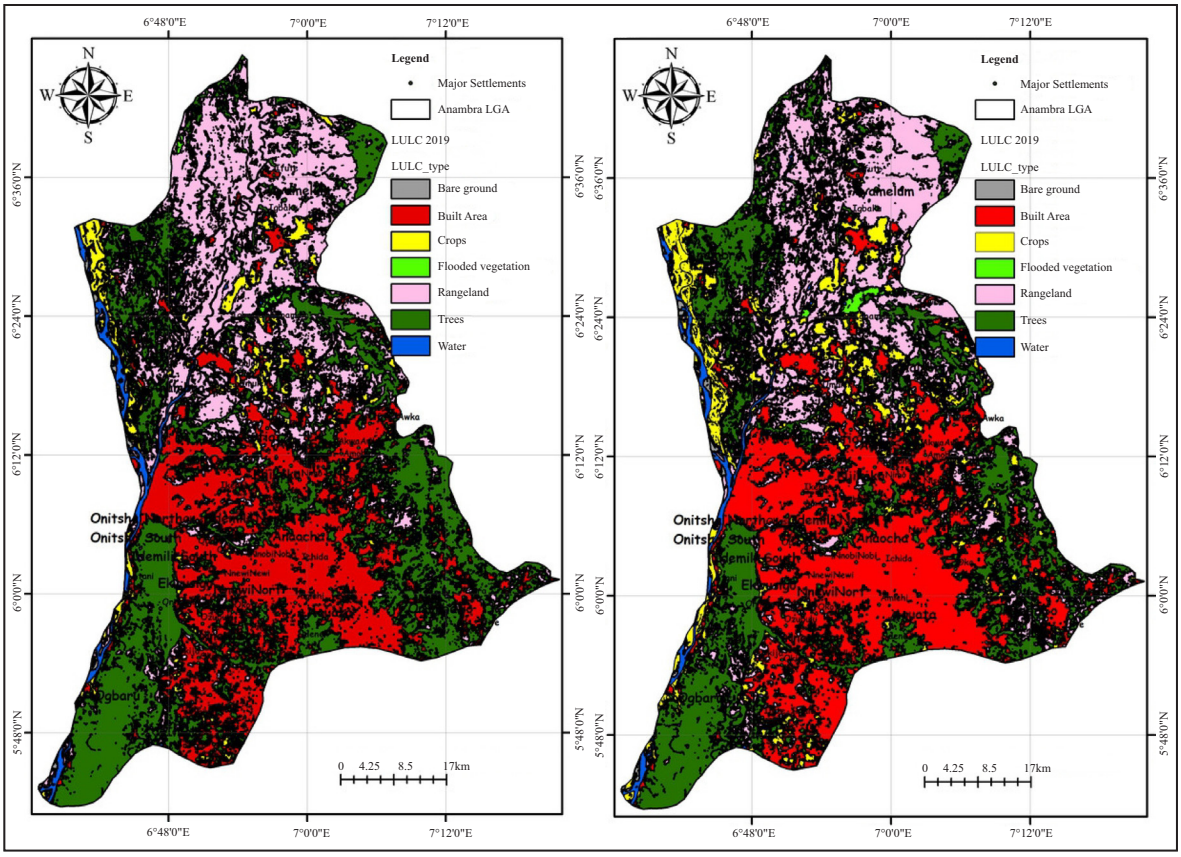


Figure 5. LULC Changes in Anambra State (a) 2019 and (b) 2024.

Table 2: LULC Changes in Anambra State

LULC Type	Area (km²) 2019	Area (km²) 2024
Water	95.79	96.15
Trees	1644.81	1345.35
Flooded vegetation	21.42	22.07
Crops	245.63	437.04
Built Area	1154.96	1329.77
Bare ground	19.22	16.63
Rangeland	1410.67	1345.51

This is more evident in developing areas such as Dunukofia, Idemili North, and Idemili South, where construction activities have replaced previously barren land.

The area of rangeland has declined from 1,410.67 km² in 2019 to 1,345.51 km² in 2024, indicating a reduction in open grasslands. This is likely due to the conversion of rangeland into built-up areas and farmlands, particularly in Oyi, Njikoka, and Orumba South. The decline in rangeland suggests increasing pressure on grazing land, which could impact livestock farming in these regions (Eldridge *et al*., 2016).

LULC changes indicate a shift towards urbanization and agricultural expansion at the expense of forest and rangeland areas. Built-up areas have increased by 15.1%, while tree cover has declined by approximately 18.2%. Similarly, agricultural land has expanded by 77.9%, reflecting an increasing demand for food production. The relatively stable water body area suggests that hydrological conditions have remained unchanged over the period.

LULC in Rural Areas

LULC analysis of rural areas in Anambra State from 2019 to 2024 reveals significant changes in land cover distribution, as illustrated in Figure 6. The comparison of LULC statistics in Table 3 highlights key trends across major land cover types.

The built-up area increased from 169.85 km² in 2019 to 210.57 km² in 2024, representing a 24% growth. This expansion is predominantly observed in LGAs such as Orumba North, Orumba

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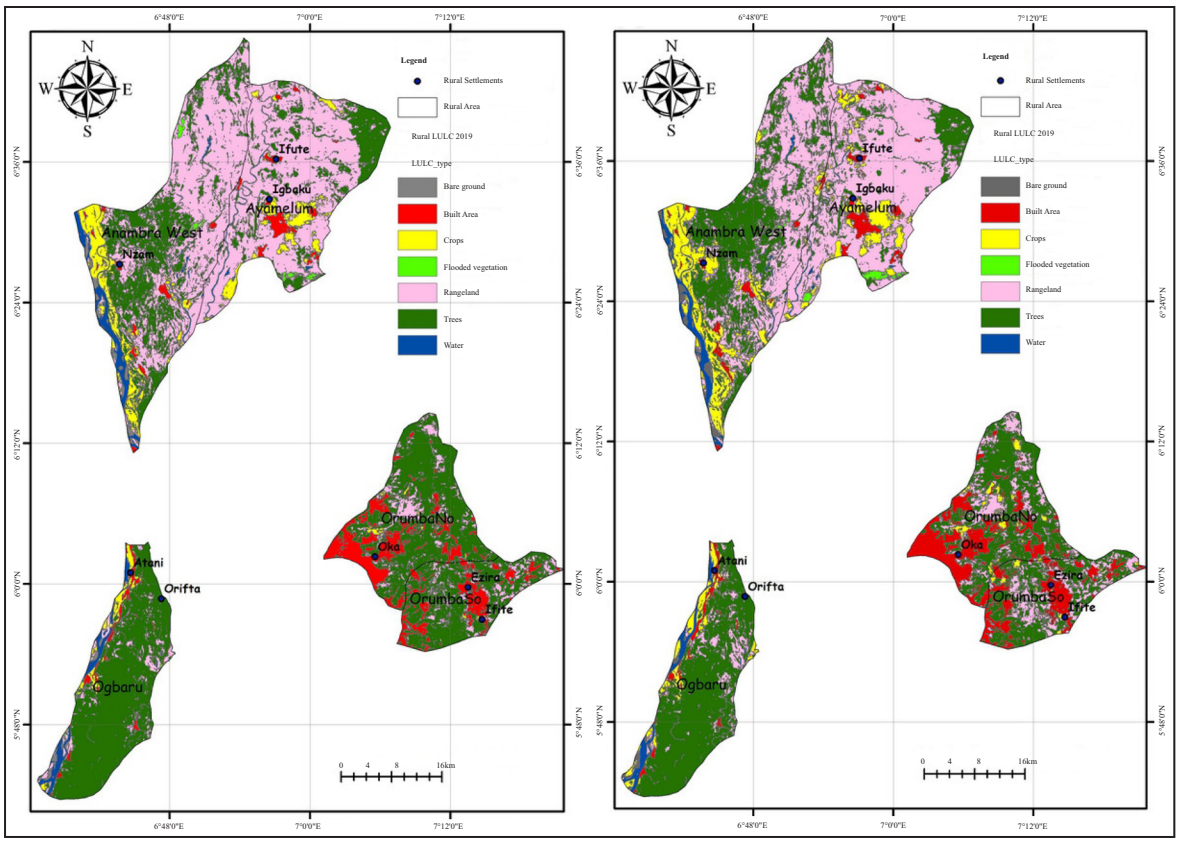


Figure 6. Comparison of Rural LULC Changes in Anambra State (a) 2019 and (b) 2024.

Table 3: Rural LULC Changes in Anambra State

LULC Type in Rural Areas	Area (km²) 2019	Area (km²) 2024
Water	67.89	69.09
Trees	1014.67	908.89
Flooded vegetation	13.67	12.15
Crops	127.86	219.88
Built Area	169.85	210.57
Bare ground	13.37	15.36
Rangeland	892.69	864.06

South, Anambra West, and Ogbaru, where rural settlements such as Oka, Atani, and Orifite have experienced infrastructural development and population increase. The increase in built-up areas in these rural regions suggests a gradual shift toward urbanization, possibly driven by rural-urban migration and increased housing demand (Liao *et al*., 2024). The tree cover area experienced a significant decline, from 1,014.67 km² in 2019 to 908.89 km² in 2024, representing a 10.4% reduction. The loss of forested land is especially pronounced in Ayamelum, Anambra West, and Orumba South, where deforestation has intensified due to agricultural expansion and logging activities.

The cropland area increased from 127.86 km² in 2019 to 219.88 km² in 2024, representing a 72% increase. This expansion is particularly evident in Ayamelum, Anambra West, and Orumba North, where farming activities have intensified due to higher food demand and agricultural commercialization. This trend aligns with government policies promoting food security and commercial agriculture, yet it also raises concerns about deforestation and soil depletion (Ajibade *et al*., 2020). The rangeland area slightly declined from 892.69 km² in 2019 to 864.06 km² in 2024, indicating a 3.2% decrease. This decline is attributed to land conversion for farming and built-up areas, particularly in Anambra West and Ogbaru, where grazing lands are being replaced by croplands and settlements (Emmanuel *et al*., 2020).

The water body area remained relatively stable, with a minor increase from 67.89 km²

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in 2019 to 69.09 km² in 2024, reflecting a 1.8% growth. This stability suggests that significant rivers and lakes, such as The Niger River in Ogbaru and Anambra West, have maintained their extents, possibly due to improved water management and conservation efforts (Ukpai *et al*., 2021). The bare ground area showed a minor increase from 13.37 km² to 15.36 km², indicating a 14.9% rise. Developing rural settlements within Orumba South and Ayamelum are reclaiming abandoned or underdeveloped lands for future use, making this change more noticeable. The flooded vegetation area saw a slight decline from 13.67 km² in 2019 to 12.15 km² in 2024, representing an 11.1% reduction. This trend is likely due to seasonal variations and drainage improvements in flood-prone areas such as Anambra West and Ogbaru.

Urban LULC Changes

LULC changes in urban areas of Anambra State between 2019 and 2024 reveal significant shifts in land use, particularly in urban expansion, deforestation, and agricultural development. As depicted in Figure 7, urban growth is evident across major LGAs, including Onitsha North, Onitsha South, Nnewi North, Idemili North, and Awka South. The analysis of LULC statistics in Table 4 provides a comparative assessment of the spatial distribution of various land cover types over the five years.

The built-up area increased significantly from 203.45 km² in 2019 to 231.41 km² in 2024, marking an increase of approximately 13.7%. This trend is more prominent in Onitsha North, Onitsha South, and Nnewi North, where rapid urbanization and industrialization have led to increased infrastructure development. In Awka South, the administrative seat of the state, there has been a steady expansion of residential, commercial, and institutional buildings, contributing to the growth in built-up areas. The tree cover area decreased from 111.28 km² in 2019 to 64.09 km² in 2024, reflecting a 42.4% loss of forested land. This decline is most notable in Idemili North, Awka South, and Nnewi North, where forested lands have been cleared to accommodate new developments, including housing, road networks, and industrial zones. The continued reduction in tree cover raises concerns about biodiversity loss, UHI effects, and air quality deterioration.

The crop area experienced a significant expansion from 7.87 km² in 2019 to 24.13 km² in 2024,

Table 4. Urban LULC Changes in Anambra State

LULC Type in Urban Area	Area (km²) 2019	Area (km²) 2024
Water	5.13	5.08
Trees	111.28	64.09
Flooded vegetation	0.10	0.00
Crops	7.87	24.13
Built Area	203.45	231.41
Bare ground	0.60	0.04
Rangeland	39.35	43.04

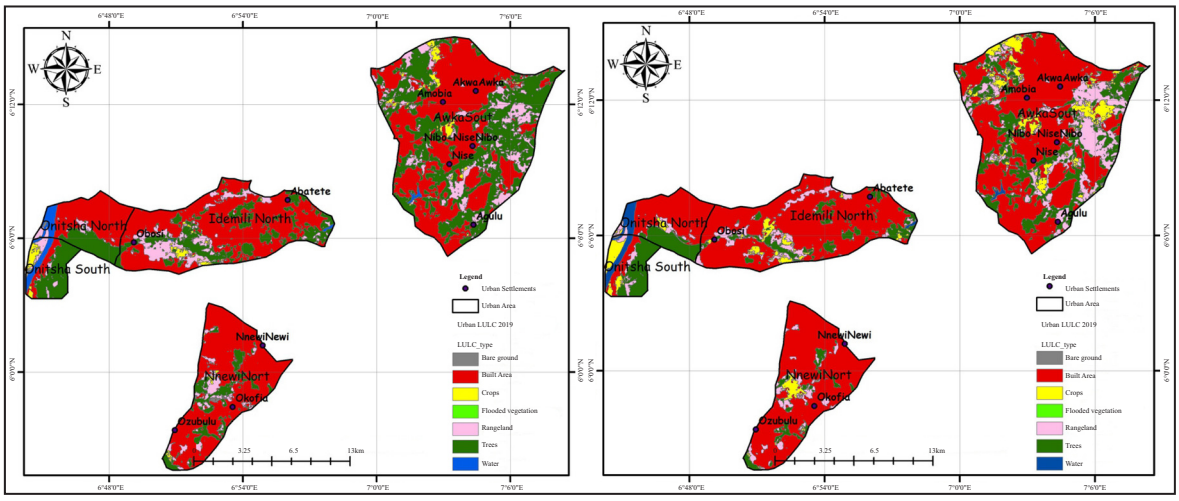


Figure 7. Comparison of Urban LULC Changes in Anambra State (a) 2019 and (b) 2024.

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marking a 206.5% increase. Peri-urban areas like Amobia, Nibo, and Abatete are witnessing this growth, as urban farming gains prominence in response to rising food demand. The increase in cropland suggests that while urbanization is accelerating, some areas within urban LGAs are being preserved for agricultural use, possibly as a response to food security concerns. The rangeland area expanded slightly from 39.35 km² to 43.04 km², representing a 9.4% increase. The increase in rangeland is primarily seen in Awka South and Nnewi North, where open spaces and undeveloped lands are still available. This trend suggests that although urbanization is advancing, there are still areas designated for grazing and natural vegetation within urban settlements (Ifeanyi *et al*., 2024). The water body area remained relatively stable, with a slight decrease from 5.13 km² in 2019 to 5.08 km² in 2024, reflecting a 0.97% reduction. The Niger River in Onitsha and other minor urban water bodies have largely maintained their extents, despite encroachment pressures from land reclamation activities.

The bare ground area reduced significantly from 0.60 km² in 2019 to 0.04 km² in 2024, representing a 93.3% decline. This change indicates that most previously undeveloped lands have been converted into either built-up areas or croplands, particularly in Onitsha and Awka South, where urban expansion is most intense. Flooded vegetation, which covered 0.10 km² in 2019, will have completely disappeared by 2024. This suggests improved drainage systems and urban planning efforts that have mitigated flood-prone zones, especially in low-lying urban areas like Onitsha South and Nnewi North.

The LULC changes observed between 2019 and 2024 highlight the intensification of urbanization and agricultural activities at the expense of forest cover and bare ground areas. The 13.7% increase in built-up areas and the 206.5% rise in cropland indicate increasing land conversion to accommodate population growth and food demand. However, the 42.4 % decline in tree cover raises environmental concerns, particularly regarding deforestation, air pollution, and climate resilience. The spatial distribution of urban expansion is most pronounced in Onitsha, Nnewi, and Awka, with significant land cover modifications seen in Idemili North and Awka South.

Comparative Assessment of LULC Changes in Rural and Urban

Urban areas have experienced a 13.7% increase in built-up land, rising from 203.45 km² in 2019 to 231.41 km² in 2024. This expansion is prominent in Onitsha North, Onitsha South, Nnewi North, and Awka South, where commercial and residential developments are rapidly replacing vegetative cover. Conversely, rural regions such as Orumba North, Orumba South, and Anambra West have seen a 24% increase in built-up areas, from 169.85 km² to 210.57 km², indicating gradual urbanization driven by population growth and infrastructure development. One of the most significant disparities between rural and urban LULC changes is in tree cover reduction. Urban tree cover declined by 42.4%, from 111.28 km² to 64.09 km², primarily in Idemili North, Awka South, and Nnewi North, where deforestation has been driven by real estate expansion and industrialization. In contrast, rural areas experienced a 10.4% decline in tree cover, from 1,014.67 km² to 908.89 km², with deforestation largely linked to agricultural expansion, especially in Ayamelum, Anambra West, and Orumba South.

Agricultural land-use trends differ significantly between urban and rural settings. Rural cropland increased by 72%, from 127.86 km² to 219.88 km², reflecting a strong push towards food production, particularly in Ayamelum and Anambra West. In urban areas, cropland grew more dramatically, by 206.5 %, from 7.87 km² to 24.13 km², mainly due to peri-urban farming in Nibo, Abatete, and Amobia. This suggests that even within urban centres, agriculture is becoming a strategic land use. Rangeland exhibited slight changes in both regions, with rural areas witnessing a 3.2% decrease (from 892.69 km² to 864.06 km²), while urban areas saw a 9.4% increase (from 39.35 km² to 43.04 km²). The urban increase suggests that some undeveloped

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lands remain, particularly in Awka South and Nnewi North.

Spatial Distribution and Thermal Variability of LST and UHI Effects

Spatial Analysis of LST and UHI Effects

The reliability of the LST and UHI results is further supported by their consistency with established NDVI-temperature relationships and known spatial patterns of urbanization across Anambra State, providing indirect validation in the absence of ground-based measurements.

The LST and UHI intensity analysis in Anambra State reveals spatial variations in thermal conditions across different LGAs. As depicted in Figure 8, the LST ranges from 25.92°C to 45.49°C, while UHI intensity varies between 11.02°C and 30.59° C. The corresponding area coverage for different temperature ranges is summarized in Table 5.

The lowest LST values (25.92°C - 31.37° C) and UHI intensities (11.02° C - 16.47°C) cover approximately 329.50 km², predominantly observed in Ogbaru, Anambra West, and Ayamelum LGAs. These areas are characterized by dense vegetation, wetlands, and proximity to major water bodies such as The Niger River and Omambala River, which help regulate surface temperatures. The moderate LST range (31.38° C− 33.82° C) and UHI intensity (16.48° C —18.92° C) span about 947.27 km² and encompass regions like Awka North, Orumba North, and parts of Idemili North and Oyi. These areas have a mix of urban settlements, agricultural lands, and rangelands, leading to intermediate temperature conditions. A significant portion of the state, 1,345.33 km²,

Table 5. Area Distribution of LST and UHI Intensity in Anambra State

LST (°C)	UHI (°C)	Area (km²)
25.92 - 31.37	11.02 - 16.47	329.50
31.38 - 33.82	16.48 - 18.92	947.27
33.83 - 35.67	18.93 - 20.77	1345.33
35.68 - 37.51	20.78 - 22.61	1410.36
37.52 - 45.49	22.62 - 30.59	559.87

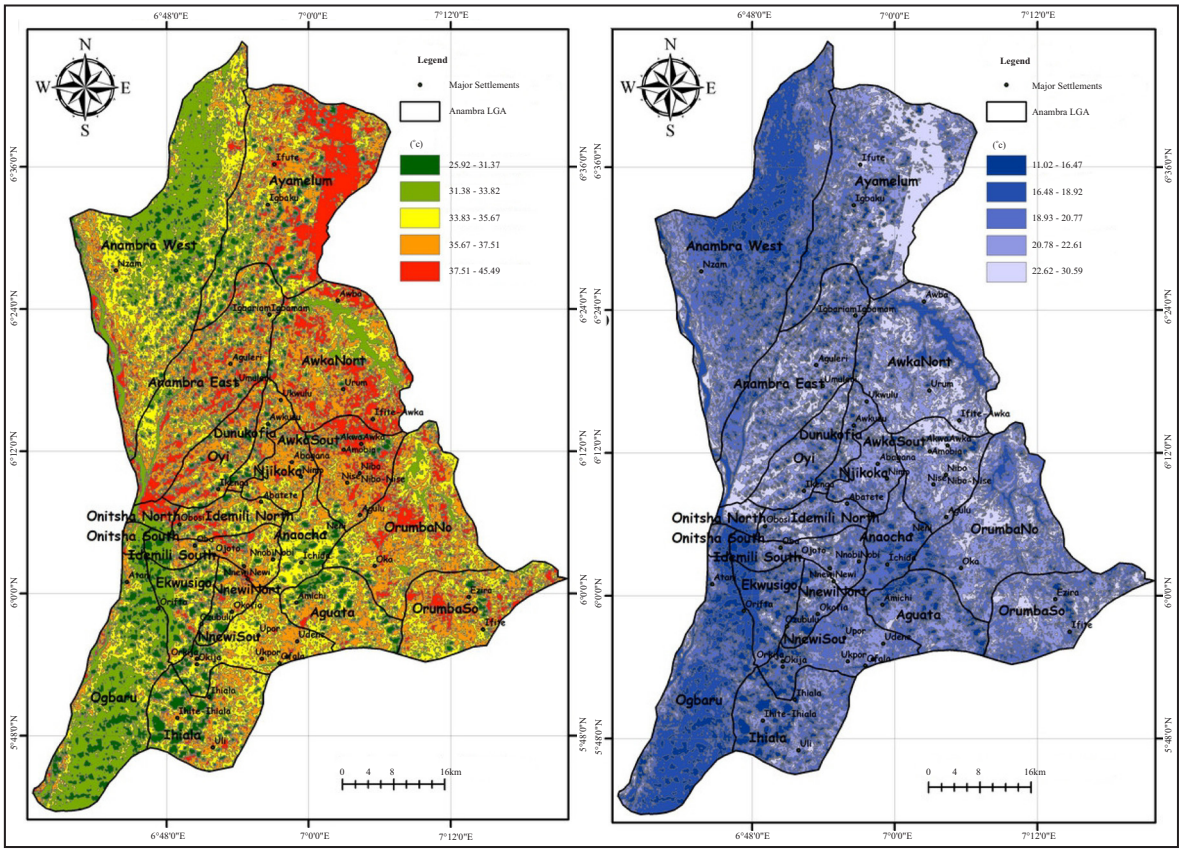


Figure 8. LST and UHI distribution in Anambra State.

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experiences LST between 33.83°C and 35.67° C, with UHI intensities ranging from 18.93° C to 20.77° C. This thermal zone covers Awka South, Nnewi North, and parts of Idemili South and Njikoka, where increased urbanization, road networks, and industrial activities contribute to higher heat retention.

The highest temperature zones (35.68° C - 45.49° C) and extreme UHI intensities (20.78° C - 30.59° C) account for 1,970.23 km², mainly observed in Onitsha North, Onitsha South, Nnewi North, Idemili North, and Awka South. These are the most densely populated and urbanized LGAs, with extensive built-up areas and limited vegetation cover. The high thermal conditions in these regions are indicative of the UHI effect, where artificial surfaces such as concrete and asphalt retain heat, raising nighttime temperatures and intensifying heat stress.

The findings indicate that approximately 40.3 % of Anambra State (1,970.23 km²) experiences high-temperature conditions (above 35.68° C), correlating with the most urbanized regions. The expansion of built-up areas, as observed in the earlier LULC analysis, has directly contributed to this increase in surface temperature. Conversely, the coolest regions (below 31.37° C) account for only 9.5 % (329.50 km²), emphasizing the need for the conservation of green spaces and improved urban planning to mitigate heat island effects.

Thermal Landscape of Rural LST and UHI Variability

LST and UHI analysis for rural areas of Anambra State between 25.92° C and 45.49° C highlights significant spatial variations in thermal conditions. As shown in Figure 9, LST is highest in areas with reduced vegetation cover and increased land-use changes. At the same time, UHI intensity ranges from 11.02° C to 30.59° C, emphasizing temperature disparities between natural landscapes and built-up environments. The corresponding area distribution for different temperature ranges is summarized in Table 6.

The lowest LST range (25.92° C - 31.37° C) and UHI intensity (11.02° C - 16.47° C) account for 168.27 km², predominantly observed in Ogbaru, Anambra West, and parts of Ayamelum LGAs. These areas contain extensive wetlands and water bodies such as the Niger River and Omambala River, which provide a cooling effect and contribute to lower surface temperatures. The moderate temperature range (31.38° C- 33.82° C) and UHI intensity (16.48° C - 18.92° C) cover approximately 619.34 km², spanning regions like Ayamelum, Orumba North, and Anambra East. These LGAs consist of a mix of agricultural land, scattered settlements, and semi-forested landscapes, which moderate temperature variations.

A significant portion of rural Anambra State, 667.04 km², experiences LST between 33.83° C and 35.67° C, with UHI intensities from 18.93° C to 20.77° C. These thermal zones dominate Orumba North, Orumba South, and sections of Anambra West, where increasing agricultural expansion and reduced forest cover contribute to moderate heat retention. The highest temperature zones (35.68° C - 45.49° C) and extreme UHI intensities (20.78° C - 30.59° C) cover approximately 844.94 km², concentrated mainly in Orumba South, Anambra East, and parts of Ayamelum. These regions have higher temperatures due to widespread deforestation, increased bare ground, and limited vegetation. Settlements such as Ezira, Oka, and Ifite fall within this category, with agricultural land expansion and infrastructure developments playing a crucial role in elevating surface temperatures.

The findings indicate that 48.5 % of the studied area (844.94 km²) experiences high thermal conditions (above 35.68° C), correlating with areas undergoing rapid land conversion. Conversely, the most extraordinary zones (below 31.37° C) account for only 9.7 % (168.27 km²), mainly in wetland and riverine areas.

Urban Heat Distribution

The analysis of LST and UHI intensity across urban areas of Anambra State highlights significant thermal variations influenced by land cover changes and urban expansion. As depicted in Figure 10, the LST values range from 25.92° C

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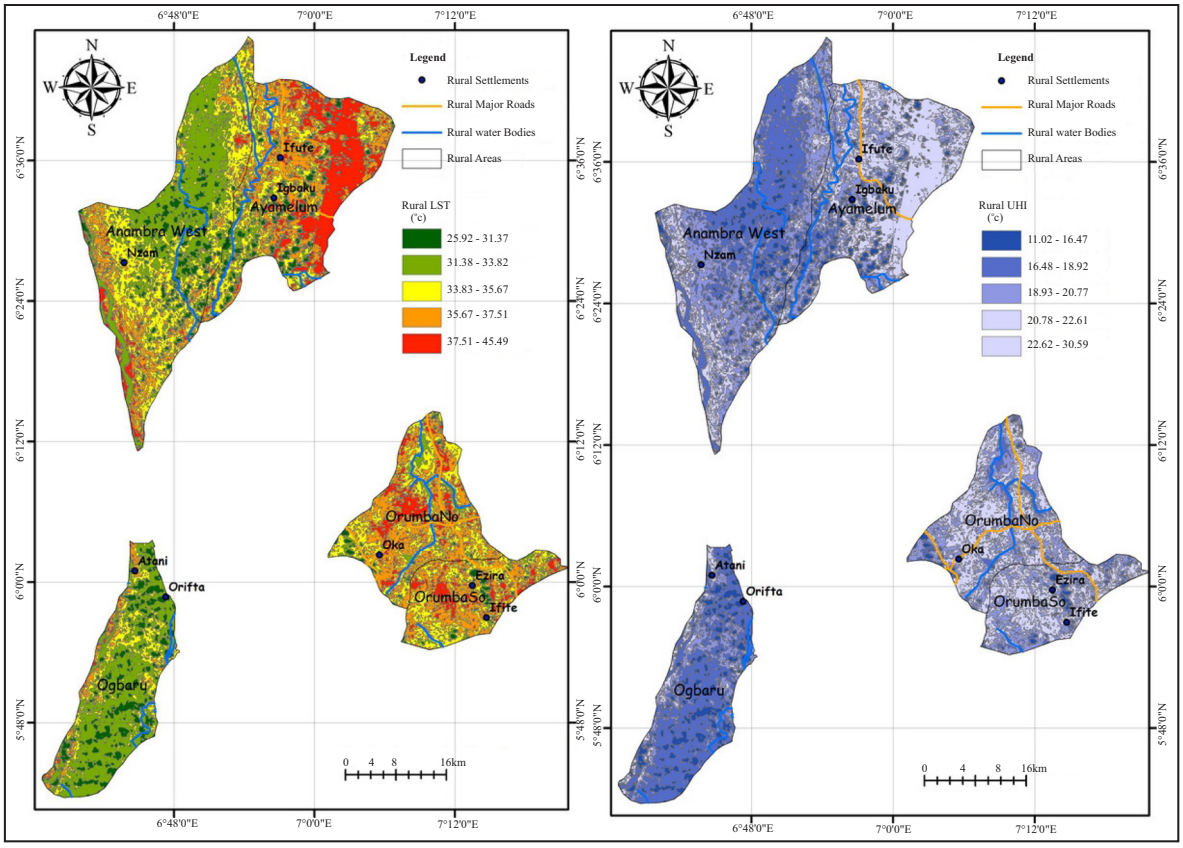


Figure 9. Rural LST and UHI patterns in Anambra State.

Table 6. Distribution of LST And UHI Intensity in Rural Anambra State

LST (°C)	UHI (°C)	Area (km²)
25.92 - 31.37	11.02 - 16.47	168.27
31.38 - 33.82	16.48 - 18.92	619.34
33.83 - 35.67	18.93 - 20.77	667.04
35.68 - 37.51	20.78 - 22.61	579.12
37.52 - 45.49	22.62 - 30.59	265.82

to 45.49° C, while UHI intensity varies between 11.02° C and 30.59° C. These differences are driven by the extent of built-up areas, vegetation cover, and the presence of water bodies. The area coverage for each temperature range is summarized in Table 7.

The lowest temperature range (25.92° C - 31.37° C) and UHI intensity (11.02° C - 16.47° C) cover only 21.54 km², found in Onitsha South, parts of Awka South, and sections of Idemili North. These areas have small patches of vegetation and are near water bodies, which help regulate temperature. The moderate LST range (31.38° C - 33.82° C) and UHI intensity (16.48° C - 18.92° C) span 42.98 km², covering regions such as Nnewi North, Awka South, and sections of Idemili North. These LGAs exhibit mixed land use, including urban settlements, open green spaces, and tree clusters that mitigate heat accumulation. A significant portion of the urban landscape, 84.09 km², falls within the 33.83° C - 35.67° C range, with UHI intensities from 18.93° C to 20.77° C. These areas are seen in Onitsha North, Idemili North, and Nnewi North, where extensive urbanization and infrastructure development contribute to increased surface temperatures. The highest temperature zones (35.68° C - 45.49° C) and extreme UHI intensities (20.78° C - 30.59° C) occupy approximately 219.16 km², primarily in Onitsha North, Nnewi North, and Idemili North. These LGAs, which are highly urbanized, exhibit significant heat accumulation due to dense built-up areas, industrial activities, and limited vegetation cover.

The findings indicate that 62.1% of urban Anambra State (219.16 km²) experiences high

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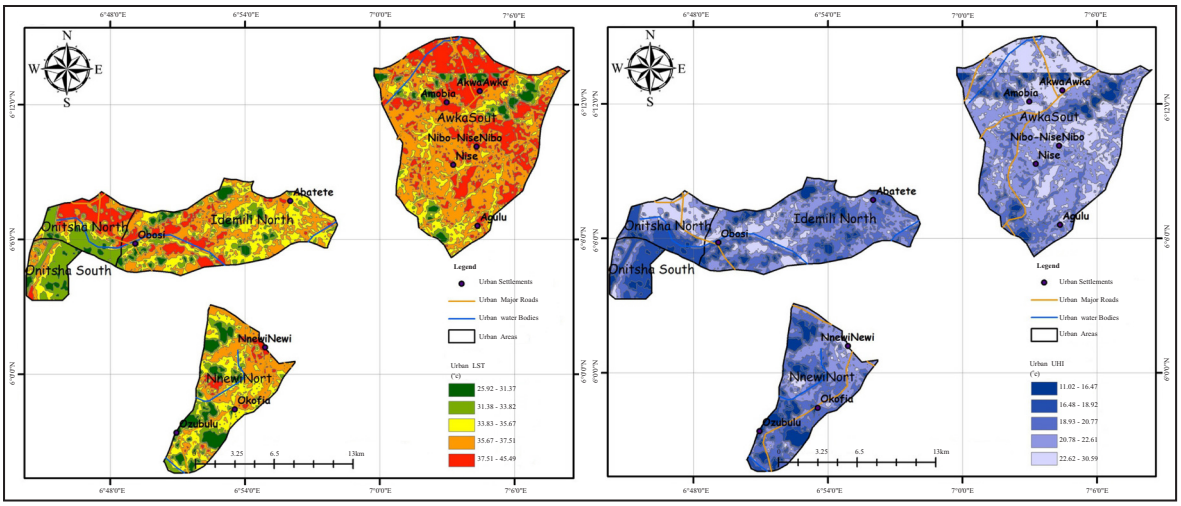


Figure 10. Urban LST and UHI patterns in Anambra State.

Table 7. Area Distribution of LST And UHI Intensity in Urban Anambra State

LST (°C)	UHI (°C)	Area (km²)
25.92 - 31.37	11.02 - 16.47	21.54
31.38 - 33.82	16.48 - 18.92	42.98
33.83 - 35.67	18.93 - 20.77	84.09
35.68 - 37.51	20.78 - 22.61	147.53
37.52 - 45.49	22.62 - 30.59	71.63

thermal conditions (above 35.68° C), aligning with the expansion of built-up areas. In contrast, only 9.7 % (21.54 km²) maintains a cooler environment, primarily in regions with preserved vegetation and proximity to water bodies. Urban areas like Onitsha, Nnewi, and Idemili North demonstrate the most significant UHI effects, as artificial surfaces such as asphalt and concrete retain heat, causing elevated temperatures. The presence of green spaces in Awka South and parts of Nnewi North slightly moderates the temperature, highlighting the importance of urban vegetation in mitigating heat stress.

Urban and Rural Thermal Variability

LST and UHI effects in urban and rural areas of Anambra State exhibit distinct spatial variations, primarily influenced by land use patterns, vegetation cover, and urban expansion. Urban areas experience significantly higher LST and UHI intensities compared to rural settings due to the dominance of the built-up regions, industrial activities, and reduced vegetation (Ahmed *et al*., 2020; Ekwe *et al*., 2020). In contrast, rural areas maintain relatively lower temperature profiles due to natural landscapes and agricultural land use.

Urban areas, as represented in Figure 9, exhibit a significant concentration of high-temperature zones. Approximately 62.1 % (219.16 km²) of the urban landscape experiences LST values above 35.68° C, with UHI intensities exceeding 20.78° C (Table 7). This trend is most pronounced in Onitsha North, Onitsha South, Nnewi North, and Idemili North, where dense urban infrastructure, road networks, and industrialization contribute to extreme heat accumulation. In contrast, only 9.7 % (21.54 km²) of metropolitan areas remain in the most incredible temperature range of 25.92° C - 31.37° C, primarily in locations such as Awka South, parts of Nnewi, and sections of Idemili North, where patches of green spaces and water bodies provide a cooling effect.

Rural areas, depicted in Figure 8, exhibit a broader distribution of temperature zones, with a more significant proportion of the landscape maintaining moderate thermal conditions. The lowest LST range of 25.92° C - 31.37° C is observed in 168.27 km², primarily in Ogbaru, Anambra West, and Ayamelum, where extensive wetlands and riverine landscapes help regulate surface temperatures. Unlike urban settings, rural areas retain a significantly higher proportion of moderate-temperature zones, with 619.34 km²

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falling within the 31.38° C - 33.82° C range and 667.04 km² experiencing LST values between 33.83° C and 35.67° C. The highest LST values exceeding 35.68°C occur in Orumba South, Anambra East, and parts of Ayamelum, covering 844.94 km², mainly due to deforestation, increasing agricultural activities, and land use conversion. The UHI effect is also more pronounced in urban regions, where impervious surfaces like asphalt, concrete, and rooftops trap heat, raising nighttime temperatures (Awuh *et al*., 2021). Urban areas experience UHI intensities reaching 30.59° C, while rural areas, though still affected, maintain relatively lower intensities with maximum values around 22.6° C. The lower UHI effect in rural regions is attributed to the higher presence of trees, open lands, and water bodies, which help dissipate heat (Huang *et al*., 2021).

The expansion of built-up areas in urban LGAs intensifies heat accumulation, necessitating improved urban planning strategies such as increased vegetation cover, green infrastructure, and heat mitigation policies. In contrast, while rural areas experience relatively lower UHI effects, the continued deforestation and agricultural expansion observed in Orumba South, Anambra East, and Ayamelum could gradually elevate rural temperatures. Thus, sustainable land-use planning, afforestation programmes, and better water management strategies are essential to mitigate rising LST and UHI impacts across both urban and rural landscapes in Anambra State.

Physical Drivers of Thermal Variability in Anambra State

The spatial variation of LST and UHI intensity observed across Anambra State is not only a function of land cover distribution but is also controlled by underlying physical mechanisms, including surface moisture availability, atmospheric humidity, thermal properties of construction materials, and energy balance processes.

One of the primary drivers of thermal variability is surface moisture and evapotranspiration (Ahmadpour *et al*., 2025; Ogunbode *et al*., 2025). Areas with dense vegetation and proximity to water bodies, such as Ogbaru and Anambra West, exhibit lower LST values due to enhanced evapotranspiration. Vegetation facilitates latent heat flux, where a significant portion of incoming solar radiation is used for moisture evaporation rather than sensible heat, thereby reducing surface temperature (Balogun and Daramola, 2018; Adeyeri *et al*., 2026). In contrast, deforested and agricultural regions, particularly in Orumba South and Ayamelum, experience reduced evapotranspiration and increased sensible heat flux, leading to elevated LST values.

Another critical factor influencing thermal patterns is atmospheric humidity. High humidity levels, especially in riverine and wetland environments, contribute to increased heat absorption in the atmosphere, but reduce surface heating through evaporative cooling processes (Okon *et al*., 2021). This explains the relatively lower temperature ranges observed in floodplain regions despite high solar radiation input (Nooni *et al*., 2025). Conversely, areas with reduced vegetation and moisture availability exhibit lower humidity and higher surface heating rates.

The thermal properties of urban materials also play a significant role in UHI formation (Mohamed *et al*., 2025). Built-up areas dominated by asphalt, concrete, and roofing materials exhibit high heat capacity and low albedo, allowing them to absorb and store solar radiation during the day and release it gradually at night (Vujovic *et al*., 2021; Lefevre *et al*., 2025). This thermal inertia leads to persistent elevated temperatures in urban centres such as Onitsha, Nnewi, and Awka. The low emissivity and reduced permeability of these materials further limit heat dissipation and moisture infiltration, intensifying the UHI effect.

Surface albedo and radiative balance contribute to the observed temperature differences. Natural surfaces such as vegetation and water bodies typically have higher albedo and reflect a greater proportion of incoming solar radiation (Trlica *et al*., 2017; Nurfaizah *et al*., 2025). In contrast, impervious urban surfaces absorb more radiation, increasing net heat gain. This difference in radiative behaviour explains the strong

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correlation between built-up expansion and the increased LST observed in the study.

Urban geometry and anthropogenic heat release further amplify thermal variability. High-density urban areas with closely spaced buildings reduce airflow and trap heat within urban canyons, limiting convective cooling (Koko *et al*., 2021). Human activities such as transportation, industrial operations, and energy consumption also contribute additional heat to the urban environment, reinforcing UHI intensity (Das *et al*., 2024; Tran *et al*., 2026).

The integration of these physical processes evapotranspiration, humidity regulation, material thermal properties, radiative balance, and anthropogenic heat provides a comprehensive explanation for the spatial thermal patterns observed in Anambra State. This mechanistic understanding strengthens the interpretation of the LST and UHI results beyond descriptive analysis and highlights the complex interactions between land cover and climate dynamics.

Impact of Slope Variations on LULC Changes

The comparison of slope distribution and LULC patterns in Anambra State gives important insights into how terrain influences land development, agriculture, and environmental sustainability. The spatial analysis highlights significant variations in slope values across different LGAs, affecting the distribution of urban, agricultural, and natural land cover types.

Flat and low-lying regions, with slopes ranging from 0° to 1.86°, dominate Ogbaru, Anambra West, and parts of Ayamelum, aligning with riverine floodplains along the Niger River and Omambala River. These areas support water bodies (95.79 km² in 2019 to 96.15 km² in 2024) and flooded vegetation (21.42 km² to 22.07 km²), essential for wetland biodiversity and agriculture. The relatively flat terrain facilitates cropland expansion, with agricultural land increasing from 245.63 km² to 437.04 km², particularly in Ayamelum, Anambra East, and Ogbaru. However, these regions are prone to seasonal flooding, posing risks to settlements like Atani, Nzam, and Ifite, emphasizing the need for flood-resilient infrastructure and sustainable water management practices (Chukwuma *et al*., 2021).

Moderate slopes between 1.87° and 6.60° characterize Awka North, Idemili North, Oyi, and Njikoka, where urbanization has intensified. These LGAs exhibit built-up area expansion from 1,154.96 km² in 2019 to 1,329.77 km² in 2024, driven by population growth in major cities like Awka, Onitsha, and Nnewi. The gentle terrain supports infrastructure development, making it conducive for residential and commercial growth. However, rapid urbanization has led to tree cover reduction from 1,644.81 km² to 1,345.35 km², raising concerns about biodiversity loss and heat island effects. Urban planning in these areas should integrate green infrastructure to mitigate temperature increases and prevent excessive land sealing (Yang *et al*., 2022).

Steeper slopes, ranging from 6.61° to 11.34°, are concentrated in Aguata, Orumba North, and Orumba South, where settlements like Umunze, Oko, and Ekwulobia are located. These regions have seen a decline in rangeland from 1,410.67 km² to 1,345.51 km², primarily due to agricultural expansion and settlement development. The slope steepness in these areas increases erosion susceptibility, with land clearing for farming exacerbating soil degradation. Deforestation in these highland zones has also contributed to land instability, necessitating soil conservation measures such as terracing and agroforestry (Asmamaw and Mohammed, 2018). The Aguata-Orumba highlands, especially around Umunze, Ajalli, and Ezira, exhibit the highest slope values, exceeding 11.35°. These regions experience severe gully erosion, aggravated by vegetation loss and unregulated farming. The conversion of forested land into croplands and urban expansion in these steep zones threatens soil stability and infrastructure.

Quantitative Relationship Between Slope and UHI/LST

To complement the qualitative assessment of slope influence on thermal patterns, a quantitative

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analysis was conducted to evaluate the relationship between slope, LST, and UHI intensity.

The Pearson correlation results indicate a weak negative relationship between slope and LST ($r \approx -0.18$ to -0.25) and between slope and UHI intensity ($r \approx -0.15$ to -0.22). This suggests that areas with higher slope gradients tend to exhibit slightly lower surface temperatures, although the relationship is not strong. The regression analysis further supports this observation, with low coefficients of determination ($R^2 < 0.10$), indicating that slope alone explains only a small proportion of temperature variability across the studied area. This confirms that while slope contributes to thermal regulation through enhanced runoff, reduced heat retention, and improved air circulation, it is not a dominant driver of UHI formation.

Spatially, lower temperature values were more consistently associated with steeper terrains in the Aguata and Orumba regions, whereas higher temperatures were concentrated in flatter, urbanized areas such as Onitsha, Nnewi, and Awka. However, these thermal patterns are more strongly influenced by land cover characteristics, particularly the extent of built-up areas and vegetation loss, than by slope variations alone.

These findings align with previous studies (Xian, *et al*., 2022; Koko *et al*., 2021), which highlight that topography exerts a secondary control on urban thermal environments, while anthropogenic land-use changes remain the primary determinant of UHI intensity.

The weak correlation observed reinforces the need to consider slope as a complementary factor within a multivariable framework rather than as an independent predictor of thermal behaviour.

Impact of LST and UHI on Different LULC Types in Urban and Rural Areas

The spatial distribution of LST and UHI intensity across various LULC types in Anambra State highlights the significant impact of urbanization and landuse changes on thermal conditions. The interplay between built-up areas, vegetation loss, agricultural expansion, and water bodies has led to variations in surface temperature across urban and rural regions, with notable implications for environmental sustainability, human health, and land management strategies.

The built-up areas in Anambra State have expanded significantly, increasing from 1,154.96 km² in 2019 to 1,329.77 km² in 2024. This growth has contributed to higher LST and intensified UHI effects, particularly in highly urbanized LGAs such as Onitsha North, Onitsha South, Nnewi North, Awka South, and Idemili North. These regions recorded LST values exceeding 35.68° C, with UHI intensities reaching 30.59° C, demonstrating the classic UHI effect caused by heat-retaining surfaces such as asphalt roads, concrete structures, and industrial zones (Nwakaire *et al*., 2020). In contrast, areas with significant tree cover, particularly in rural LGAs such as Ayamelum, Orumba North, Orumba South, and Anambra West, recorded lower LST and UHI intensities. The total tree cover in Anambra State has declined from 1,644.81 km² in 2019 to 1,345.35 km² in 2024, leading to higher heat retention in areas undergoing deforestation. The removal of vegetation in these rural regions has contributed to temperature increases, with LST values ranging from 33.83° C to 35.67° C and UHI intensities reaching 20.77° C in places such as Aguata, Orumba South, and Anambra East, where farmland expansion and logging activities are prominent.

Agricultural lands have expanded significantly, particularly in Ayamelum, Anambra East, and Ogbaru, where croplands increased from 245.63 km² in 2019 to 437.04 km² in 2024. While farmland expansion has supported food production, it has also altered surface temperatures. Cropland areas exhibit moderate LST values ranging from 31.38° C to 35.67° C, depending on vegetation density. However, excessive clearing of forests for agriculture, particularly in Orumba South and Anambra West, has contributed to higher LST values above 35.68° C, increasing vulnerability to climate extremes (Rangel-Peraza *et al*., 2024). Urban areas, particularly Onitsha, Nnewi, and Awka, exhibit significantly higher LST and UHI intensities than rural settings. Approximately

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62.1% of urban Anambra State (219.16 km²) experiences temperatures above 35.68° C, with the most intense UHI effects occurring in Onitsha North, Onitsha South, and Nnewi North, where commercial activities and high-rise developments dominate. The absence of green spaces and the dominance of artificial surfaces trap heat, causing persistent nighttime warming. Rural areas such as Ogbaru, Anambra West, and Ayamelum exhibit significantly lower LST and UHI intensities due to the cooling influence of water bodies and vegetation (Li *et al*., 2024). About 168.27 km² of rural areas maintain temperatures below 31.37° C, benefiting from the cooling effect of the Niger River, the Omambala River, and extensive wetlands. These regions demonstrate how natural landscapes help mitigate heat stress, emphasizing the importance of forest conservation and sustainable agricultural practices.

Future Urbanization Scenarios and Implications for LST and UHI

Based on the observed trend of increasing built-up areas and declining vegetation cover between the study periods, it is reasonable to project that continued urbanization will further intensify thermal conditions, particularly in rapidly growing urban centres such as Onitsha, Awka, and Nnewi. If current landuse trajectories persist, the replacement of vegetated surfaces with impervious materials such as asphalt and concrete will likely result in higher heat absorption, reduce evapotranspiration, and increase surface temperatures.

A scenario-based projection suggests that areas currently classified as peri-urban may transition into fully urbanized zones within the next decade, leading to an expansion of UHI hotspots. This could increase average LST values by an estimated 1-3° C in densely built-up areas, consistent with trends reported in similar tropical urban environments. Furthermore, the loss of green infrastructure and natural land cover may reduce the cooling capacity of the landscape, thereby exacerbating heat stress, energy demand, and environmental health risks. Without intervention, these changes could lead to more pronounced spatial temperature disparities between urban and rural areas.

However, alternative scenarios that incorporate sustainable urban planning strategies such as urban greening, afforestation, green roofs, and controlled land-use development could significantly mitigate these effects. Increasing vegetation cover and preserving natural landscapes would enhance evapotranspiration and reduce surface heating, thereby moderating UHI intensity. These projections emphasise the necessity of proactive urban planning policies that integrate geospatial insights into land-use decision-making. By adopting climate-sensitive development strategies, policymakers can manage urban growth while minimizing its thermal and environmental impacts.

The observed expansion of built-up land and decline in tree cover highlight the need for coordinated land-use management and heat-mitigation measures across Anambra State. In Onitsha, Nnewi, and Awka, urban planning should prioritise parks, tree-lined streets, and appropriately designed green roofs, consistent with established urban heat mitigation approaches and evidence of vegetation-related cooling in Nigerian cities (Han et al., 2022; Balogun and Daramola, 2018; Ekwe et al., 2020). These interventions should prioritise neighbourhoods with limited vegetation, reflecting the unequal distribution of cooling benefits documented by Li et al. (2024). Reforestation and afforestation should complement the protection of existing tree cover in Orumba South, Aguata, and Ayamelum, extending the integration of urban development and forestry examined by Yang et al. (2022) to the landscapes identified in this study. In agricultural areas, maintaining vegetation cover and introducing locally appropriate soil-conservation practices should be prioritised, given the relationship between agricultural land-cover changes and surface warming reported by Rangel-Peraza et al. (2024). Agroforestry and erosion-control measures should be evaluated for vulnerable slopes, with implementation guided by locally mapped erosion risks, consistent with the spatial

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conservation approaches discussed by Ajibade et al. (2020) and Asmamaw and Mohammed (2018). In flood-prone Ogbaru, Anambra West, and Ayamelum, drainage improvements, flood-resilient infrastructure, wetland protection, and restrictions on inappropriate floodplain development should be coordinated using flood-vulnerability information, building on the findings of Chukwuma et al. (2021) and Emmanuel et al. (2020). Land-use zoning should also direct development away from environmentally sensitive areas and retain connected green spaces, responding to the infrastructure and land-cover pressures documented by Adewumi and Agbasi (2024) and Akaolisa et al. (2023). Where paving is necessary, reflective and permeable materials should be assessed for local suitability, drawing on the mitigation options reviewed by Nwakaire et al. (2020) and Vujovic et al. (2021). Finally, community education and participation should support these measures by connecting vegetation conservation, heat awareness, and adaptation planning with local development priorities, consistent with the sustainable-development implications discussed by Okon et al. (2021).

Conclusions

This study investigated the spatial and temporal dynamics of LST and UHI intensity in relation to LULC changes and topographic characteristics in Anambra State, Nigeria. Using integrated geospatial techniques involving Landsat imagery, NDVI, DEM-derived slope analysis, and UHI computation, the study provides a comprehensive assessment of how urban expansion influences thermal patterns in a tropical environment. The findings reveal a clear and consistent increase in built-up areas over time, accompanied by a corresponding decline in vegetation cover. This transformation has led to a significant rise in LST values across major urban centres, particularly in Onitsha, Awka, and Nnewi. Areas dominated by impervious surfaces exhibited the highest temperatures, while vegetated and less developed regions maintained relatively lower thermal signatures. The study further demonstrates that LULC change is the dominant driver of UHI intensity, with built-up expansion directly contributing to localized heat accumulation. Although slope was found to influence temperature distribution, the quantitative analysis confirms that its effect is relatively weak compared to land cover dynamics, indicating that topography plays a secondary role in shaping thermal variability. A key contribution of this study lies in the integration of LST, UHI, LULC, and slope within a unified geospatial framework, providing a more holistic understanding of urban thermal processes in a rapidly urbanizing tropical setting. The incorporation of both qualitative spatial analysis and quantitative statistical validation enhances the robustness of the findings and distinguishes this work from previous studies that focused on single-variable assessments. The results highlight the growing environmental implications of uncontrolled urban expansion, including increased heat stress, reduced thermal comfort, and potential impacts on public health and energy demand. Without intervention, continued urbanization is likely to intensify UHI effects and expand high-temperature zones into peri-urban areas. To mitigate these impacts, the study emphasizes the importance of sustainable land-use planning strategies, including urban greening, preservation of natural vegetation, and controlled development of built-up areas. These measures can enhance the thermal resilience of urban environments and support climate-adaptive urban development. This study provides valuable geospatial insights for policymakers, urban planners, and environmental managers, offering a scientific basis for designing effective strategies to manage urban heat and promote sustainable urban growth in Anambra State and similar tropical regions.

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