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QUANTIFYING URBAN MORPHOLOGY–UHI RELATIONSHIPS IN HOT-DRY CLIMATES: AN EMPIRICAL STUDY FROM NIGERIA

Abdulhamid, F. ^{1*}, Malgwi, E. M.¹, Aminu, S. S.¹

¹Department of Architecture, Modibbo Adama University, Yola, Nigeria

Corresponding Author: abdulhamidfahad@gmail.com

Abstract

Urban heat island (UHI) intensity in cities continues to intensify with rapid urbanization, yet empirical relationships between urban morphology and UHI formation in hot-dry climates remain poorly quantified. This study aimed to establish the relationship between urban morphological parameters and UHI intensity in Yola, Nigeria, a rapidly growing city in Sub-Saharan Africa's hot-dry climate zone. Using 18 months of microclimate monitoring data from 12 strategically selected sites, measured UHI intensities ranging from 2.8°C to 4.2°C across different urban forms were recorded. Results showed a strong correlations emerged between UHI intensity and building density ($r = 0.847$, $p < 0.001$), vegetation cover ($r = -0.776$, $p < 0.001$), and impervious surface ratio ($r = 0.812$, $p < 0.001$). Building density exceeding 60–65% correlated with UHI intensification beyond 3.5°C, while vegetation coverage above 40% maintained UHI below 3.0°C. Diurnal analysis revealed a 195% UHI intensity increase from daytime (2.9°C) to evening peak (6.2°C at 18:00–21:00), with pronounced nocturnal persistence (4.8°C at midnight). Climate change projections (combined CMIP6/CORDEX-Africa climate model outputs (5-model ensemble) under RCP 2.6, 4.5, and 8.5) indicated potential UHI doubling to 8.5°C by 2050 under business-as-usual scenarios, though aggressive mitigation could limit intensification to 4.1°C. These findings provide empirical evidence for density controls, vegetation preservation requirements, and surface material regulations in rapidly urbanizing hot-dry regions globally.

Keywords: Building density; Hot-dry climate; Urban heat island; Urban morphology; Vegetation cover

1. INTRODUCTION

The urban heat island (UHI) phenomenon defined as the elevated air and surface temperatures in urban areas relative to surrounding rural regions, is one of the most significant manifestations of anthropogenic climate modification at the local scale. Intensities range from 1–2°C in small towns to 8–12°C in major metropolitan areas, driven by replacement of vegetation with low-albedo impervious surfaces, reduced evapotranspiration, anthropogenic heat release, and modified wind patterns (Loh & Bhiwapurkar, 2022; Zemba et al., 2025). Global urbanization is projected to reach 68% by 2050, with urban populations in Africa growing at 3–4% annually, disproportionately exposing developing regions with limited adaptive capacity (Ermolina et al., 2021). Climate change compounds these effects by elevating baseline temperatures and increasing extreme heat frequency, creating potentially lethal thermal conditions during heat waves.

Despite extensive UHI research in temperate cities, critical gaps persist in tropical and developing-country contexts. A systematic review found fewer than 15% of empirical UHI studies addressed tropical climates

and fewer than 8% focused on Sub-Saharan African cities, despite this region experiencing the world's fastest urbanization (Abedrabboh et al., 2025). Tropical hot-dry climates differ fundamentally from temperate contexts in their year-round high temperatures, intense low-latitude solar radiation, large diurnal temperature ranges, and pronounced dry–wet seasonality which are conditions that alter energy balance partitioning and create uncertainty about the applicability of established UHI–morphology relationships. Developing-country urbanization patterns (rapid informal settlement growth, limited planning oversight, low-cost materials) further require context-specific strategies rather than direct transfer from high-income temperate cities.

Nigeria exemplifies the convergence of factors creating critical UHI vulnerability in rapidly urbanizing tropical developing countries. As Africa's most populous nation with approximately 220 million residents and projected population of 400 million by 2050, Nigeria faces unprecedented urbanization challenges (Torsen & Oaya, 2018). Current urban population of approximately 115 million (52% urbanization rate) will grow to an estimated 280 million (70% urbanization) by 2050, representing addition of 165 million urban residents over 30 years which is equivalent to creating 3–4 megacities the size of Lagos (Agabi, 2023). This urbanization occurs primarily through peripheral expansion and informal settlement densification, with minimal formal planning guidance or infrastructure provision.

Nigeria's geographic position near the equator creates inherent thermal stress. Mean annual temperatures range from 26–28°C in coastal regions to 28–30°C in northern Sahel zones, with typical daily ranges of 24–38°C. Recent temperature trends show concerning increases with 2021 recorded as the hottest year in four decades, with increasing frequency of extreme heat events exceeding 40°C in northern cities (NIMET, 2025). Climate change projections indicate further warming of 1.5–3.0°C by 2050 under moderate emission scenarios, elevating already-high baseline temperatures and compounding UHI effects.

The country's climatic diversity creates varied UHI manifestation contexts. Six distinct climate zones span from tropical humid (Am) in the coastal Niger Delta, through tropical savannah (Aw) in the central regions, to hot semi-arid (BSh) in the northern Sahel (Mohammed et al., 2019). Each zone exhibits different temperature regimes, rainfall patterns, vegetation characteristics, and humidity levels, necessitating climate-specific understanding of UHI formation and appropriate mitigation approaches. The Sudan savannah zone (Aw climate), extending across northern central Nigeria and encompassing major cities including Kano, Kaduna, Yola, and Maiduguri, represents particularly vulnerable conditions such as high temperatures year-round, pronounced dry seasons, limited natural water availability for vegetation, and large diurnal temperature ranges amplifying UHI thermal stress (Agabi, 2023).

Existing Nigerian UHI research provides valuable foundation but critical gaps remain. Studies in Lagos, Abuja, Kano, and Port Harcourt have documented UHI existence through satellite thermal imagery and limited ground monitoring, identifying intensity ranges of 2–6°C (Bassett et al., 2020; Isioye et al., 2020; Mohammed et al., 2019). However, these studies typically employ remote sensing surface temperature analysis rather than atmospheric UHI measurement directly relevant to human thermal comfort. Few studies have quantitatively analysed morphological drivers at scales relevant for planning intervention. Temporal analysis focuses primarily on long-term trends rather than diurnal and seasonal patterns critical for understanding peak thermal stress periods and mitigation timing (Adinna et al., 2009; Popoola et al., 2022). Future projections under combined climate change and urbanization scenarios remain largely unexplored.

This study addressed these gaps through systematic empirical investigation in Yola metropolis, Adamawa State, a rapidly growing secondary city with representative Sudan savannah climate, diverse morphological conditions, and strategic importance as a typology experiencing accelerated growth across the Sahel region. The specific objectives are to: (1) quantify statistical correlations between urban morphology parameters and atmospheric UHI intensity; (2) identify critical morphological thresholds where UHI intensification accelerates nonlinearly; (3) characterize diurnal and seasonal UHI patterns specific to the hot-dry tropical

climate; (4) project future UHI evolution under combined climate change and urbanization scenarios; and (5) derive evidence-based planning and regulatory recommendations applicable to hot-dry cities globally.

2. METHODOLOGY

Study Area

Yola metropolis (9.2°N, 12.5°E, 186m a.s.l.) is the capital of Adamawa State in northeastern Nigeria, covering approximately 120 km². Population grew from ~150,000 (2006) to over 400,000 (2023) at 5.8% annually, well above the national urban average of 3.8% (Salihu, 2024). The climate classifies as tropical savannah (Köppen Aw), with a 6-month dry season (November–April, <50 mm precipitation, RH 15–35%, solar radiation 20–25 MJ/m²·day) and wet season (May–October, 700–900 mm, RH 60–80%). Monthly mean temperatures range from 26.2°C to 31.8°C, with dry season diurnal ranges of 16–18°C and extremes exceeding 42°C in March–April. The urban core (Jimeta) features building density 65–78%, minimal vegetation (10–20%), and extensive paved surfaces; established residential neighbourhoods show moderate density (45–60%) with compound layouts and moderate vegetation (30–45%); and peripheral informal settlements exhibit variable density (30–70%) with limited vegetation (15–30%) (Ezra et al., 2021; Salihu, 2024; Zemba et al., 2025). Dominant construction materials includes uninsulated sandcrete hollow block walls ($R \sim 0.3 \text{ m}^2 \cdot \text{K/W}$) and unceilinged corrugated iron sheet roofing (albedo 0.15–0.30, $R \sim 0.08 \text{ m}^2 \cdot \text{K/W}$), created poor baseline thermal performance on which UHI effects superimpose.

Site Selection and Morphology Quantification

Twelve monitoring sites were selected by stratified sampling across 8 GIS-identified urban form typologies to span the full urban–rural gradient (Table 1). Urban morphology parameters were quantified for 500m-radius circular zones centered on each site using WorldView-3 multispectral imagery (0.3 m resolution). Building footprints were extracted by supervised maximum likelihood classification (89% accuracy); vegetation cover by NDVI thresholding (NDVI > 0.35, 92% accuracy); and impervious surfaces by combined spectral classification and manual digitization. Building heights were obtained by laser rangefinder field survey (30–50 buildings per typology), and street canyon aspect ratios calculated as mean building height divided by street width. The 500m radius was validated by sensitivity analysis confirming correlation stability at 400–600m.

Table 1. Monitoring Site Characteristics and Urban Morphology Parameters

Site Type	Building Density (%)	Vegetation (%)	Impervious (%)	Mean UHI (°C)	Max UHI (°C)	Night UHI (°C)
Rural Reference	5	85	10	0.0	0.0	0.0
Peri-Urban Transition	18	68	28	1.4	1.9	1.6
Low-Density (High Veg.)	32	55	45	2.4	3.0	2.8
Low-Density (Mod. Veg.)	38	44	53	2.8	3.4	3.2
Low-Density (Low Veg.)	42	35	59	3.0	3.7	3.5
Medium-Density (A)	51	42	57	3.2	3.8	3.9
Medium-Density (B)	58	33	66	3.5	4.1	4.3
High-Density (Compound)	63	28	71	3.7	4.3	5.0
High-Density (Linear)	71	21	78	3.9	4.7	5.4
Mixed Commercial-Residential	69	18	81	4.0	4.8	5.6
Commercial Core	78	15	85	4.2	5.1	5.8
Commercial Periphery	74	17	82	4.1	4.9	5.7

Microclimate Monitoring and Data Quality

Standardized instrument arrays were deployed at all 12 sites for 18 months, capturing over 1.5 full annual cycles. Air temperature and relative humidity were measured by HOBO MX2301A sensors ($\pm 0.2^{\circ}\text{C}$, $\pm 2.5\%$ RH) in Stevenson screen radiation shields (total temperature uncertainty $\pm 0.4^{\circ}\text{C}$, well below the $2.8\text{--}4.2^{\circ}\text{C}$ UHI range). Wind speed and direction were recorded by Davis Instruments anemometers at 3 m height; solar radiation by Apogee SP-110 pyranometers ($\pm 5\%$). All sensors logged at 15-minute intervals with cellular transmission (HOBOLink). Battery backup maintained continuous operation through frequent grid outages (8–12 hours daily). UHI intensity was calculated as urban site temperature minus simultaneous rural reference temperature. Supplementary mobile traverse campaigns sampled 43 locations per season to provide spatial mapping. Quality control combined automated range and spike checks with monthly calibration verification (NIST-traceable reference thermometers); sensors drifting beyond 0.5°C were replaced. Short gaps (< 3 h) were linearly interpolated; longer gaps (3–24 h) estimated by regression from neighbouring sites. Overall data availability averaged 94.2%.

Statistical Analysis and Future Projections

UHI–morphology relationships were quantified using Pearson correlation (bivariate) and multiple linear regression (multivariate), with variance inflation factors assessing multicollinearity and leave-one-out cross-validation confirming generalizability. Morphological thresholds were identified by piecewise regression (Muggeo 2003 method) with 10,000-resample bootstrap confidence intervals. Diurnal and seasonal patterns were characterized through composite hourly profiles by season, with paired t-tests testing seasonal differences (significance threshold $p < 0.05$). All analyses were stratified by synoptic condition, wind regime, and season to isolate morphological effects from meteorological variability. Future UHI projections combined CMIP6/CORDEX-Africa climate model outputs (5-model ensemble) under RCP 2.6, 4.5, and 8.5 with three urbanization trajectories (business-as-usual, compact growth, and green growth), inserting projected morphological conditions into the calibrated regression model. Results are reported as ensemble means with interquartile uncertainty ranges.

3. RESULTS

UHI Intensity across Urban Morphological Gradients

Measured UHI intensities exhibited clear spatial gradients corresponding to urban morphological characteristics, confirming hypothesized relationships between built environment characteristics and local thermal conditions. Mean annual UHI intensity ranged from 0.0°C at the rural reference site to 4.2°C at the commercial center, representing a 4.2°C increase across the full urban–rural gradient. Evening peak UHI intensity (18:00–21:00) showed higher magnitudes, ranging from 0.0°C to 5.1°C , while nocturnal UHI intensity (22:00–06:00) exhibited the greatest differentiation (0.0°C to 5.8°C), indicating pronounced nighttime thermal retention in dense urban areas.

Spatial UHI mapping from intensive field campaigns confirmed patterns from fixed-site monitoring and revealed fine-scale spatial heterogeneity not fully captured by the 12-site network. The commercial core exhibited the most intense UHI conditions, with temperatures $4.8\text{--}5.1^{\circ}\text{C}$ above rural reference during evening campaigns. Temperature gradients at urban–rural boundaries were relatively steep (approximately 1°C per 500m in transitional zones), while within-urban spatial variation reflected local morphological heterogeneity, with vegetated compounds and parks creating localized cool islands $1.5\text{--}2.0^{\circ}\text{C}$ cooler than surrounding dense built fabric.

Seasonal comparison revealed significantly higher UHI intensities during the dry season compared to wet season. Dry season mean UHI across all urban sites averaged 3.8°C compared to 2.6°C during wet season,

representing 46% seasonal difference. This contrast reflects multiple seasonal factors: dry season's lower cloud cover and higher solar radiation driving greater surface heating; reduced vegetation transpiration under water stress conditions; dry Harmattan winds with lower turbulent mixing; and soil desiccation reducing evaporative cooling. The larger dry season UHI coincides with the already higher baseline temperatures (35–42°C daytime maximums), creating the most severe thermal stress conditions during March–April.

Statistical Correlations between Morphology and UHI

Bivariate correlation analysis confirmed strong statistically significant relationships between all major morphological parameters and UHI intensity (Table 2). Building density exhibited the strongest positive correlation with mean annual UHI ($r = 0.847$, $p < 0.001$), followed by impervious surface ratio ($r = 0.812$, $p < 0.001$). Vegetation cover showed strong negative correlation ($r = -0.776$, $p < 0.001$). Mean building height showed moderate positive correlation ($r = 0.634$, $p < 0.05$), while street canyon aspect ratio exhibited a positive correlation of moderate strength ($r = 0.591$, $p < 0.05$).

Table 2. Correlation Coefficients between Urban Morphology Parameters and UHI Intensity

Morphological Parameter	Mean UHI (r)	Peak UHI (r)	Night UHI (r)	p-value
Building Density (%)	0.847	0.863	0.891	< 0.001
Impervious Surface Ratio (%)	0.812	0.828	0.856	< 0.001
Vegetation Cover (%)	-0.776	-0.798	-0.832	< 0.001
Mean Building Height (m)	0.634	0.648	0.671	< 0.05
Street Canyon Aspect Ratio	0.591	0.607	0.623	< 0.05
Sky View Factor	-0.558	-0.572	-0.589	< 0.05

From the table 2, Multiple regression produced a predictive model for mean annual UHI ($R^2 = 0.924$, adjusted $R^2 = 0.887$, RMSE = 0.18°C; cross-validated RMSE 0.24°C):

$$UHI = 0.041 \times \text{Building_Density} - 0.028 \times \text{Vegetation_Cover} + 0.017 \times \text{Impervious_Ratio} + 0.023 \times \text{Height} + 0.312$$

VIF values for included predictors ranged from 1.8 to 3.2, indicating acceptable multicollinearity. Cross-validation using leave-one-out approach yielded RMSE of 0.24°C, demonstrating good predictive performance relative to the 4.2°C UHI range across monitoring sites. Building density and impervious surface ratio contributed most substantially to model fit, together accounting for 74% of total variance explained.

Morphological Threshold Analysis

Piecewise regression analysis identified critical threshold values in UHI–morphology relationships where intensification rates changed substantially. For building density, a threshold at $62 \pm 3\%$ (bootstrap 95% CI) was identified, above which the UHI increase per percent density unit increased by 68% compared to the below-threshold rate. Specifically, each 10% increase in building density was associated with 0.31°C UHI increase below the threshold and 0.52°C increase above it, demonstrating accelerating intensification at high densities. This threshold aligns with observations from temperate climate studies reporting thresholds at 60–75% density, suggesting a generalizable physical mechanism rather than climate-specific behaviour.

Vegetation cover exhibited a threshold at $38 \pm 4\%$ (bootstrap 95% CI), below which cooling benefit per percent vegetation decreased substantially. Each 10% increase in vegetation cover provided 0.42°C cooling above the 38% threshold but only 0.21°C cooling below it, indicating diminishing marginal returns at low vegetation coverage. This threshold may reflect vegetation patch fragmentation effects: isolated small trees

or shrubs in predominantly built environments provide less effective cooling than connected vegetation providing canopy continuity and facilitating evapotranspiration from larger leaf area.

Impervious surface ratio showed less distinct threshold behaviour compared to building density and vegetation cover, with relatively consistent UHI sensitivity across the observed range. This finding suggests that impervious surface effects operate more linearly than vegetation and building density effects, possibly because the primary impervious surface mechanism (reduced evapotranspiration through elimination of vegetated soil) operates proportionally rather than threshold-dependent.

Diurnal and Seasonal UHI Patterns

Diurnal UHI patterns showed characteristic hot-dry climate signatures (Table 3). Daytime UHI (10:00–16:00) was modest at 2.9°C as intense insolation heated both urban and rural surfaces substantially. UHI amplified sharply during late afternoon as high-thermal-mass urban surfaces released stored heat while rural surfaces cooled through evapotranspiration, reaching a peak of 6.2°C at 18:00–21:00, a 114% increase over daytime values. Nocturnal UHI persistence (4.8°C at pre-dawn hours) was particularly pronounced compared to temperate city patterns, reflecting the high thermal mass of concrete and masonry construction materials absorbing large amounts of solar energy during the intense daytime insolation. The relatively low nighttime cloud cover during dry season minimized longwave radiation trapping over rural areas, while urban geometry limited longwave emission from street canyon surfaces, maintaining the urban–rural temperature differential throughout the night. This nocturnal pattern has important implications for nighttime thermal comfort and cooling energy demand.

Table 3. Diurnal UHI Pattern at Commercial Centre Site (Dry Season Mean)

Time Period	UHI Intensity (°C)	Urban Temp (°C)	Rural Temp (°C)	UHI Phase
02:00–06:00 (Pre-dawn)	4.8	26.4	21.6	Nocturnal persistence
06:00–10:00 (Morning)	3.1	31.2	28.1	Rapid decrease
10:00–14:00 (Midday)	2.5	39.8	37.3	Daytime minimum
14:00–18:00 (Afternoon)	3.4	41.2	37.8	Building phase
18:00–21:00 (Evening peak)	6.2	36.1	29.9	Peak UHI
21:00–02:00 (Night)	5.4	31.3	25.9	High nocturnal UHI

Seasonal comparison confirmed the dry season amplification hypothesis. Dry season (November–April) mean UHI across all monitoring hours at the commercial site averaged 3.8°C compared to 2.6°C during wet season, a 46% seasonal difference. Wet season diurnal patterns showed lower peak UHI (4.1°C maximum vs. 6.2°C dry season) and reduced nocturnal persistence (3.2°C pre-dawn vs. 4.8°C dry season), reflecting wet season’s higher humidity, increased cloud cover reducing solar radiation loading, vegetation transpiration from adequately watered plants, and higher wind speeds enhancing convective mixing.

Future UHI Projections

Under business-as-usual conditions (RCP 8.5 + current urbanization), mean UHI in Yola’s commercial core is projected to reach 8.5°C by 2050 approximately 100% above current 4.2°C with climate warming contributing ~2.1°C and uncontrolled urbanization ~2.2°C (Table 4). The aggressive mitigation scenario (RCP 2.6 + green growth) is the only pathway stabilizing UHI at current levels by 2050 (4.1°C), demonstrating that proactive planning intervention can fully offset climate-driven intensification. Scenario uncertainty ranges ($\pm 1.4^\circ\text{C}$ and $\pm 0.9^\circ\text{C}$ respectively) do not overlap scenario means, confirming robust differentiation for policy planning.

Table 4. Future UHI Intensity Projections under Combined Climate–Urbanization Scenarios

Scenario	2030 (°C)	2040 (°C)	2050 (°C)	Climate Contribution (°C)	Urban Contribution (°C)
Business-as-usual (RCP 8.5 + Current Growth)	5.6	7.1	8.5	2.1	2.2
Moderate mitigation (RCP 4.5 + Compact Growth)	5.0	6.0	6.8	1.4	1.2
Aggressive mitigation (RCP 2.6 + Green Growth)	4.6	4.4	4.1	0.7	−0.8
Climate change only (No urban change)	4.9	5.8	6.3	2.1	0.0
Urban change only (No climate change)	5.0	5.8	6.4	0.0	2.2

The aggressive mitigation scenario (RCP 2.6 combined with green growth policies) is the only pathway achieving stable or declining UHI intensity through 2050, with projected UHI of 4.1°C (essentially no change from current conditions despite climate warming) due to compensating UHI reductions from improved urban morphology (vegetation requirements, density controls, cool surface materials). This scenario demonstrates that proactive urban planning intervention can offset climate change contributions to UHI intensification, though implementation requires sustained policy commitment and investment in green infrastructure.

Uncertainty ranges in 2050 projections span approximately $\pm 1.4^{\circ}\text{C}$ (one standard deviation) for business-as-usual and $\pm 0.9^{\circ}\text{C}$ for aggressive mitigation scenarios, reflecting combined uncertainty from climate model variability, empirical morphology–UHI relationship uncertainty, and urbanization trajectory uncertainty. Despite these uncertainties, the scenarios are well-separated (minimum inter-scenario difference of 1.8°C at 2050), providing robust differentiation for policy planning purposes.

4. DISCUSSION

UHI–Morphology Relationships in Hot-Dry Climate Context

The strong correlations between building density, vegetation cover, impervious surface ratio, and UHI intensity ($r = 0.847, -0.776, 0.812$, respectively) confirm that fundamental UHI–morphology relationships established in temperate city research extend to tropical hot-dry climate contexts. However, the magnitude and character of these relationships exhibits important climate-specific features. The pronounced evening peak UHI (6.2°C) substantially exceeding daytime UHI (2.9°C) distinguishes Yola’s pattern from temperate cities where daytime and nocturnal UHI are more comparable. This hot-dry climate signature reflects the intense daytime solar loading on high-thermal-mass urban surfaces, which store energy for delayed evening release, amplified by the dry conditions limiting both urban and rural evapotranspiration but with greater proportional reduction in rural areas.

The identified building density threshold at 62% aligns with temperate climate thresholds (typically 60–75%), suggesting that physical mechanisms governing density–UHI relationships (primarily sky view factor reduction and thermal mass accumulation) operate consistently across climate zones despite different absolute UHI magnitudes. This finding has important practical implication such as density control regulations developed in temperate city contexts may be applicable in tropical settings, though calibration to local climate conditions is warranted. The vegetation threshold at 38% shows some deviation from temperate observations (typically 30–40%), potentially reflecting greater vegetation water stress in the hot-dry climate reducing cooling efficiency at lower coverage levels.

The strong nocturnal UHI persistence (4.8°C at pre-dawn) exceeds typical temperate city patterns and has important implications underappreciated in current literature. While research in tropical cities frequently emphasizes daytime thermal stress, nocturnal UHI critically affects sleep quality, nighttime physiological recovery from daytime heat exposure, and next-day thermal resilience. In Yola, where indoor nighttime temperatures frequently exceed 28–32°C even without UHI effects, the additional 4–6°C of nocturnal UHI creates conditions substantially compromising sleep quality and health for residents unable to afford mechanical cooling.

Implications for Urban Planning Policy

Empirically derived morphological thresholds provide direct evidence base for planning regulatory controls, addressing a critical need for scientifically defensible density and vegetation standards in rapidly urbanizing Nigerian cities. The 62% building density threshold translates directly to maximum plot coverage ratio of 0.62, a standard planning regulatory instrument. Applying this standard to new development approvals would prevent threshold exceedance while allowing development densities substantially higher than current suburban standards typically applied. Retrofitting existing high-density neighbourhoods exceeding the threshold presents greater challenge but could be addressed through incentive programs promoting roof greening, courtyard vegetation enhancement, and façade material improvement.

The 38% vegetation coverage requirement translates to specific urban green space standards applicable at neighbourhood scale. Implementation pathways include: minimum plot landscaping requirements (typically 20–30% of private plot area for residential development); mandated street tree planting at defined spacing along all new roads; development density bonuses for green roof installation; and preservation requirements protecting existing mature trees during redevelopment. The disproportionate UHI cooling effectiveness of connected vegetation above the 38% threshold suggests clustering vegetation requirements rather than distributing uniformly, favouring approaches creating contiguous green corridors over isolated landscaping patches.

Surface material regulations targeting pavements and roofing would directly address impervious surface ratio and albedo concerns. Specifying minimum reflectance values for roof materials (albedo ≥ 0.50 compared to current dark roofing albedo of 0.15–0.30) could reduce UHI intensity by 0.5–1.0°C based on sensitivity analysis of the regression model. Implementation is feasible through building code amendments, with limited cost premium for white or light-coloured roofing alternatives. Cool pavement specifications for major roads and public spaces would provide additional cooling benefits, though higher upfront cost and maintenance requirements necessitate prioritization on high-traffic urban areas with greatest heat generation.

Comparison with Existing Literature

This study's findings both corroborate and extend existing knowledge on UHI–morphology relationships. Correlation coefficients for building density ($r = 0.847$) and vegetation cover ($r = -0.776$) are consistent with values reported in temperate city studies (typically $r = 0.6$ – 0.9 for density and $r = -0.5$ to -0.8 for vegetation), confirming applicability of these relationships across climate contexts and supporting the broader generalizability of morphological drivers (Banerjee et al., 2022; Bost, 2022). The UHI intensity range of 2.8–4.2°C across monitoring sites falls within the 2–6°C range reported for comparable Nigerian cities (Lagos, Abuja, Kano) in previous studies employing satellite surface temperature analysis, though methodological differences (atmospheric vs. surface UHI measurement) preclude direct comparison (Isioye et al., 2020; Mohammed et al., 2019; Popoola, et al., 2022).

The pronounced evening peak UHI pattern identified in this study contrasts with temperate city observations where nocturnal UHI typically builds gradually through the evening and night. Comparison with limited tropical city studies from Ouagadougou, Burkina Faso and Niamey, Niger suggests this pronounced evening peak may be characteristic of Sub-Saharan African hot-dry cities, potentially driven by

the combination of intense solar loading, limited vegetation, and dry surface conditions unique to this climate context (Wonorahardjo et al., 2020, 2022). This pattern warrants dedicated research attention as it implies different temporal distribution of extreme thermal stress compared to temperate city models currently dominating urban heat health research.

Future projection results (business-as-usual 8.5°C by 2050) exceed projections from comparable tropical city studies, which typically project 4–6°C UHI under business-as-usual scenarios. This higher projection reflects Yola's combination of strong climate warming signal (RCP 8.5 projects 2.1°C warming for northeastern Nigeria by 2050, higher than tropical average), rapid urbanization rate (5.8% annually, among the world's fastest), and starting morphological conditions already approaching thermal thresholds. The finding that aggressive mitigation can stabilize UHI at current levels (4.1°C by 2050) despite climate warming provides essential evidence that planning intervention is both necessary and potentially effective.

Limitations and Future Research

Key limitations include the 12-site network's incomplete capture of within-typology heterogeneity across 120 km²; building height uncertainty from field survey versus LiDAR; an 18-month period that cannot fully characterize interannual ENSO-related variability; and urbanization projections that represent plausible scenarios rather than precise forecasts. Priority future research directions include: replication across other Nigerian hot-dry cities (Kano, Kaduna, Maiduguri) to assess geographic generalizability; coupling atmospheric UHI monitoring with building energy performance data; and epidemiological studies linking UHI exposure to health outcomes to strengthen the policy case for intervention.

Recommendations for Practice

Three priority regulatory measures are empirically supported: (1) maximum building coverage ratio of 0.62 in all new development; (2) minimum neighbourhood-scale vegetation cover of 40%, enforced through private landscaping requirements, public green space standards, and tree preservation; and (3) minimum roof reflectance of 0.50 in building codes for all new construction and major roof replacements. Together, these measures are projected to limit future UHI intensification to the moderate mitigation trajectory. Integration into currently developing regulatory frameworks is most cost-effective during initial development, when compliant design carries minimal premium over conventional construction.

5. CONCLUSIONS

This study provided the first comprehensive empirical quantification of urban morphology–UHI relationships in Sub-Saharan Africa's hot-dry climate zone. Eighteen months of microclimate monitoring across 12 sites in Yola metropolis yielded four principal findings:

Strong, statistically significant correlations confirm building density ($r = 0.847$), impervious surface ratio ($r = 0.812$), and vegetation cover ($r = -0.776$) as the primary morphological UHI drivers, with effect magnitudes comparable to temperate city research. A multiple regression model achieved $R^2 = 0.924$, enabling evidence-based calibration of planning standards.

Critical morphological thresholds were empirically identified: building density exceeding 62% is associated with 68% higher UHI sensitivity, while vegetation below 38% exhibits diminishing marginal cooling returns. These thresholds translate directly to actionable regulatory controls, maximum plot coverage of 0.62 and minimum vegetation cover of 40%.

Diurnal analysis revealed a distinctive hot-dry climate UHI signature: a pronounced evening peak of 6.2°C substantially exceeding daytime values (2.9°C), with nocturnal persistence of 4.8°C imposing severe overnight thermal stress exceeding temperate city patterns in both magnitude and duration.

Future projections indicate potential UHI doubling to 8.5°C by 2050 under business-as-usual development. Aggressive mitigation combining RCP 2.6 emissions reductions with green urban growth policies can stabilize UHI at 4.1°C, demonstrating that planning intervention can fully offset climate-driven intensification. The current regulatory development window in Nigerian cities represents the most cost-effective opportunity to implement these standards.

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