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Urban fabric analysis of Benin City and its implications for the urban canopy heat island in the dry season

Emmanuel Iruobe Aruya[1]*, Blessing Ozien Aruya[2] and Yahaya Zayyana Ibrahim[1]

[1]Department of Meteorology and Climate Change Science, African Aviation and Aerospace University, Abuja.
[2]Department of Geography and Environmental Management, Ahmadu Bello University, Zaria.

*Corresponding author. Email: aruya.emmanuel@aaau.edu.ng

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ABSTRACT: The rapid growth in population and urbanisation in Benin City has altered the urban morphology, resulting in a consistent rise in temperature known as the urban heat island phenomenon. This study was designed to examine the relationship between the urban fabric and Urban Canopy Heat Island (UCHI) in Benin City in the dry season. The study classified Benin City into Local Climate Zones (LCZs). Ten LCZs were used, and the urban fabric analysis was done using Google Earth imagery. The urban fabric analysis was used to classify the selected stations into surface fractions (built-up, paved, bare land and vegetation). A thermochrone iButton data logger was placed in each of the LCZs, which recorded temperature at 30-minute intervals. Linear regression analysis was employed to evaluate the impact of surface cover composition on mean UCHI intensities within the study area. The results of the analysis showed that temperature varied across the LCZ, with the highest temperature being 29.70°C and the lowest, 27.72°C. UCHI intensity showed that FS has the highest UCHI with 3.03°C, followed by TM with 3.01°C and PS and BR with 2.98°C each. The lowest value of UCHI was recorded in WI with 1.70°C. The coefficient of determination (R^2) revealed that the percentage of paved surfaces had the highest influence in the dry season, with an R^2 value of 0.6917 (69%), while the percentage of vegetation had the least influence, with an R^2 value of 0.0064 (1%). The study confirms an urban bias in temperature in Benin City as a result of urban morphology, which has strong implications on the bio-climatological aspect of the urban environment and the physiological comfort of the urban inhabitants. Therefore, it is strongly recommended that there should be regulations on the adoption of climate-sensitive planning and building design schemes.

Keywords: Benin, surface fraction, Urban Canopy Heat Island (UCHI), urban heat island, urbanisation.

INTRODUCTION

Currently, 56% (about 4.4 billion) of the world's population resides in urban centres (Devereux, 2001). The worldwide urban population is predicted to reach approximately 6 billion people by 2045, with the majority of this expansion taking place in Asia and Africa (Chakraborty and Lee, 2019). Changes to the earth's surface during urbanisation (e.g increase in impervious cover, reduced vegetation) are major drivers of urban climate change. A significant obstacle in managing urbanisation is the Urban Heat Island (UHI) effect, a phenomenon in which urban centres are warmer than their rural counterparts (Aruya, 2022).

UHI is classified into three categories based on scale and measurement technique; first, Surface Urban Heat Island (SUHI) refers to the differences in surface temperature measured by thermal infrared remote sensing. Second, Urban Canopy Heat Islands (UCHI) refer to differences in ambient air temperature measured within the urban canopy layer. The air layer between the ground and building roofs or trees is known as the urban canopy layer. Third, high air temperatures within the urban boundary layer, which is referred to as Urban Boundary Layer Heat Islands (UBLHI). This layer is situated above the urban canopy layer (Pomerantz *et al*., 2000). This study focuses on Urban Canopy Heat Islands (UCHI). The focus on UCHI is because it directly impacts human thermal comfort levels and has implications for policymakers.

Urban impermeable surfaces have higher thermal capacity, thermal conductivity and lower albedo than their rural counterparts (Coraiola *et al*., 2012; Comrie, 2000). These predominantly impervious surfaces have higher rates of solar radiation absorption, which they use in warming the air above them through the processes of radiation and convection. Thus, the larger the proportion of paved surfaces found in a given area, the higher the heat absorbed from solar radiation and the greater the amount released to heat the overlaying air and vice versa. Also, urban structures and their layouts can also increase surface roughness (Mizuno *et al*., 2024), thereby having an impact on thermal comfort and UHI. The main ways that UHI affects the health of urban dwellers are by increasing heat-related health risks, creating additional thermal discomfort in many cities due to specific urban development patterns and geographic conditions, and exposing them to more heat stress (Ibrahim and Ash'aari, 2023).

Many cities have shown signs of warming aggravated by urban geometry, suggesting that as the trend toward urbanisation continues, heat stressors will only get worse in the future (Anurogo *et al*., 2023). Zhou *et al*. (2016), for instance, examined the spatiotemporal patterns of UHI in China and found that as the intensity of urban growth intensified, both the daytime and nocturnal temperatures rose noticeably. The percentage distribution of pervious and impervious surfaces in Osaka, Japan (Takebayashi and Moriyama, 2022), Phoenix, Arizona, USA (Myint *et al*., 2010), Londrina, Brazil (Coraiola *et al*., 2012), Onitsha, Nigeria (Nduka, 2011), and Yola, Nigeria (Adebayo and Zemba, 2003) are among the other studies on the effects of pervious and impervious surface covers on UHI development.

Benin City serves as the principal administrative and socio-economic centre for both Oredo Local Government Area and Edo State in Nigeria. Benin City is a humid tropical urban settlement which comprises three Local Government Areas, namely Egor, Ikpoba Okha and Oredo. It is located within Latitudes 6°20´55"N to 6°58´39"N and Longitudes 5°35´18"E to 5°41´18"E (Okhakhu, 2010). The study area has a tropical climate characterised by two distinct seasons, the wet and dry seasons. The wet season occurs between April to November, and the dry season from December to March, with a break in August. The peak of the dry season is January. Rainfall, temperature, wind and relative humidity are the most significant climatic elements in Benin City. Generally, the temperature across the city is relatively high with a very narrow variation in seasonal and diurnal ranges. The city experiences a mean annual temperature of 27.5°C throughout the year, owing to the occurrence of torrential rains, hilly terrains, unregulated deforestation, related anthropogenic activities, and the rough characteristics of the urban physical surfaces are prone to fluctuations (Okhakhu, 2010).

Benin City and its surrounding areas have experienced changes in its morphology over the years as a result of increasing population. Building patterns have drastically changed from single-story to multi-story structures, corrugated zinc to aluminium roofing sheets, and louvres to sliding windows that capture sunlight during the day and release sensible heat at night. These have markedly altered the surface properties of the area and hence have modified the energy balance of the area and resulted in increased temperature of the urban canopy of Benin City (Efe, 2002; Omogbai, 1985). Given that the combined impacts of urbanisation and climate change have a great impact on future urban temperatures and exacerbate existing heat stress in Benin, understanding the UHI effect in the city is important if UHI is to be mitigated. The present study assesses how urban development influences UCHI in Benin City. The specific objectives are to determine the urban fabric of Benin City, determine the spatial air temperature variation in the dry season and examine the relationship between surface cover fractions and UCHI development in Benin City.

MATERIALS AND METHODS

The data used for this study include geo-coordinates, satellite imagery and eye-level photographs of sites, temperature data and surface cover data. Geo-coordinates consist of latitudes and longitudes of the sites that were selected for temperature and surface cover data collection (Figure 1). Other metadata collected that were relevant to this research include the predominant function of the area (residential, commercial, industrial, educational, etc). Traffic flow was graded as heavy, medium or light

Using Google Earth software, satellite images of data collection points were acquired. The precise location of the sites was determined using their geo-coordinates. Both LCZ categorisation and the estimation of surface cover composition percentages, as employed by Coraiola *et al*. (2012), were conducted using Google Earth imagery. The temperature data was gathered using the DS1921G-F5 thermocron iButton data recorder in accordance with Stewart and Oke (2012) Local Climate Zones (LCZ) classification scheme. These consist of temperatures in degrees Celsius for each of the selected sites within the study area (Table 1). The data loggers were programmed to record air temperature at 30 minutes intervals throughout the study period. The calibration of the iButtons makes it effective for the area under study (Balogun *et al*., 2021). This study covers only the dry season (1 January 2025 to 31 January 2025), which is the peak of the dry season in Benin City.

The surface cover data consists of percentages of pervious, impervious and vegetated surface covers at each of the selected sites. These were obtained from Google Earth satellite imagery of the selected sites. For each site, an area with a radius of 300 m with the location

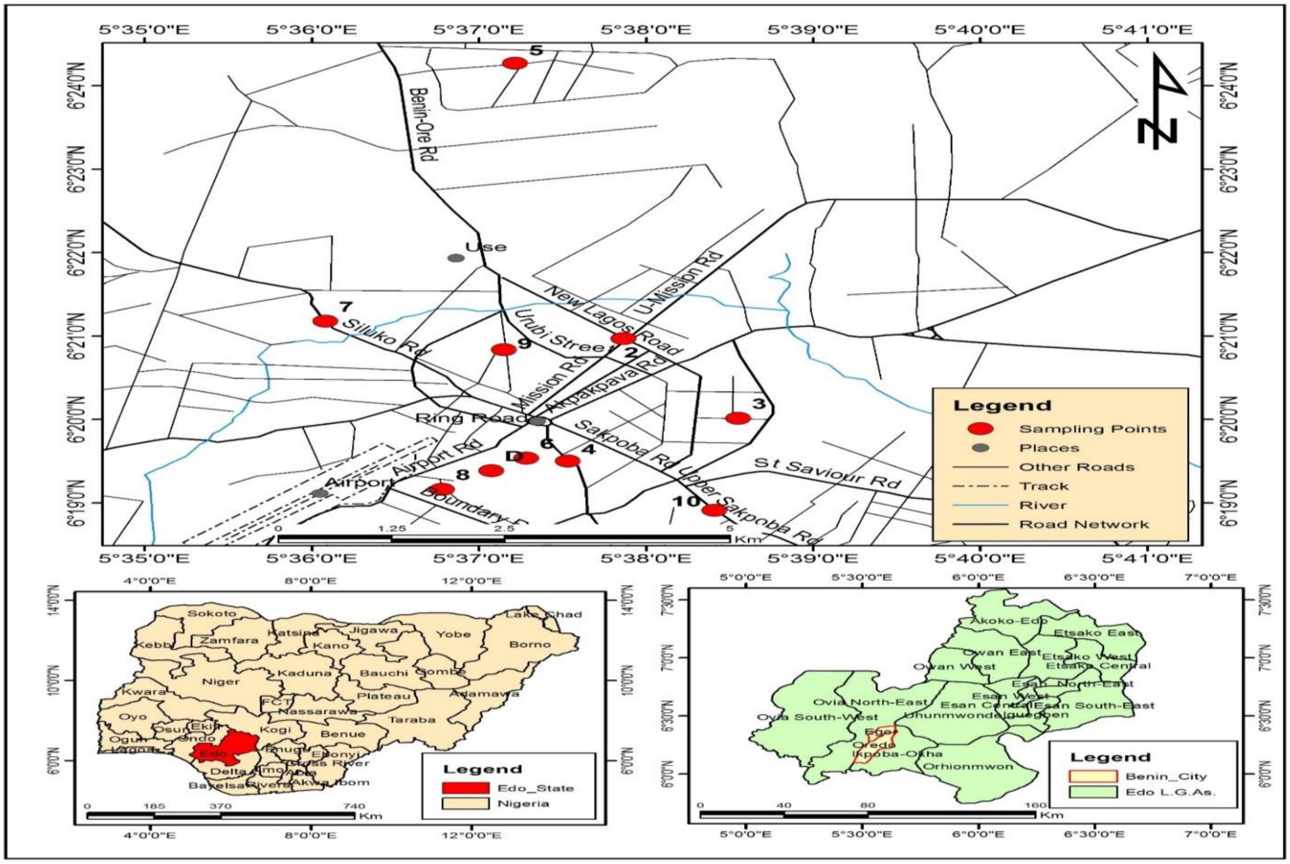


Figure 1. Map of Benin showing selected data collection site (**Source:** Adapted and modified from Benin City Map, 2024).

Table 1. Selected sites, their corresponding LCZ designations and code for temperature recording station in each LCZ.

Site	Location names	Coordinates	LCZ	Designation	Station code
1	New Benin	6°20´58"N - 5°37´52"E	LCZ 2	Compact midrise	NB
2	Textile mill road	6°21´32"N - 5°36´54"E	LCZ 3	Compact low-rise	TM
3	Permanent Secretariat	6°19´30"N - 5°37´32"E	LCZ 4	Open high-rise	PS
4	Faculty of Social Science	6°24´16"N - 5°37´13"E	LCZ 5	Open midrise	FS
5	G.R.A Benin	6°19´32"N - 5°37´17"E	LCZ 6	Open low-rise	GR
6	Nifor	6°33´27"N - 5°37´27"E	LCZ D	Low plants	NI
7	Welu, Igor Axis	6°21´32"N - 5°36´58"E	LCZ 7	Lightweight low-rise	WI
8	Kada Plaza	6°19´32"N - 5°37´31"E	LCZ 8	Large low-rise	KP
9	Wire Road	6°20´50"N - 5°37´9"E	LCZ 9	Sparsely built	WR
10	Nigerian Brewery	6°20´48"N - 5°39´54"E	LCZ 10	Heavy industry	BR

of the temperature sensor at the centre was used. This is called "footprint" or circle of influence of the sensor. For a height of 2 m, a radius of 300m is appropriate (Stewart and Oke, 2012). It is from this selected area that the percentages of surface composition were calculated.

Data analysis

Percentages of pervious and impervious surfaces in each of the selected LCZs (300m radius from the position of the temperature sensor) were calculated from the downloaded Google Earth satellite imagery of each LCZ, using Georeferenced Information Processing System (SPRING) software version 2.0, unsupervised classification. The surface composition was then categorised into impervious surfaces (buildings/roofs, paved sidewalks, roads, parking lots), pervious surfaces (bare soil) and pervious surfaces (vegetated surfaces).

To determine UCHI, first, the average temperature value

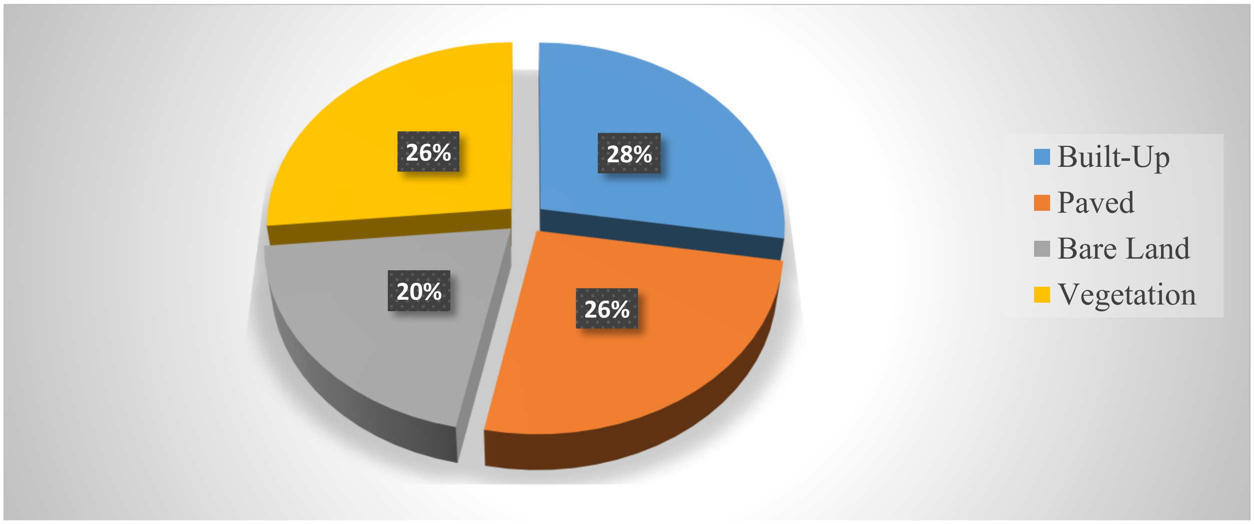


Figure 2. Percentage distribution of surface cover elements in the study area.

for every hour of the study period was calculated from the recorded temperature data of each site. It is from this hourly temperature data that UCHI was computed. UCHI was determined as follows: UCHI = T_LCZn - T_LCZ_D" Where: T = temperature of a sample station, n = built type zone from 1 to 10 and D = land cover type zone and control station (low plants). Secondly, the Mean UCHI (arithmetic mean) for each LCZ type was calculated for the dry season.

The effect of surface cover composition on variation of UCHI among the LCZs was achieved using simple linear regression analysis. Percentages of respective surface cover categories were classified as independent variables, while the mean UCHI of each zone (site) was used as the dependent variable. This yielded the relative contribution of each surface cover category (through the coefficient of determination, R^2).

RESULTS AND DISCUSSIONS

Urban fabric analysis of Benin City

The urban fabric or surface cover types (in hectares) within the footprint of Benin City reveal that 10 classes align with Stewart and Oke (2012) LCZ classification scheme. This is shown in Table 2. Furthermore, as revealed in Table 3, in terms of bare land, WR has the highest with 45.44%, followed by BR with 43.34% and NI with 27.89%. Indeed, as expected, in the vegetation surface cover fraction, NI has the highest with 71.22% while TM has the lowest with 6.79%. The high percentage of vegetation cover revealed by NI is because, as a control station, the amount of pervious surface (bare land and vegetation) must be high to reduce its influence on temperature (Stewart and Oke, 2012).

The percentage distribution of elements of surface cover in the study area is presented in Figure 2. Figure 2 indicates that built-up has the highest fraction in the study area with 28%, vegetation and paved are second with 26% each, while bare land is the least with 20%. As clearly seen, there is variation in surface cover in the study area; however, this variation is not too significant.

Spatial air temperature variation for the dry season

From Figure 3, it is evident that FS has the highest mean temperature in January with a value of 29.70°C while TM, BR, PS and WR followed with 29.69, 29.66, 29.65 and 29.61°C, respectively. The lowest value was recorded in NI with a value of 27.72°C.

The result of the mean spatial variation in the study area slightly differs from the work of Abdulhameed (2011), as the highest mean value recorded (29.70°C) in January is higher than what was obtained at Kano (26.21°C) in January. Although both studies are located within different climatic belts. The thermal characteristics of each LCZ are determined by variations in the morphology of the urban fabric, which causes variations in air temperature. Human activity also affects each zone's thermal properties. This is evident from the fact that FS has the largest proportion of paved (impervious) surface, and, human activity, being an academic institution, it absorbs more heat energy from solar radiation, which, when released, warms the air above it. The mean temperature of FS and TM does not differ significantly. Heat emissions from automobiles due to the condensed urban layout, heavy traffic, etc., could also be a contributing factor to the high temperatures in FS and TM. The highest temperature recorded at NI (27.72°C) is related to the area's preponderance of pervious and vegetated surfaces because pervious surfaces have a greater capacity to hold moisture, which causes a significant portion of sensible heat to be lost as latent heat

Table 2. Classification of selected sites into surface fractions.

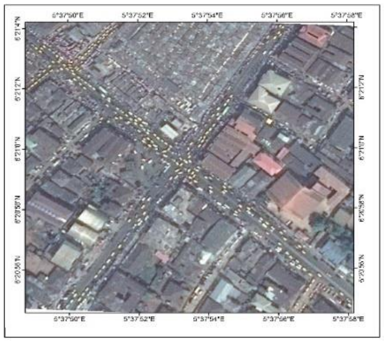
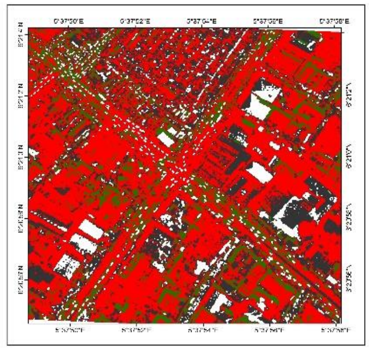
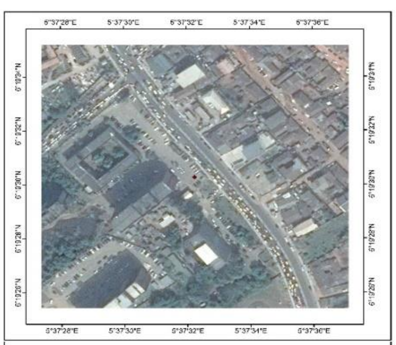
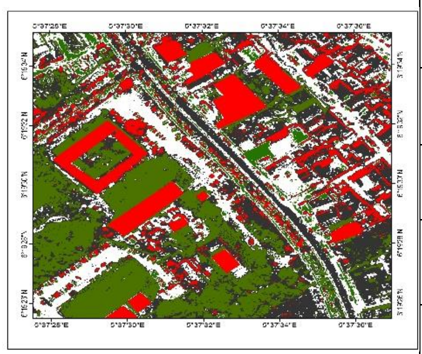
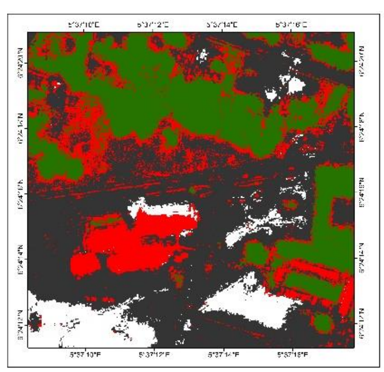
Station Code	Image Before Classification	Classified Image	Surface Composition	(ha)	(%)
NB			Built-up	5.18	57.56
			Paved Surface	2.24	24.89
			Bare Land	0.74	8.22
			Vegetation	0.84	9.33
			Total	**9.00**	**100.00**
TM			Built-up	3.82	42.44
			Paved Surface	2.55	28.33
			Bare Land	2.02	22.44
			Vegetation	0.61	6.79
			Total	**9.00**	**100.00**
PS			Built-up	1.77	19.67
			Paved Surface	2.75	30.56
			Bare Land	2.20	24.44
			Vegetation	2.48	27.56
			Total	**9.00**	**100.00**
FS			Built-up	1.87	20.78
			Paved Surface	3.81	42.33
			Bare Land	0.92	10.22
			Vegetation	2.40	26.67
			Total	**9.00**	**100.00**

Table 2. Contd.

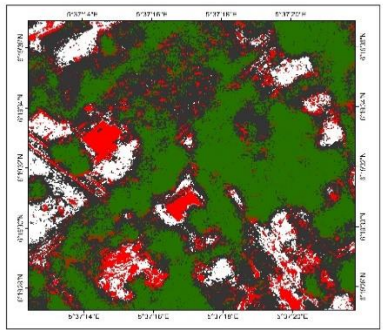
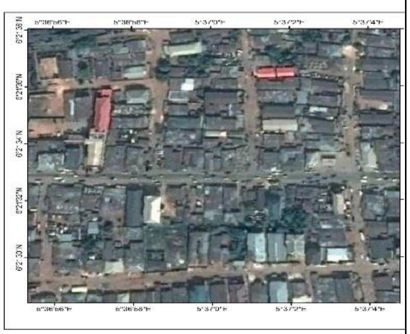
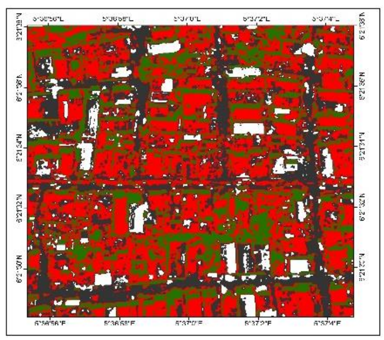
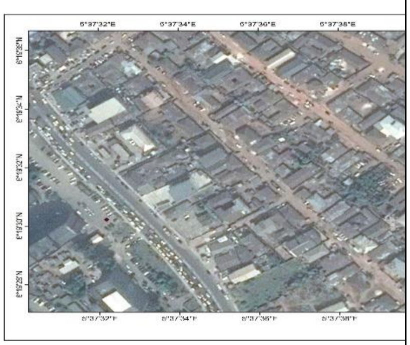
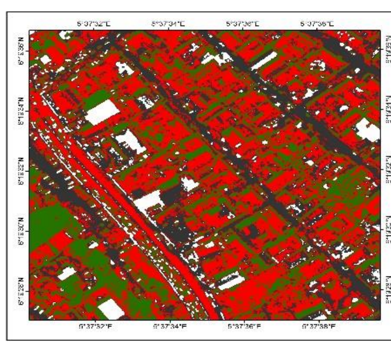
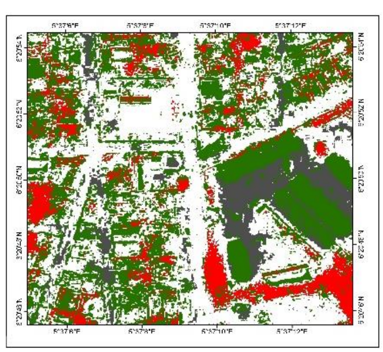
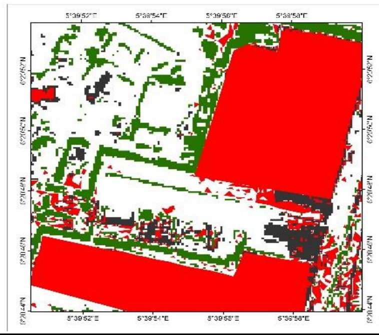
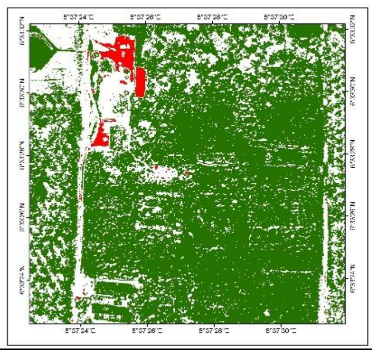
Station Code	Image Before Classification	Classified Image	Surface Composition	(ha)	(%)
GR			Built-up	0.99	11.00
			Paved Surface	3.60	40.00
			Bare Land	0.98	10.89
			Vegetation	3.43	38.11
			Tota	**9.00**	**100.00**
WI			Built-up	3.76	41.78
			Paved Surface	2.58	28.67
			Bare Land	0.70	7.78
			Vegetation	1.96	21.77
			Total	**9.00**	**100.00**
KP			Built-up	4.00	44.44
			Paved Surface	3.00	33.33
			Bare Land	0.42	4.67
			Vegetation	1.58	17.56
			Total	**9.00**	**100.00**
WR			Built-up	1.04	11.56
			Paved Surface	0.99	11.00
			Bare Land	4.09	45.44
			Vegetation	2.88	32.00
			Total	**9.00**	**100.00**

Table 2. Contd.

Station Code	Image Before Classification	Classified Image	Surface Composition	(ha)	(%)
BR			Built-up	2.29	25.44
			Paved Surface	1.56	17.33
			Bare Land	3.90	43.34
			Vegetation	1.25	13.89
			Total	**9.00**	**100.00**
NI			Built-up	0.08	0.89
			Paved Surface	0.00	0.00
			Bare Land	2.51	27.89
			Vegetation	6.41	71.22
			Total	**9.00**	**100.00**

Source: Author's analysis (2025) and Google Earth imagery classification.

Table 3. Percentage surface cover fractions.

Surface cover fractions (%)	NB (%)	TM (%)	PS (%)	FS (%)	GR (%)	WI (%)	KP (%)	WR (%)	BR (%)	NI (%)
Built-up	57.56	42.44	19.67	20.78	11.00	41.78	44.44	11.56	25.44	0.89
Paved Surface	24.89	28.33	30.56	42.33	40.00	28.67	33.33	11.00	17.33	0.00
Bare Land	8.22	22.44	22.21	10.22	10.89	7.78	4.67	45.44	43.34	27.89
Vegetation	9.33	6.79	27.56	26.67	38.11	21.77	17.56	32.00	13.89	71.22
Total	100	100	100	100	100	100	100	100	100	100

Source: Author's analysis (2025) and Google Earth imagery classification.

of vaporisation through the process of evaporation. Also, significant reductions as a result of vegetation cover were recorded at Uxbridge, UK, Cuiaba and Hong Kong (Tan and Ng, 2014).

Spatial variation of UCHI in the dry season

It can be clearly seen from Figure 4 that FS has the highest UCHI with 3.03°C, followed by TM with 3.01°C and PS and BR with 2.98°C each. The lowest value of UCHI in the dry season was recorded in WI with 1.70°C. The high development of UCHI in FS and TM is closely attributed to extensive impervious surface and anthropogenic heat emissions, which reduce evaporative cooling and increase nighttime heat retention.

However, it can also be seen that WI has the lowest UCHI in the dry season despite having over 70% of impervious surfaces. Possible explanation for this is thermal storage resulting from the lack of tall skyscrapers that would have restricted thermal radiation, reduced turbulent exchanges that allow thermal radiation to be emitted from the vertical building surfaces and prevailing wind direction at this time of the year, which allows the site to constantly receive fresh and cooler wind supply from the countryside. This result agrees with the findings of Usman (2016) in Kaduna Metropolis that upwind edges of cities tend to be cooler than city centres due to the supply of

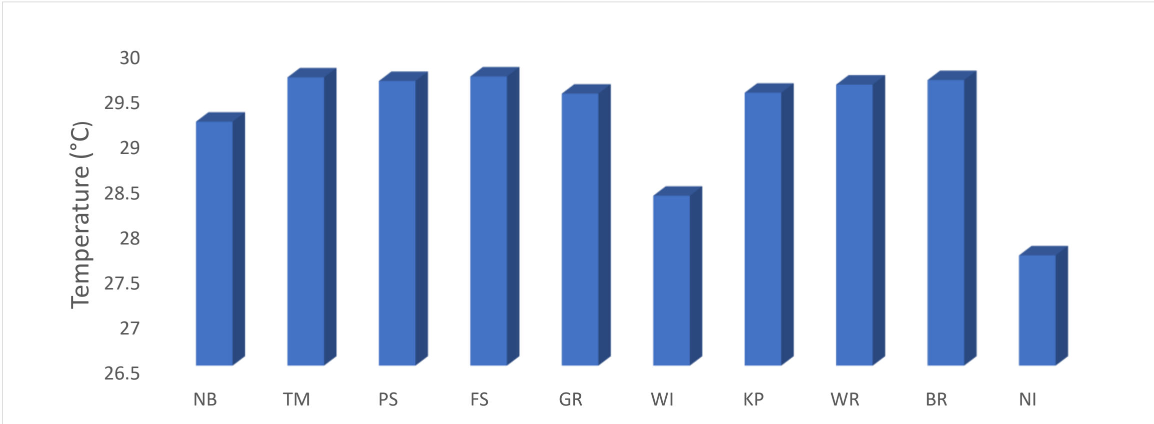


Figure 3. Mean spatial air temperature variation for January (dry season).

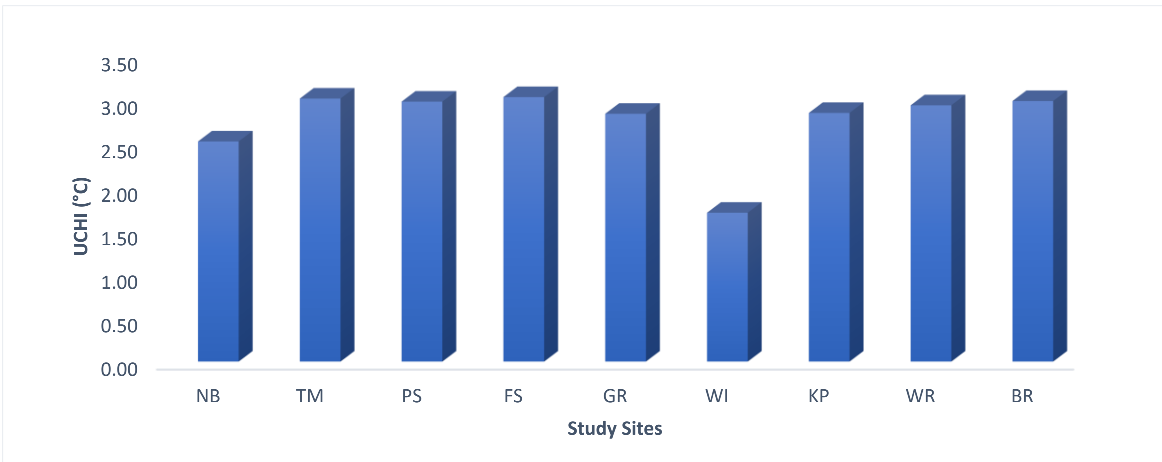


Figure 4. UCHI variation in the dry season.

fresh air from the countryside.

However, it can also be seen that WI has the lowest UCHI in the dry season despite having over 70% of impervious surfaces. Possible explanation for this is thermal storage resulting from the lack of tall skyscrapers that would have restricted thermal radiation, reduced turbulent exchanges that allow thermal radiation to be emitted from the vertical building surfaces and prevailing wind direction at this time of the year, which allows the site to constantly receive fresh and cooler wind supply from the countryside. This result agrees with the findings of Usman (2016) in Kaduna Metropolis that upwind edges of cities tend to be cooler than city centres due to the supply of fresh air from the countryside

Relationship between surface cover fractions and UCHI variation in Benin City

This section assesses whether there is a significant relationship between surface cover fractions and UCHI variations in the dry season. From Figure 5, the coefficient of determination (R^2) was 0.5707, which indicates that the percentage of building area accounts for 57% of the variation of UCHI. It is evident that the percentage of built-up fractions has a great influence on the variation of spatial mean UCHI in the study area. Also, there exists a positive linear relationship between the parameters. The high value of R^2 in the study area is a result of the thermal properties of building materials, which increase solar absorption and emissivity.

Most buildings in Benin City that usually had zinc and asbestos roofing sheets, which lead to net radiation traverse across major land uses, are giving way to aluminium roofing sheets, with resulting changes in radiation characteristics of the surfaces. Similarly, the height of these buildings and the way in which they are arranged affect the rate of escape at night of the sun's energy absorbed during the day by building materials. Also, in comparison with other UHI research in the world,

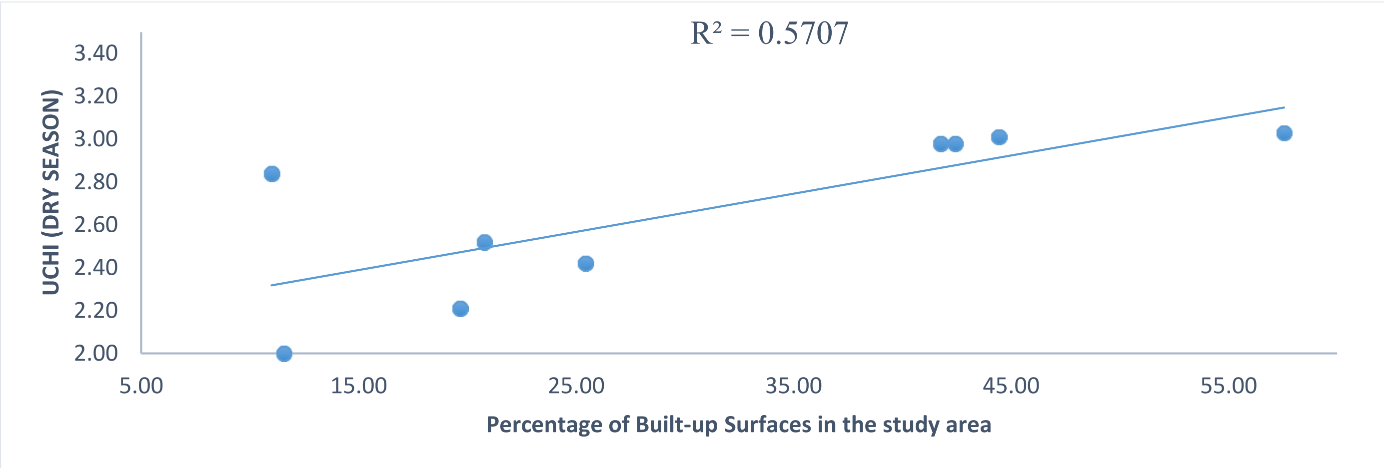


Figure 5. Relationship between percentage of built-up and mean UCHI in the dry season.

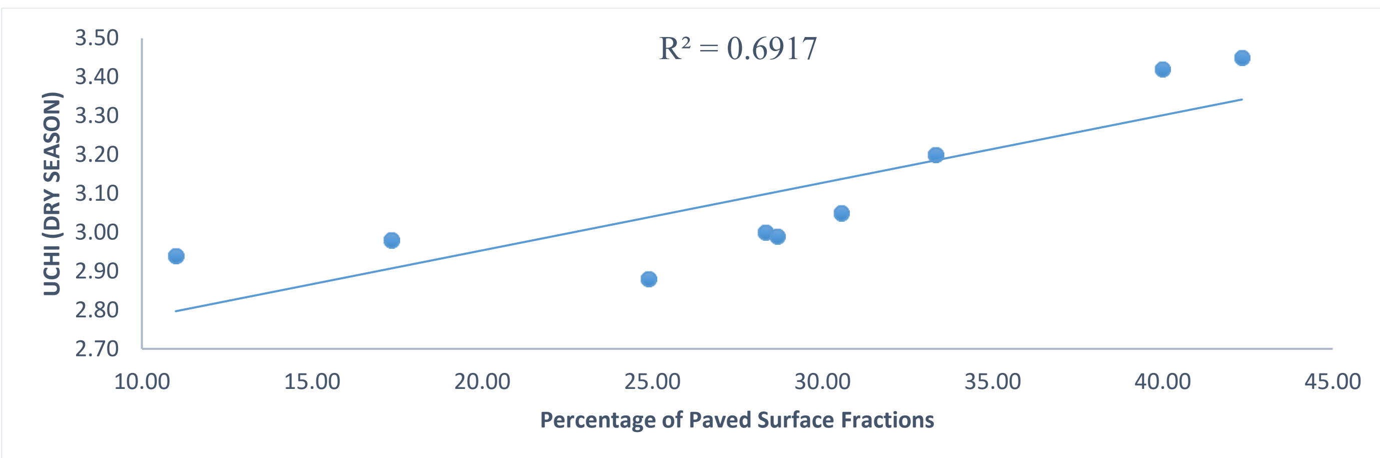


Figure 6. Relationship between percentage of paved surface and mean UCHI in the dry season.

the R^2 value of 0.5707 is lower than what was obtained in Singapore (R^2 = 0.719) (Li and Roth, 2009), Bangkok, Thailand (R^2 = 0.878) (Srivanit and Kazunori, 2011), Kuala Lumpur (R^2 = 0.843) (Ibrahim and Samah, 2011),

Furthermore, the effect of paved surfaces on variation of mean UCHI (Figure 6) showed an R^2 value of 0.6917 and a positive linear regression was observed between the parameters. This indicates that 69% of the variation in mean UCHI in the study area is determined by paved surfaces. The result portrayed by the linear regression reveals that in terms of impervious surfaces, paved surfaces had the greatest influence on mean UCHI when compared with other fractions. The high effect of impervious surfaces on mean UCHI in the study area is because, as revealed by Ramamurthy and Bou-Zeid (2014), impervious surfaces are capable of evaporating at higher rates than vegetated surfaces when wet due to their higher storage of heat prior to rain events.

In a similar vein, from Figure 7, an R^2 value of 0.1718 was recorded, indicating that bare land had a 17% influence on mean UCHI variation in the study area. The reduction in R^2 indicates low effects of the percentage of bare land on mean UCHI in the study area. Explanations for this is the reduction in absorption and storage of heat, which reduces ambient air temperature, hence reducing UCHI development. The result of this analysis is similar to what was obtained in Kaduna by Usman (2016), where an R^2 value of 0.189 was recorded for the dry season.

Finally, from Figure 8, it can be seen that an R^2 value of 0.0064 was recorded, indicating about 1% influence of the percentage of vegetation on the spatial variation of mean UCHI in the study area. There exists a negative linear regression between the parameters, which means that as the percentage of vegetation decreases, there is a corresponding increase in mean UCHI variation in the study area.

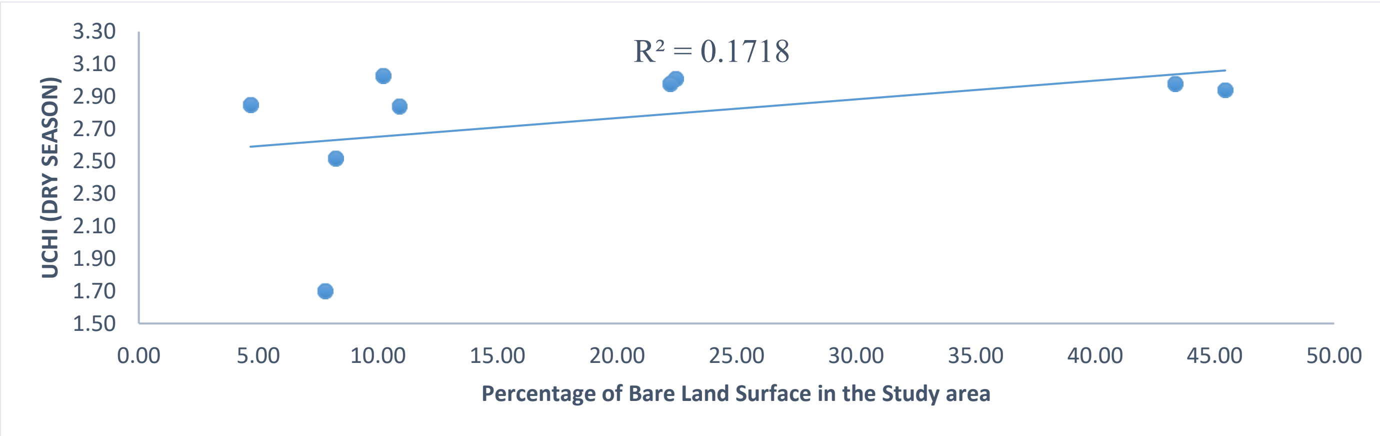


Figure 7. Relationship between percentage of bare land and mean UCHI in the dry season.

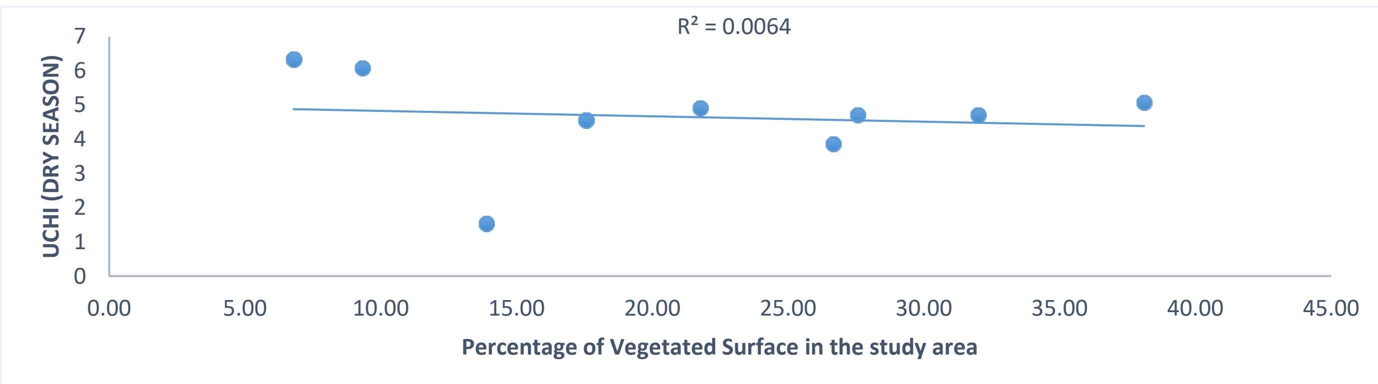


Figure 8. Relationship between percentage of vegetation and mean UCHI in the dry season.

Conclusion

The study found urban bias in temperature, confirming the urban canopy heat island in Benin City due to variations in urban morphology. This variation (69%) was determined by paved surfaces. The study also revealed a notable spatial fluctuation in the distribution of temperature within the urban canopy. The study is limited to the dry season, and only January was used to determine the entire dry season.

Recommendations

Given the findings, it is advised that urban policymakers and practitioners assume immediate responsibility for incorporating urban climate issues into planning across the board and enacting laws governing the use of climate-sensitive building design and planning schemes. This should be implemented within the next 10 years, considering the rise in impervious surfaces in Benin City and the increasing effects of climate change. The state government should also implement cool pavement and roofing for new developments, enforce maximum impervious cover in residential zones and require building orientation and ventilation standards to reduce heat accumulation.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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