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CHARACTERIZATION OF THE URBAN HEAT ISLAND EFFECT IN TWO CONTRASTING NEIGHBORHOODS OF YOPOUGON (ABIDJAN, CÔTE D'IVOIRE)

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ABSTRACT

In West Africa, population growth and rapid urbanization are contributing to the development of urban heat islands (UHIs), characterized by temperature differences between urban areas and their surroundings due to daytime heat accumulation and nighttime heat release. These conditions can adversely affect human well-being. In Côte d'Ivoire, studies based on in situ UHI measurements remain scarce, as previous research has primarily relied on metropolitan-scale land surface temperature data. This study characterizes UHI intensity and temporal variability in two contrasting neighborhoods of Yopougon, Abidjan: Millionnaire, an upper-income residential neighborhood, and Toit Rouge, a working-class neighborhood. Indoor and outdoor temperature measurements were collected from August 2024 to March 2025. An empirical classification scheme based on the observed distribution of UHI intensity was developed, and the Wilcoxon–Mann–Whitney test was used to compare temperatures between neighborhoods. Mean UHI intensity reached 7.30°C in Toit Rouge and 6.82°C in Millionnaire. UHI intensity peaked during the dry season and at night and exhibited greater temporal persistence in Toit Rouge. Indoor measurements also revealed that homes did not provide adequate thermal relief at night. These findings highlight substantial thermal differences between neighborhoods within the same municipality and underscore the importance of neighborhood-scale UHI assessments. They also

demonstrate the need to consider the built environment in urban planning, particularly through interventions targeting residential buildings and public spaces, to mitigate UHI effects and their potential impacts on human well-being in Côte d'Ivoire.

Keywords: Urban Heat Island; In Situ Measurements; Tropical Classification; Yopougon; West Africa

1 INTRODUCTION

Africa is characterized by considerable climatic diversity, which increases its vulnerability to the impacts of climate change [1]. Yet, it is among the continents that contribute the least to the greenhouse gas emissions responsible for driving climate change [2]. Among the various manifestations of climate change, rising temperatures are a major concern for Africa, particularly West Africa [3]. Since the mid-1970s, this region has experienced increases of 1–3°C in mean annual and seasonal temperatures [4]. Furthermore, between 1961 and 2014, the frequency of very hot days and tropical nights increased by 1–9 days and 4–13 nights per decade, respectively, while cold nights became increasingly rare [5,6]. However, this temperature increase is spatially heterogeneous, varying considerably across regions and countries [7].

Urbanization further exacerbates local temperature variability by modifying the microclimate and creating distinct urban climatic conditions. Consequently, urban areas often experience higher temperatures than their surrounding rural environments, a phenomenon known as the urban heat island (UHI) effect [8,9]. This phenomenon is partly driven by heat accumulation during the day and its gradual release at night. However, persistent nighttime thermal discomfort, associated with limited temperature declines, can adversely affect human well-being, making the UHI effect an important public health concern [10]. Nevertheless, UHI intensity varies according to local urban characteristics, highlighting the need for site-specific assessments [11].

In West Africa, the limited body of research on UHIs indicates that their occurrence and intensity are strongly influenced by land use, building density, vegetation cover, and proximity to water bodies [12–14]. Meanwhile, rapid population growth in West African cities is driving accelerated urbanization, accompanied by the expansion of built-up areas [15]. This urban expansion results in land-use changes and vegetation loss, conditions that increasingly favor UHI development [16].

Côte d'Ivoire exemplifies this trend. Over the years, the country has become one of the most urbanized in West Africa, with its urbanization rate increasing from 20% in 1963 to 32% in 1975, 42.5% in 1998, approximately 50.2% in 2014, and 53.5% in 2021 [17]. This sustained and accelerating urbanization is largely driven by the Abidjan District, which has an urbanization rate of 97.4% [17]. Projections by the German Development Cooperation (GIZ) indicate that temperatures in Côte d'Ivoire could increase by 1.7–3.7°C by 2080, depending on greenhouse gas emission scenarios [18]. Furthermore, urban expansion and regional heat waves can interact and reinforce one another, potentially intensifying the UHI effect [19].

In Côte d'Ivoire, to the best of our knowledge, studies characterizing the UHI effect using in situ measurements remain scarce. Ymba [14], in a study conducted in Abidjan, relied primarily on land surface temperature data, which provide only a partial representation of the thermal conditions to which urban populations are exposed. Therefore, the present study aims to characterize UHI intensity and temporal variability in two contrasting neighborhoods of Yopougon (Abidjan) using in situ temperature measurements collected both indoors and outdoors in residential buildings.

2 MATERIALS AND METHODS

2.1 Study Area

Yopougon is the most populous municipality in the Autonomous District of Abidjan. It has an equatorial climate and is located within a hot, humid subequatorial climatic zone [20]. The municipality has an estimated population of 1,571,065 inhabitants and covers an area of 153 km^2, accounting for approximately 24.9% of Abidjan's total population (6,321,017 inhabitants) [17,21]. Furthermore, Yopougon is characterized by dense urbanization and a highly dynamic yet socio-spatially heterogeneous urban fabric, with neighborhoods exhibiting diverse morphological and socioeconomic characteristics [22]. Accordingly, the neighborhoods selected for this study represent contrasting urban typologies: Millionnaire (Zone A), an upper-income residential neighborhood, and Toit Rouge (Zone B), a working-class neighborhood.

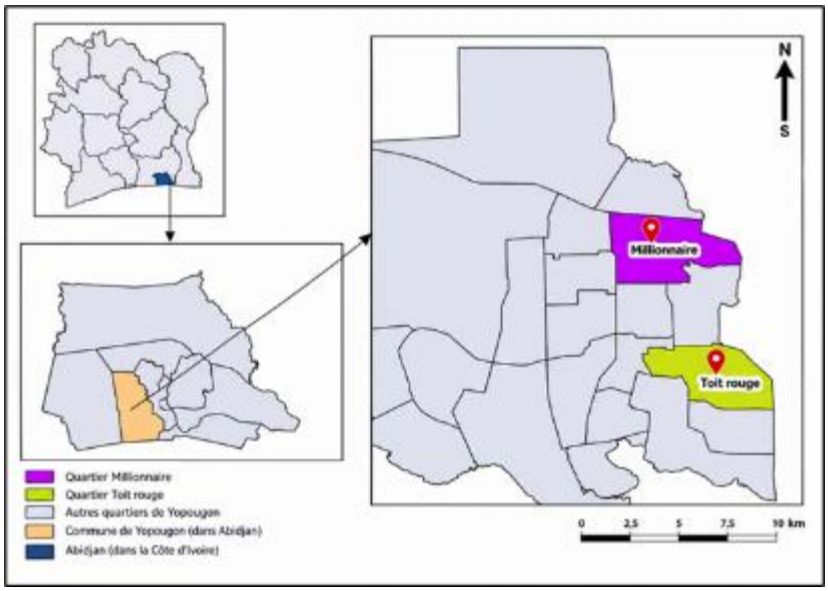

Figure 1: Overview of the study area.

2.2 Meteorological Data

Hourly measurements of air temperature (T, °C), relative humidity (RH, %), atmospheric pressure (hPa), and dew point temperature (°C) were collected using PurpleAir PA-II-SD sensors (PurpleAir, Inc., Salt Lake City, UT, USA). A total of eight sensors were deployed across four households, with two households selected in each of the two study neighborhoods (Millionnaire and Toit Rouge). Each household was equipped with one indoor sensor and one outdoor sensor, resulting in four sensors per neighborhood: two indoor and two outdoor sensors.

Measurements were collected from August 2024 to March 2025. The hourly measurements were subsequently aggregated into daily averages for each variable.

Daily meteorological data, including relative humidity (%), mean, minimum, and maximum air temperatures (°C), and daily temperature range, were obtained from NASA's Prediction of Worldwide Energy Resources (POWER) database (https://power.larc.nasa.gov/data-access-viewer) for the same observation period. These data were extracted for the northern part of Yopougon, adjacent to Banco National Park, and used as reference data for calculating UHI intensity. Daily UHI intensity (Equation 1) was calculated using the conventional approach of determining the air temperature difference between an urban area and its surrounding reference area, following Oke's [9] definition. In this study, the urban area was defined as the eastern part of Yopougon, encompassing the Millionnaire and Toit Rouge neighborhoods.

(1) $$\Delta T_{avg} = UHI_d = T_{\text{sensor EXT}} - T_{\text{ref}}$$

- ΔT_{avg} : Difference in daily mean air temperature.
- $UHI_{_d}$: Daily mean urban heat island intensity.
- $T_{_sensor_EXT}$: Daily mean outdoor air temperature in the urban area.
- $T_{_ref}$: Daily mean air temperature in the suburban reference area.

An initial classification based on fixed thresholds commonly used in the literature on the urban heat island (UHI) effect was first applied. This classification, derived from the intensity values described by Oke [9] for temperate climates, distinguishes four intensity levels: weak UHI (< 1 °C), moderate UHI (1–2 °C), strong UHI (2–3 °C), and very strong UHI (> 3 °C). However, applying this classification to the observed data proved unsuitable for tropical environments, where the temperature difference between urban and reference areas may be systematically higher than that observed in temperate climates [23]. Indeed, all recorded daily values exceeded the 3 °C threshold, resulting in 100% of the days being classified as experiencing a "very strong" UHI.

Because this classification did not allow for differentiation across neighborhoods, seasons, or intensity levels, an alternative classification adapted to the tropical context was developed. This adapted UHI classification was based on a combined approach incorporating the conventional classification, the mean, and the standard deviation of the observed distribution, following Zhang et al. [24] and Bahi et al. [25]. The thresholds were established using the overall mean and its standard deviation (χ = 1), with both statistics calculated across the two study neighborhoods to ensure comparability through the application of common thresholds. Accordingly, four intensity levels were defined, as

presented in Table 1, using the general threshold formula (Equation 2) [24]. Indoor overheating was assessed by calculating the temperature difference between indoor and outdoor environments within each neighborhood, separately for daytime (6:00 a.m.–7:00 p.m.) and nighttime (7:00 p.m.–6:00 a.m.).

(2) :

$$\text{Threshold} = \text{Mean} \pm \chi\,(\text{SD})$$

- χ = number of standard deviations separating the threshold from the mean. In this study, $\chi = 1$

Table 1: Urban Heat Island (UHI) Classification Adapted to the Tropical Context

	UHI Intensity threshold	UHI Intensity Category
1	UHI ≤ Mean UHI* - 1 SD	Weak
2	Mean UHI* - 1 SD ≤ UHI ≥ mean	Moderate
3	mean ≤ UHI* ≥ Mean UHI* +1(SD)	Strong
4	UHI ≥ Mean UHI* +1(SD)	Very strong

* **(3)** :$$UHI = \frac{UHI_j(Millionnaire)\times n_M + UHI_j(Toit\ Rouge)\times n_{TR}}{n_M + n_{TR}}$$

Where:

- $UHI_j(Millionnaire)$ = UHI intensity in Millionnaire.
- $UHI_j(Toit\ Rouge)$ = UHI intensity in Toit Rouge.
- n_M= Number of observations in Millionnaire.
- n_{TR} = Number of observations in Toit Rouge.

2.3 Statistical Analysis

To compare perceived heat intensity across neighborhoods, the Friedman test was applied to paired measurements, followed by pairwise Wilcoxon signed-rank tests with Bonferroni correction. The Wilcoxon–Mann–Whitney test was used for inter-neighborhood comparisons (Millionnaire, Zone A, vs. Toit Rouge, Zone B). The Kruskal–Wallis test was used to assess seasonal variations in UHI intensity within each neighborhood by comparing values across the three seasons. Thermal persistence was assessed using the autocorrelation function (ACF), while differences between indoor and outdoor temperatures were evaluated using the Wilcoxon signed-rank test. All statistical tests were performed at a 5% significance level, and effect sizes were systematically reported.

3 RESULTS

3.1 Calculation and Classification of UHI Intensity

The mean daily UHI intensity was 6.82°C in Millionnaire (an upper-income residential neighborhood) and 7.30°C in Toit Rouge (a working-class neighborhood), with a statistically significant difference between the two neighborhoods (Wilcoxon–Mann–Whitney test, $p < 0.001$; $r = 0.27$).

Across both neighborhoods (n = 352 days), the overall mean daily UHI intensity was 7.07°C, with a standard deviation (SD) of 0.99°C. Accordingly, the classification thresholds were established at the overall mean (7.07°C), one standard deviation below the mean (6.08°C), and one standard deviation above the mean (8.05°C), defining four intensity categories (Table III). Each daily UHI value was classified according to these thresholds, which were applied consistently across both neighborhoods to enable comparisons of the distribution of UHI intensity categories. Based on this classification, the mean UHI intensities in Millionnaire (6.82°C) and Toit Rouge (7.30°C) fell within the *moderate* and *strong* categories, respectively.

Table 2: Adapted UHI intensity classification and number of days by neighborhood

UHI intensity level	UHI intensity range	Millionnaire (n = 172)	Toit Rouge (n = 180)
Weak	UHI ≤ 6.08°C	36 (20.9%)	24 (13.3%)
Moderate	6.08°C < UHI ≤ 7.07°C	64 (37.2%)	37 (20.6%)
Strong	7.07°C < UHI ≤ 8.05°C	59 (34.3%)	77 (42.8%)
Very strong	UHI > 8.05°C	13 (7.6%)	42 (23.3%)

Nb: n represents the number of days.

An analysis of Figure 2 reveals distinct patterns in the distribution of UHI intensity categories across the two neighborhoods. In Millionnaire, the moderate UHI category accounts for the largest proportion of days (n = 64, 37.2%), whereas the strong UHI category predominates in Toit Rouge (n = 77, 42.8%). Furthermore, days classified as experiencing a very strong UHI were approximately three times more frequent in Toit Rouge (23.3%) than in Millionnaire (7.6%).

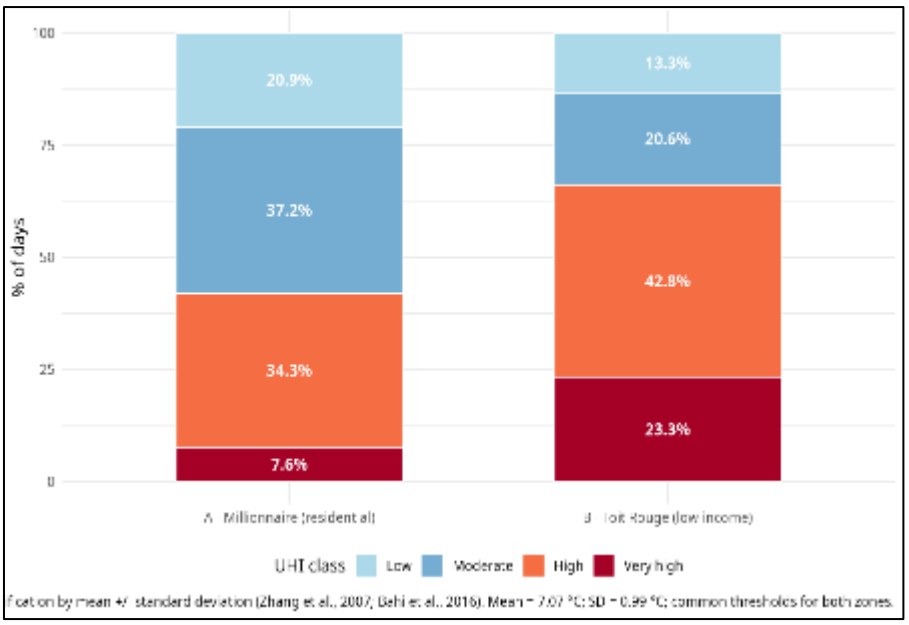

Figure 2: Distribution of UHI intensity classes by neighborhood

3.2 Spatiotemporal Variability and Monthly UHI Profiles

UHI intensity varied significantly across seasons in both neighborhoods. The highest UHI intensities were recorded during the dry season (November–March), with mean values of 7.2°C in Millionnaire and 7.7°C in Toit Rouge, compared with approximately 6°C during the rainy season (Figure 3). The monthly UHI profiles further highlight the predominance of higher UHI intensity in Toit Rouge (working-class neighborhood) over most of the study period, particularly from November through February, when the differences between the two neighborhoods were greatest and daily UHI intensity values were highest (Figure 4). However, this pattern was reversed in August and September, when UHI intensity was higher in Millionnaire (Zone A, residential neighborhood), despite the smaller number of observation days.

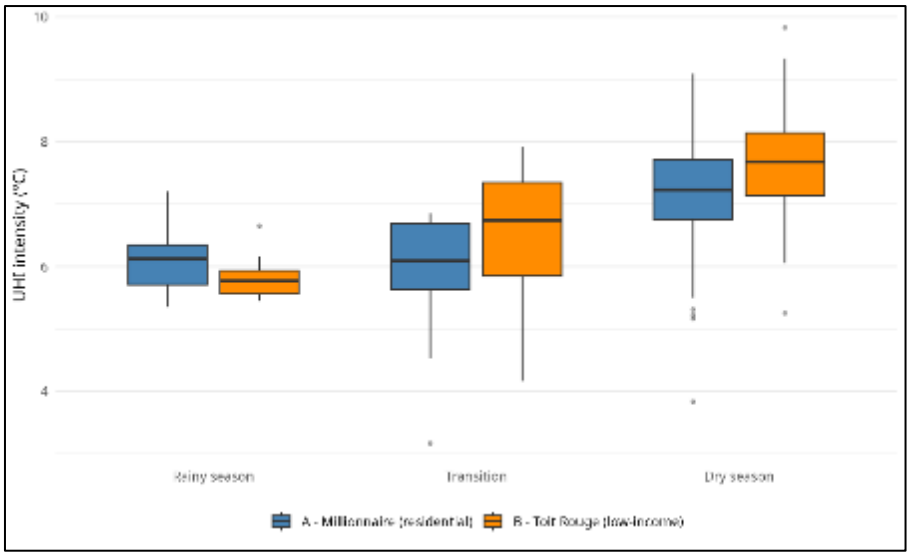

Figure 3: Seasonal Variation in UHI Intensity by Neighborhood

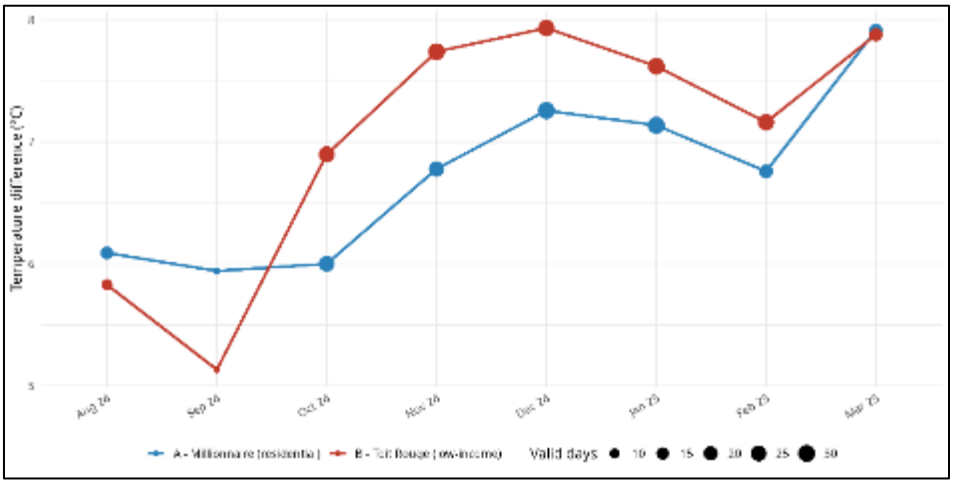

Figure 4: Monthly Variation in UHI Intensity by Neighborhood

First-order temporal autocorrelation analysis revealed greater temporal persistence of UHI intensity in Toit Rouge (r = 0.76) than in Millionnaire (r = 0.58) (Figure 5). This autocorrelation gradually decreased in Toit Rouge but remained significant over a period of one to two weeks, whereas a shorter persistence was observed in Millionnaire.

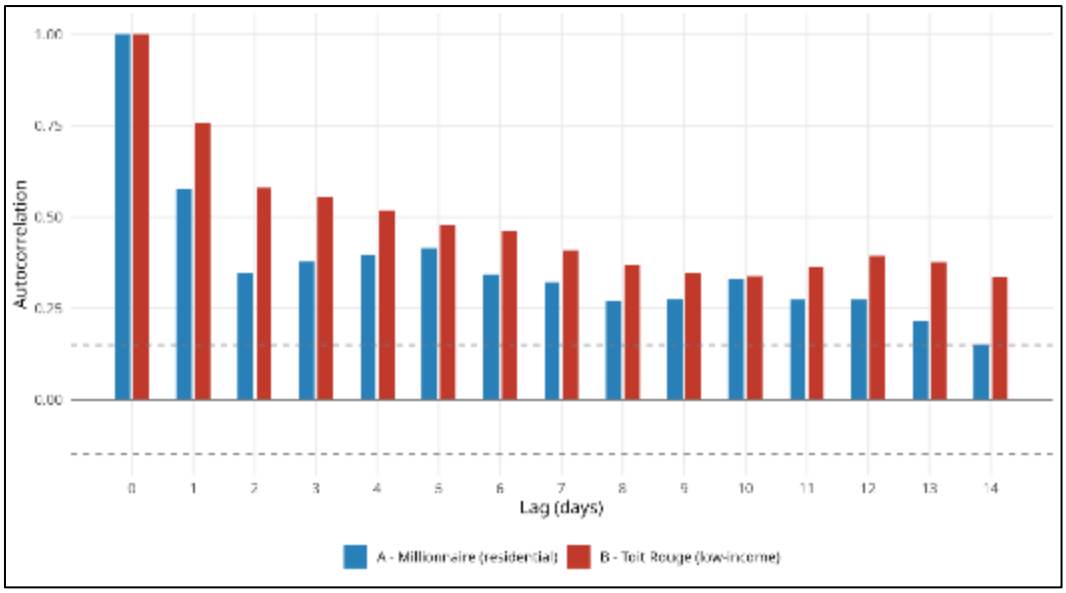

Figure 5: Temporal Autocorrelation of UHI Intensity by Neighborhood

In the four monitored homes, indoor temperatures were significantly higher than outdoor temperatures, with median differences of +0.6°C in Millionnaire and +1.1°C in Toit Rouge (Wilcoxon signed-rank test, $p < 0.001$ in both cases). This difference was negligible during the daytime (−0.7°C in Millionnaire and +0.6°C in Toit Rouge) but increased at night, reaching +2.0°C in Millionnaire and +1.4°C in Toit Rouge. Indoor temperatures were higher than outdoor temperatures on 88%–100% of the observed nights (Figure 6).

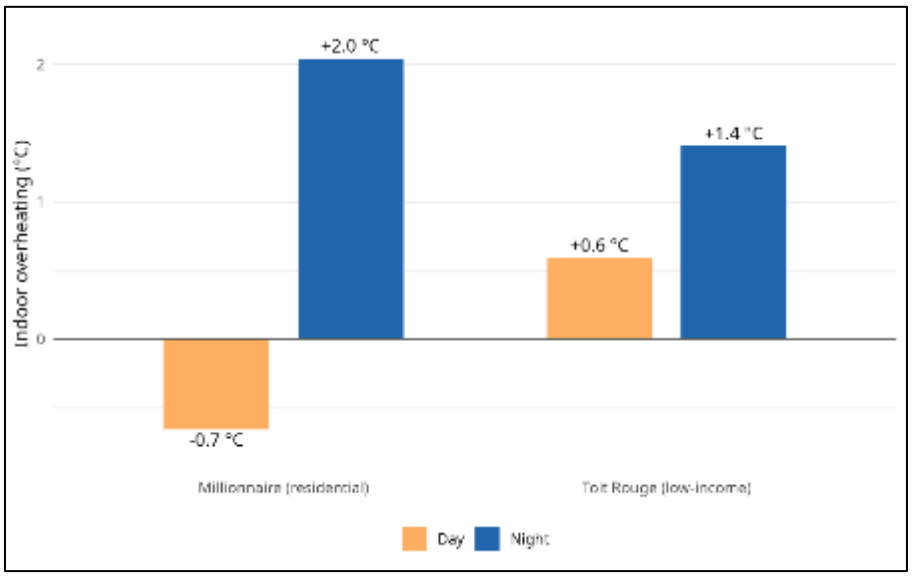

Figure 6: Daytime and Nighttime Urban Heat Exposure Measurements

4 DISCUSSION

4.1 Characterization of UHI Intensity

Analysis of UHI intensity revealed mean values of 6.82°C and 7.30°C in the Millionnaire and Toit Rouge neighborhoods, respectively. These values exceed the thresholds established in Oke's classification [26], with the highest intensity category being exceeded on almost every day of the observation period. This finding justified the adoption of an empirical classification scheme. In Toit Rouge, most days during the study period were characterized by strong UHI conditions. Similarly, Wemegah et al. [27] reported substantial heat island intensity in Accra, with values of approximately 4.07°C (1991), 5.79°C (2002), and 4.86°C (2017), based on surface temperature measurements. These findings provide a useful point of comparison with the results of the present study.

The differences in UHI intensity between the two neighborhoods may be explained by variations in land-use patterns and urban morphology. Toit Rouge is characterized by dense development and narrow streets, which may restrict ventilation and limit nighttime cooling. Road traffic, another potential source of anthropogenic heat, is also considerably more intense in this neighborhood than in Millionnaire. These observations are consistent with those of Ymba [14], who used surface temperature data to identify areas at risk of heat stress in Yopougon, particularly in the densely built-up central sectors of the municipality. The study also reported lower heat stress intensity in the central-western and southern sectors.

Overall, these findings confirm the presence of a pronounced UHI effect in Yopougon and highlight the potential influence of building density on its intensity. Furthermore, they underscore the occurrence of substantial heat island effects in tropical cities, with magnitudes comparable to, or even greater than, those reported in temperate cities. This difference may be related to the distinct climatic dynamics of tropical and temperate regions. West Africa lies within the tropics, where monthly mean temperatures generally remain above 18°C, unlike in temperate climates. Consequently, whereas UHI effects in temperate cities are predominantly nocturnal, thermal stress in tropical cities may persist throughout the day [28]. Similar findings were reported by Amorim and Dubreuil [23], who investigated UHI characteristics under temperate and tropical climatic conditions in Rennes, France, and Presidente Prudente, in western São Paulo State, Brazil, respectively. They found that UHI intensity was greater in the tropical setting, reaching approximately 6°C, compared with 3.5°C in the temperate setting.

These differences further support the need to adapt UHI classification systems developed for temperate climates to tropical African environments, as undertaken in the present study. The adapted classification was based on the local distribution of observed values, specifically the mean and standard deviation, following the approach of Zhang et al. [24], subsequently adapted by Bahi et al. [25] to better reflect African urban contexts. This approach enabled a more refined classification of UHI intensity and facilitated the identification of distinct intensity profiles across the two study neighborhoods.

4.2 Spatiotemporal Variability of the UHI Effect

The results confirm the presence of the UHI effect in Abidjan, particularly in Yopougon. This finding is consistent with the work of Wemegah et al. [27], who also documented the significant occurrence of UHI effects in an African urban context. However, the values reported for Accra, although substantial and variable over time (approximately 4.07°C in 1991, 5.79°C in 2002, and 4.86°C in 2017), were lower than those obtained in the present study. This difference highlights the contrasting thermal characteristics observed across the two urban contexts.

In the present study, Toit Rouge was warmer than Millionnaire, with approximately three times as many days classified in the very strong UHI category (42 days versus 13 days) and a mean UHI intensity of 7.30°C. Accordingly, Toit Rouge was classified as experiencing strong UHI conditions, whereas Millionnaire was classified as experiencing moderate UHI conditions, with a mean intensity of 6.82°C. These differences in UHI intensity between the neighborhoods may be explained by well-established mechanisms of UHI formation, including building density, limited vegetation cover, surface mineralization, and the urban canyon effect [29].

Furthermore, the greater temporal persistence of elevated temperatures in Toit Rouge may be associated with its denser urban fabric compared with Millionnaire. High urban density can promote heat storage in building materials and other urban surfaces, followed by gradual heat release over subsequent hours, thereby delaying nighttime cooling. Historically, Yopougon developed as a municipality comprising neighborhoods whose names were derived from real estate development projects. Toit Rouge is one such example, with its name reflecting the roofing material used during its development [30]. Initially, this type of residential development addressed specific social housing needs, and its basic structure and layout complied with the urban planning regulations in force at the time [22]. However, over time, the neighborhood underwent several structural changes, including a reduction in natural shade and vegetation cover, partly associated with population growth. This contrasts with Millionnaire, an upper-income residential neighborhood characterized by a different urban structure. These differences suggest that urban morphology plays an important role in shaping UHI intensity [31].

The observed thermal differences between the neighborhoods may also be associated with variations in UHI persistence, potentially influenced by the Sky View Factor (SVF), defined as the proportion of the sky visible from a given location. In densely built-up streets, a lower SVF can restrict the release of heat from urban surfaces to the night sky, thereby limiting nighttime cooling. Ning et al. [32] demonstrated that the influence of urban morphological factors varies considerably across neighborhoods, with the most pronounced variations associated with the SVF. These findings are consistent with the patterns observed in the present study. In contrast, Li et al. [33] showed that although urban expansion can increase the geographical extent of areas affected by the UHI effect, it does not necessarily result in simultaneous changes in UHI intensity across all locations. Thus, urbanization does not automatically lead to a uniform deterioration in local thermal conditions.

Although differences in UHI intensity were observed between the two neighborhoods based on outdoor measurements, the results also revealed a day–night reversal in indoor thermal conditions. Homes are generally expected to provide relative thermal protection during the day. However, our findings indicate that indoor temperatures exceeded outdoor temperatures at night by 1.4–2.0°C on nearly all observed nights. This suggests the occurrence of an indoor heat-trapping phenomenon, whereby residential buildings retain heat and limit occupants' access to nighttime cooling. Such conditions may compromise physiological recovery and sleep quality, both of which depend on adequate nighttime thermal relief [34,35].

Although the findings of this study provide important insights into UHI characteristics in Yopougon, they should be interpreted in light of several limitations, particularly those related to site selection, the number of deployed sensors, and the duration of data collection. Specifically, the study was conducted in only two neighborhoods and covered a single observation period from August 2024 to March 2025. Therefore, although it provides a detailed assessment of contrasting urban thermal environments, it should be regarded as a robust but non-exhaustive case study of the municipality's thermal characteristics.

5 CONCLUSION

The characterization of urban heat island (UHI) intensity in Yopougon revealed mean daily UHI intensities of 6.82°C in the Millionnaire neighborhood and 7.30°C in the Toit Rouge neighborhood. Overall, 23.3% of the observed days in Toit Rouge were classified as experiencing very strong UHI conditions, compared with 7.6% in Millionnaire. This empirical classification scheme was developed because the conventional thresholds proposed by Oke were not suitable for distinguishing UHI intensity under the tropical climatic conditions observed in this study. During the dry season, UHI intensity was also substantially higher in Toit Rouge than in Millionnaire. The contrasting UHI intensities observed between two neighborhoods within the same municipality underscore the importance of detailed, neighborhood-scale assessments of urban heat islands in Abidjan. Furthermore, the observed indoor heat-trapping phenomenon indicates that homes do not necessarily provide adequate thermal relief at night. This finding highlights the need for interventions targeting not only public spaces but also residential buildings, particularly through improved ventilation, appropriate roofing materials, and thermal insulation, as key strategies for mitigating indoor heat exposure.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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