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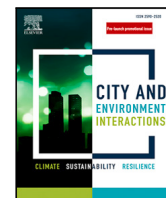
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Review articles

Urban heat island in the tropics: A review of advances, challenges, and future directions

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ABSTRACT

Urban Heat Islands (UHI), characterized by elevated temperatures in urban areas compared to their rural surroundings, represent a growing concern in the context of climate change, particularly in tropical regions. While UHI research has advanced significantly in temperate zones, tropical climates have received comparatively less systematic attention, despite their high vulnerability to global warming and rapid urbanization. This review systematically analyzes UHI studies conducted in tropical contexts between 2000 and 2024, using the PRISMA methodology. A total of 508 documents were identified through Dimensions.ai using search terms such as “Urban Heat Island” AND “Tropical” or “Tropics”. After screening and eligibility assessment, 156 studies were included. The review covers experimental and numerical approaches, remote sensing methods, and solution-oriented strategies across multiple urban scales. The term “tropics” here encompasses regions located between the Tropic of Cancer and the Tropic of Capricorn, although considerable climatic, socio-economic, and geographical diversity exists within this band. Our findings highlight a concentration of research in large metropolitan areas, with medium and smaller cities often overlooked. The lack of microclimate or neighborhood-scale and multiparameter analyses limits our understanding of localized UHI dynamics and the applicability of mitigation strategies. We identify the need for more holistic, interdisciplinary approaches that integrate diverse climate parameters and locally validated models tailored to the combined complexity of tropical climates and urban environments. Expanding UHI research in underrepresented regions and adopting multiscale strategies are crucial for advancing inclusive, climate-resilient urban planning in the tropics.

1. Introduction

The urban heat island (UHI) is defined as a positive temperature difference between an urbanized area and the surrounding rural zone. This phenomenon has been studied by the scientific community for nearly two hundred years. In 1833, Howard was the first to detect an anomaly in the temperature measurements he conducted in London [1], observing temperature differences of up to 2 °C between the city and the nearby countryside. Since then, extensive research has been conducted worldwide to understand the factors driving UHI intensity and its consequences on urban environments [2].

The primary mechanisms influencing urban overheating were identified by Oke [3]. These include urban morphology, where dense and tall buildings reduce natural ventilation; the replacement of vegetated surfaces with heat-retaining mineral materials such as asphalt and concrete; and anthropogenic heat emissions from vehicles, industries, and air conditioning systems. While these mechanisms are common to cities worldwide, the manifestation and impact of UHI differ significantly depending on climate zones, particularly in tropical regions [4,5].

Tropical climates are classified as type A in the Köppen–Geiger system [6] and represent the third most extensive climate zone globally, covering approximately 19% of the Earth’s land surface. According to this classification, a climate is defined as tropical if the average temperature of all twelve months exceeds 18 °C, indicating persistently warm conditions throughout the year. They are also marked by elevated humidity levels, driven by abundant precipitation, exceeding 60 mm per month in Tropical Rainforest (Af) zones, and by intense solar radiation. These climatic conditions are predominantly found between the Tropic of Cancer and the Tropic of Capricorn (approximately 23.5° N to 23.5° S). However, significant climatic variability exists within this tropical band, encompassing different precipitation regimes and seasonal dynamics, such as those found in Tropical Monsoon (Am) and Tropical Wet and Dry/Savannah (Aw/As) climates [6]. These environmental conditions tend to alter UHI effects, making tropical cities particularly vulnerable. Unlike in temperate regions, where UHI is generally more intense at night and may even be negative during the day, tropical cities often experience UHI throughout the day, with

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daytime peaks occurring in some cases, particularly during the wet season [7]. The combination of high solar irradiance, elevated atmospheric moisture, and the specific thermal properties of materials used in tropical urban environments generates distinct UHI dynamics that require tailored analysis and mitigation strategies.

Furthermore, many tropical cities are undergoing rapid urban expansion [8,9], often in an organic and unregulated manner. Unlike the structured grid patterns of many Western cities, urban growth in the tropics frequently follows less formalized layouts, leading to heterogeneous urban forms, increased urban sprawl, and a mix of high- and low-density developments. This rapid expansion exacerbates UHI effects by increasing land cover changes, reducing vegetation, and modifying local microclimates. Additionally, the demographic boom in tropical regions is significant: according to the IPCC, more than 90% of global population growth will occur in low-latitude areas in the coming decades [10]. This makes it crucial to develop tailored adaptation strategies for these rapidly urbanizing environments.

Several studies have highlighted the distinct UHI characteristics in tropical regions. For example, Amorim and Dubreuil [7] compared UHI intensity in a tropical Brazilian city and a temperate French city, revealing that the tropical UHI reached up to 6 °C, compared to 3.5 °C in the temperate counterpart. Moreover, Khan et al. [11] showed that UHI intensity in tropical cities tends to be highest during drier months, while Chatterjee et al. [12] found that conventional mitigation strategies, such as cool roofs or reflective pavements, tend to be less effective in tropical settings compared to vegetation-based solutions. In addition, tropical UHIs pose increased risks to human health, thermal comfort, and energy consumption, making adaptation even more pressing [13].

Previous review papers have addressed various aspects of UHI in tropical climates. For example, Liu et al. [14] provided methodological guidelines for experimental UHI studies in tropical settings, while Banerjee et al. [15] analyzed urban design strategies for thermal comfort in Singapore. Studies such as Giridharan and Emmanuel [16], Sari [17] explored how urban compactness and building design influence UHI intensity in tropical cities. Singh et al. [18] employed high-resolution modeling to quantify the contribution of anthropogenic emissions from buildings and air-conditioning systems to urban warming in Singapore, highlighting the significant role of human-induced heat in shaping tropical urban climates.

However, to our knowledge, no systematic literature review has comprehensively examined UHI in tropical climates by integrating remote sensing, observational, and numerical modeling studies while considering the latest advancements in the field. This paper aims to provide a holistic perspective on UHI research in tropical urban environments. First, we describe the study area and the methodology used to select relevant literature. Then, we review field observations approaches and remote sensing techniques applied to assess UHI dynamics and discuss numerical models used to simulate UHI effects and predict future urban climate scenarios. Finally, we evaluate UHI mitigation strategies specifically adapted to tropical contexts, highlighting their effectiveness and potential limitations. By emphasizing the unique climatic, urbanization, and socio-economic challenges of tropical cities, this review seeks to bridge existing research gaps and provide insights for more effective and context-specific urban climate adaptation strategies.

2. Methods

2.1. Study area

The Köppen classification is undoubtedly the most widely used system for categorizing climates in climate studies worldwide [6]. It is based on the global distribution of vegetation and divides climates into five major groups: equatorial (A), arid (B), warm temperate (C), snow (D), and polar (E). In this study, we focus exclusively on the equatorial climate group, further subdivided into three classes: Tropical Rainforest

(Af), Tropical Monsoon (Am), and Tropical Wet and Dry or Savannah (Aw or As) [19]. These three classes encompass the primary tropical climates.

While tropical climates (group A) may occur outside the intertropical zone, defined as the region between the Tropic of Cancer and the Tropic of Capricorn, our analysis is limited to areas within latitudes -23.5° and 23.5° to maintain consistency in data processing. Throughout this paper, the term “tropical” refers geographically to regions situated between these two tropics with a A climate according to the Köppen classification. Indeed, we also excluded studies set in other climates type occurring within the tropical zone, such as subtropical climates like Cfa or Cwa, or arid climates like Bsh or Bwh, as categorized by Peel et al. [6]. To streamline the study, we focus exclusively on regions within this defined geographical zone with corresponding Köppen A climates.

Figs. 1 and 2 illustrate the global distribution of the studies included, highlighting significant concentrations of publications in specific cities and countries. For the quantitative analysis of geographic distribution (e.g., number of studies per city), we considered each city name as cited by the original authors in titles, abstracts, or keywords. This allowed us to maintain consistency across a wide variety of study designs and data sources. The term “city” thus corresponds to the study location as declared, which may refer to a municipality, a metropolitan area, or a specific district, depending on the context of each publication. Nations such as Singapore, India, Malaysia, Brazil, and China make substantial contributions to UHI research, while others have very few or no publications. Similarly, major metropolitan areas and megacities – such as Kolkata, Kuala Lumpur, and Putrajaya – are among the most studied locations. This uneven distribution likely reflects disparities in research infrastructure and scientific output among countries. Singapore, which has the highest number of publications, stands out as a key research hub for the tropical zone, significantly contributing to the volume of studies in Southeast Asia and Af climates. In contrast, many countries in tropical Africa and small tropical islands show limited contributions [20], underscoring regions where academic resources and research funding remain insufficient to support UHI research.

Regarding the distribution of studies across Köppen tropical climate subtypes, as illustrated in Fig. 3, 44.9% of the studies are conducted in Af (Tropical Rainforest) climates, 34% in Aw (Tropical Wet and Dry), 11.5% in Am (Tropical Monsoon), and only 3.2% in As (Tropical Dry Summer), the latter represented solely by studies conducted in Chennai, India [21–23]. The remaining 6.4% of studies span multiple climate subtypes at broader spatial scales [24–27].

At first glance, this distribution suggests a dominance of studies in Af climates. However, this pattern is strongly influenced by the concentration of research conducted in Singapore, which alone contributes a disproportionately high number of publications, as previously described. Yet, according to Peel et al. [6], Aw climates account for approximately 11.5% of the global land surface, making them the most widespread tropical subtype, whereas Af and Am together occupy a smaller total area. This indicates a notable mismatch: while Aw is the most extensive tropical climate geographically, it only accounts for a third of the UHI studies in our review, compared to nearly half for Af. This imbalance likely reflects not just climatic distribution, but also uneven research capacities and infrastructure. Many regions dominated by Aw climates, such as parts of Sub-Saharan Africa or central India host fewer major research institutions or suffer from limited funding opportunities, resulting in lower scientific output on UHI despite their high exposure to urban heat. Therefore, the apparent overrepresentation of Af and underrepresentation of Aw in the literature highlight not only the influence of specific research hubs like Singapore but also a potential geographic and thematic research gap. Addressing this disparity would require targeted efforts to support UHI research in Aw or Am-dominated regions, which are both climatically significant and rapidly urbanizing, yet currently underexamined.

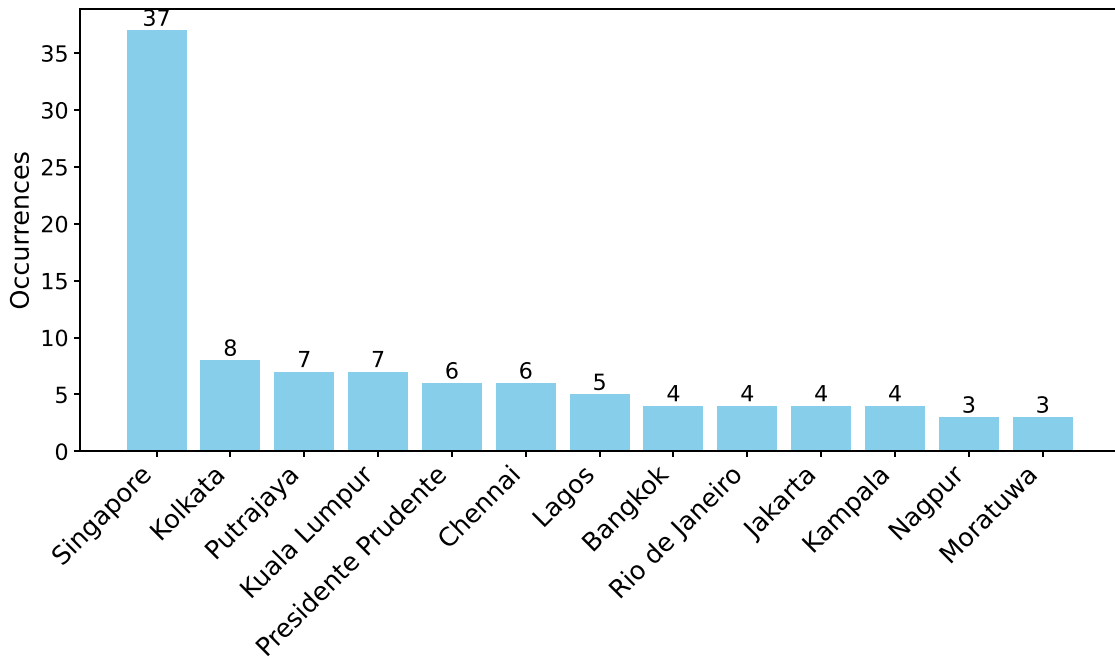


Fig. 1. Number of articles dealing with UHI per city in the tropical zone.

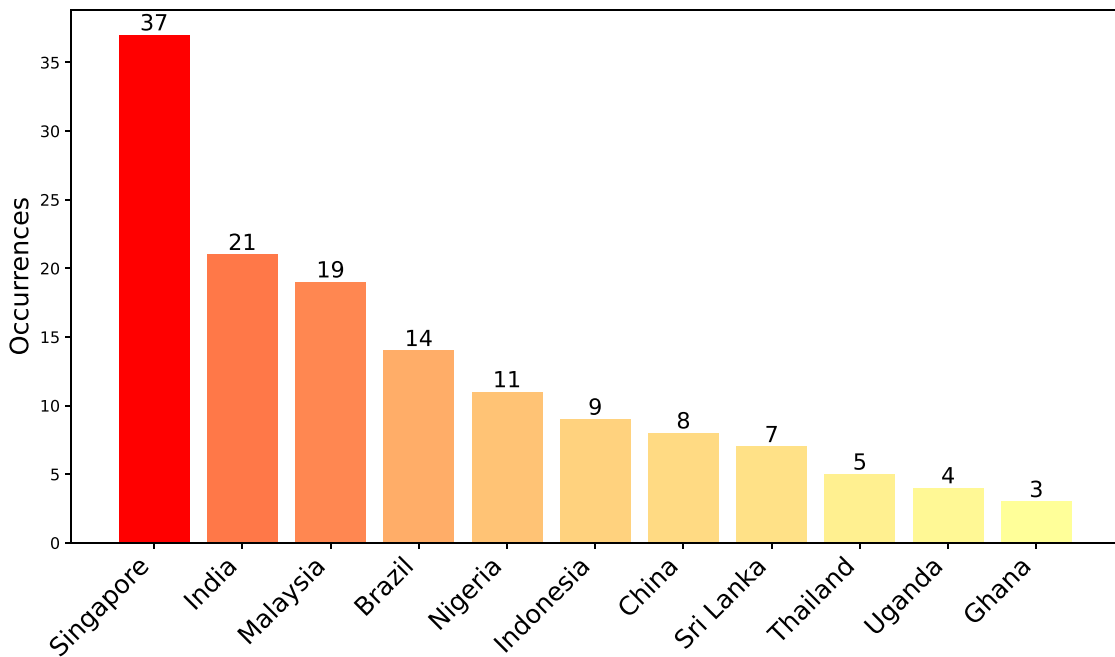
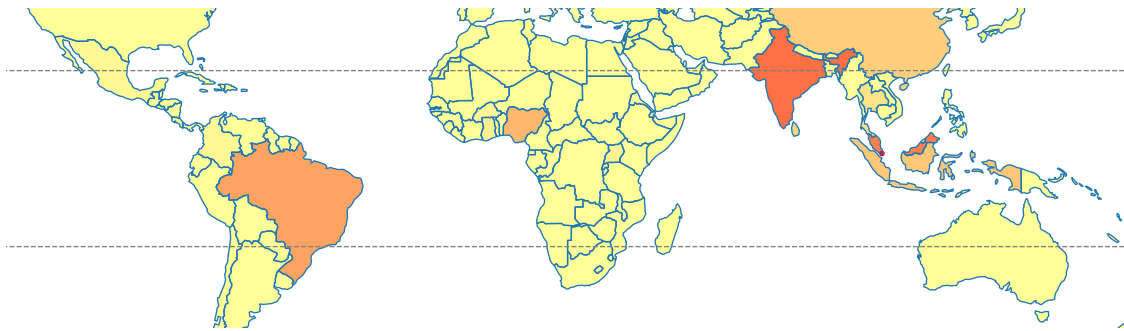


Fig. 2. Number of articles dealing with UHI per country in the tropical zone.

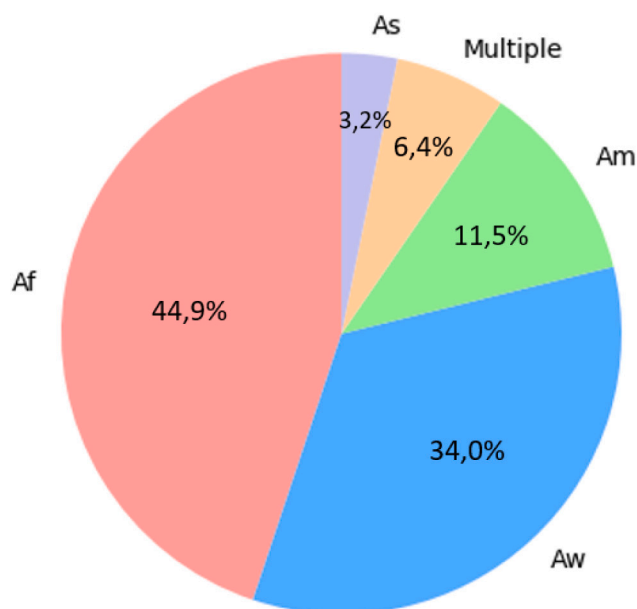


Fig. 3. Distribution of the studies by Köppen Equatorial Climate Type.

2.2. Review methodology

To conduct this review, articles were sourced from the Dimensions.ai database, which has been shown to be reliable in Thelwall [28]. The objective was to answer the research question: *How is the subject of Urban Heat Island specifically addressed in tropical regions?* following the PRISMA methodology presented in Fig. 4. To do this, we performed a search using the keywords “Urban Heat Island” AND “Tropics”, as well as “Urban Heat Island” AND “Tropical”, across titles, keywords, and abstracts for all periods up to July 2024. This search yielded 508 articles.

We applied exclusion criteria to select only original research papers, excluding review articles, book chapters, non-peer-reviewed publications, and conference proceedings. Studies that were not focused on the intertropical region, as defined in the previous section, or those not directly addressing the Urban Heat Island phenomenon (considered off-topic) were also excluded. Additionally, only papers written in English were included in the final analysis. The exclusion criteria were applied throughout the screening process, first by reviewing abstracts and titles, and then through a full-text review. As a result, 352 records were excluded based on these criteria, leaving 156 articles for further analysis. The entire selection process is summarized in Fig. 4.

The temporal distribution of the selected studies is shown in Fig. 5, highlighting the growing academic interest in UHI research in tropical contexts from 1987 to July 2024. The graph reveals a marked increase in publications after 2015, with a notable peak between 2020 and 2022, followed by a slight decline in 2023. While this trend may reflect a heightened recognition of the UHI phenomenon and its increasing relevance in the context of climate change and urban vulnerability, it should also be interpreted in light of broader changes in the scientific publishing landscape. Factors such as the expansion of open-access journals, improvements in digital indexing and dissemination, the decreasing cost and wider availability of environmental monitoring technologies (e.g., remote sensing, temperature loggers), and growing institutional pressure to publish have also contributed to the observed growth. The increase in publications is therefore the result of both a genuine intensification of interest in UHI issues and structural shifts that have facilitated and incentivized scientific output more generally.

The predominant themes of the selected studies were identified through a comprehensive reading process, which highlights the most

frequently occurring terms in the abstracts and titles. This analysis reveals the key topics and major themes addressed by the selected articles. Building on this observation, the thematic distribution of studies on UHI effects in tropical climates can be grouped into four main categories, as illustrated in Fig. 4. First, a significant number of studies focus on UHI characterization using in situ measurements or remote sensing techniques. Second, there are modeling-oriented studies that aim to develop, calibrate, or validate models for more accurate UHI simulations. Third, a subset of the literature investigates and tests mitigation strategies, employing gray, green, or blue infrastructure approaches. Notably, some studies span multiple categories, such as those that integrate numerical modeling with experimental methodologies. As a result, the total number of articles exceeds the 156 studies analyzed, reflecting the interdisciplinary and multifaceted nature of UHI research.

Given this methodological diversity, it becomes essential to distinguish the different forms that the UHI phenomenon can take, as each corresponds to different spatial domains and measurement techniques. The most commonly discussed variant is the Surface Urban Heat Island (SUHI), derived from satellite-based land surface temperature (LST) observations. In contrast, the Atmospheric UHI (also referred to as canopy-layer UHI) relies on in situ air temperature measurements taken near the ground. Other less frequently analyzed forms include the Urban Boundary Layer UHI (UBL-UHI) [29], which captures vertical temperature differences in the atmospheric boundary layer, and the Subsurface UHI (SSUHI) [30], which focuses on underground heat storage. Each of these UHI types responds to different physical processes and necessitates specific methods of observation or simulation. Clearly distinguishing them is essential to accurately interpret results and compare findings across studies.

3. UHI characterization: In situ measurements

The characterization of the UHI phenomenon can be approached in two main ways: in situ using field data or remotely through satellite imagery. First, in situ measurements methods involve using field data to analyze temperature differences between the urban canopy and surrounding rural areas, as well as the spatial distribution of temperature within the urban fabric itself. Alternatively, satellite data can be employed to examine surface temperature variations between cities and their surrounding countryside. This section focuses on the field observations methodologies employed in tropical UHI studies, while the subsequent section will delve into the remote sensing approach.

3.1. Mobile measurements along a transect

The characterization of UHI phenomena has historically relied on mobile measurements. The first such campaign was conducted by Schmidt in 1927, using a car to collect temperatures along a transect in Vienna [2]. His work enabled the early identification of UHI patterns and helped establish mobile surveys as a valuable technique for studying temperature differences across urban areas. Today, mobile transects remain widely used for capturing spatial temperature variations in urban settings, particularly in contexts with limited fixed monitoring infrastructure [14]. Mobile measurements enable fine-grained spatial mapping by moving along pre-defined routes with portable sensor units, typically mounted on vehicles. This method offers a cost-effective and flexible alternative to fixed stations. However, it only captures momentary “snapshots” of thermal conditions, which limits its capacity to observe UHI dynamics over time. This temporal limitation is especially critical in tropical climates, where rapid fluctuations in humidity, solar radiation, and cloud cover can significantly alter local thermal conditions throughout the day.

Among the reviewed studies, only seven applied mobile transects in tropical regions, a relatively low number, highlighting that this method

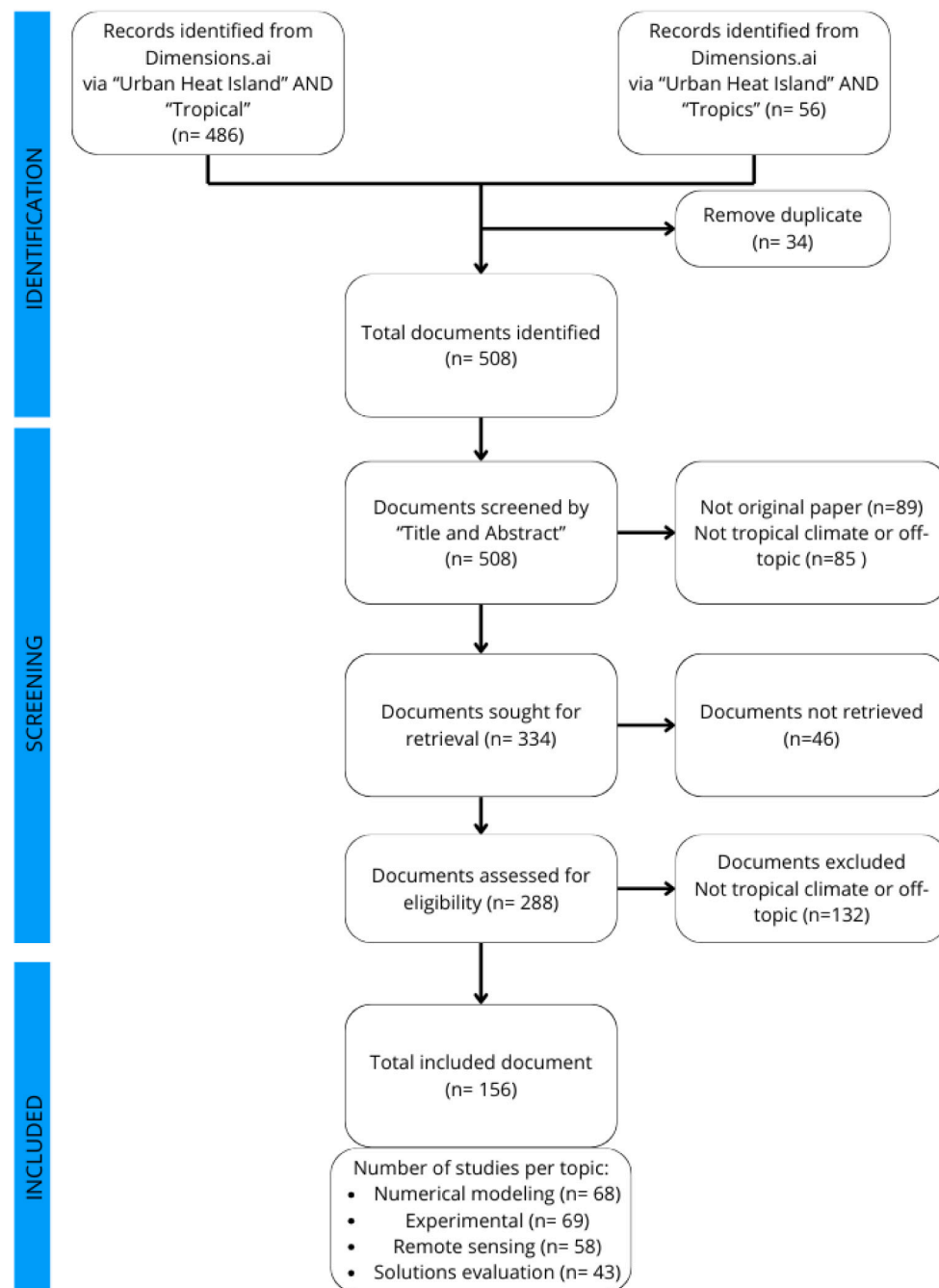


Fig. 4. Identification of studies via PRISMA methodology.

is not widely adopted in these contexts, possibly due to the logistical and temporal demands of repeated measurements. These studies vary in objectives, spatial scales, and methodologies (see Table 1). Most employed vehicles to conduct large-scale transects, particularly at night, to capture peak UHI intensity. For instance, Wong and Yu [31] conducted nighttime surveys in Singapore to assess the cooling role of green spaces, while Lindén [32] investigated nocturnal temperature contrasts in Ouagadougou. Conversely, pedestrian-based surveys, such as in Châfer et al. [33], allowed detailed assessments of microclimatic variations at the street level. These methodological choices illustrate how the mode of transport is closely tied to the scale and intent of the study: cars for city-scale or inter-neighborhood UHI assessment, and walking or cycling for fine-scale investigations in parks, pedestrian areas, or specific urban morphologies.

Temporal design also varies, with most studies focusing on nocturnal or late-afternoon measurements, periods traditionally associated with peak UHI in temperate zones. However, in tropical climates, daytime heat stress is more severe due to continuous solar radiation, especially during the wet season [33,34]. Studies that focus exclusively on nighttime measurements risk overlooking daytime thermal discomfort and may only capture one facet of urban overheating. This highlights the need for methodological approaches better tailored to the thermal dynamics of tropical climates [37].

Furthermore, while some studies claim to assess UHI, many actually examine intra-urban temperature differences (e.g., between built-up and vegetated areas), rather than contrasting urban and rural zones. This reinforces the idea that mobile transects are particularly well-suited for exploring localized thermal contrasts, but are less appropriate

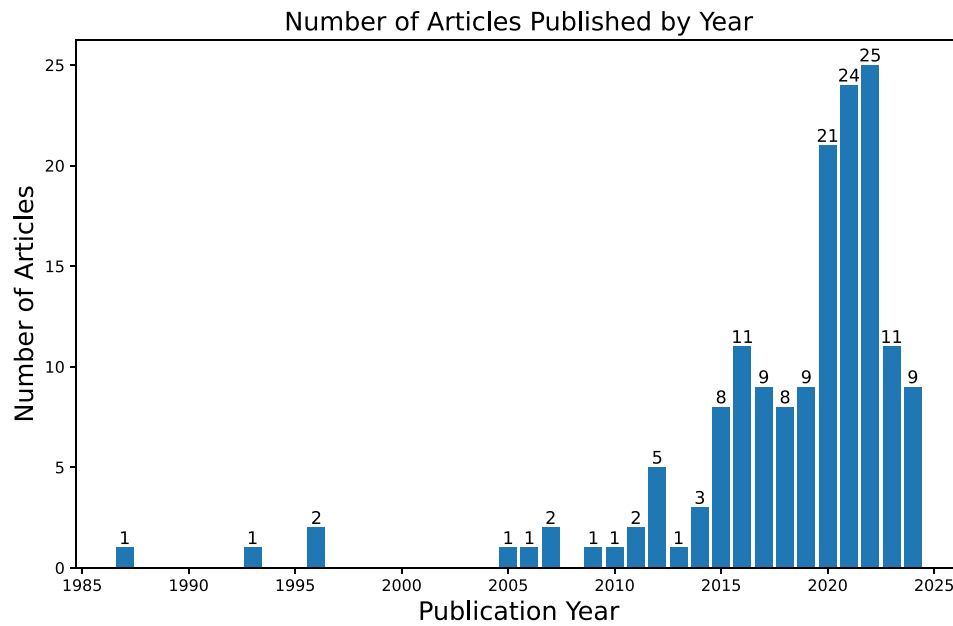


Fig. 5. Number of UHI in tropical climate articles published by year.

Table 1
Summary of mobile transect studies in tropical cities.

Study	City/Köppen	Transport mode	Measurement period	Time of day	Main objective	Urban context	Temp. difference
Wong and Yu [31]	Singapore/Af	Car	9 July & 13 Sept 2002, 2–4 a.m.	Night	Role of vegetation	Entire city, green areas	4.01 °C
Qaid et al. [34]	Putrajaya, Malaysia/Af	Car	16–18 July 2012, six times/day	Day & night	UHI and thermal comfort	Residential areas, main roads	3 °C (max in built-up areas)
Lindén [32]	Ouagadougou, Burkina Faso/Aw	Car	Oct–Dec 2003 & Nov–Dec 2004, 1 p.m. & 8 p.m.	Evening & night	Role of vegetation and water	Urban and rural sites	1.9 °C (UHI), 5 °C (cool island)
Kotharkar et al. [35]	Nagpur, India/Aw	Car	Mar–Apr 2017	Night	Urban form and UHI relation	Contrasting urban zones	3.53 °C
Cardoso et al. [36]	Paranavaí, Rancheira, Presidente Prudente, Brazil/Aw	Car	Dec 2013–Jan 2014	Evening	Morphology and vegetation effects	Medium-sized cities	2.7–6 °C
Jeganathan et al. [22]	Chennai, India/As	Car	25–31 May 2012	Morning & evening	Intraurban variations	Commercial & residential areas	3–4.5 °C
Chàfer et al. [33]	Singapore/Af	On foot	15:30–16:10/ 19:00–19:40/ 01:00–01:40	Day, evening, night	Urban morphology impact	City center, parks, buildings	1.03–4.5 °C

for quantifying broader-scale UHI intensity. Their effectiveness depends greatly on the measurement scale, transport method, both the timing of data collection (time of day) and its temporal frequency (sampling intervals), as well as the climatic context in which they are applied. Given their inherent limitations, particularly the difficulty of synchronizing mobile measurements across time and space, mobile transects should ideally be complemented by fixed stations and, where applicable, remote sensing data with adequate temporal resolution (acknowledging that most satellite imagery provides only intermittent snapshots), to ensure more robust and temporally continuous assessments of UHI patterns in tropical environments.

3.2. Fixed measurements

Fixed meteorological stations, placed in urban and rural areas, are essential for characterizing UHI by collecting continuous weather data and revealing daily and seasonal thermal patterns [38]. The intensity of UHI is typically determined by comparing temperatures from at least two stations: one urban and one rural. Networks of stations enhance spatial resolution, highlighting variations in UHI intensity across different urban zones.

Several studies have employed fixed stations for UHI analysis at various scales, particularly in tropical regions. On a national scale, Simath and Emmanuel [27] analyzed urban thermal comfort across Sri Lanka

using a station network. City-scale studies include Wong et al. [39], Yu et al. [40], and Ahmed et al. [41], who monitored UHI trends in Singapore and Putrajaya, Malaysia. In Akure, Nigeria, Balogun [42] used only two stations (urban and airport) to measure UHI intensity, while Amorim and Dubreuil [7] observed daily and seasonal variations in Presidente Prudente, Brazil showing its intensity being more important in tropical context than in temperate. Tropical regions also exhibit unique upper-tropospheric warming patterns linked to UHI. Hung and Shih [43] used surface stations and radiosondes in Taiwan to detect stronger upper-tropospheric warming, particularly between December and March, influenced by both radiative processes and local urban heat effects.

Detailed neighborhood-scale investigations include Yola et al. [44] in Indonesia, which combined multi-point measurements with simulations to study UHI. At the street level, Chow and Roth [45], Acero et al. [46] in Singapore, Sharmin et al. [47] in Dhaka, and Ramakreshnan et al. [48] in Kuala Lumpur measured temperature and humidity to assess UHI and pedestrian comfort.

Innovative micro-scale monitoring has further enriched UHI research in tropical contexts. In Kolkata, Weitz et al. [49] used miniature sensors to capture heat exposure in slums. In Singapore, Ow et al. [50] examined tree shading effects on surface temperatures, while Hwang et al. [51] studied thermal conditions in urban parks, assessing wind speed, air temperature, and mean radiant temperature. Acero et al. [52,

[53] further investigated the thermal performance and solar radiation transmissivity of standalone trees in tropical conditions, demonstrating how tree species and diffuse radiation influence outdoor microclimates.

The key results of these fixed-station studies are summarized in Table 5 in Appendix A. This compilation highlights how UHI intensities vary significantly across tropical cities, depending on local climate (e.g., Aw, Af, Am), urban morphology, and measurement scale. A clear distinction emerges between different tropical climate types. In tropical savanna climates (Aw), such as in Nigeria [42] or Brazil [7], nocturnal UHI intensities often exceed 2–4 °C during the dry season, sometimes reaching up to 7 °C in specific urban morphologies. Conversely, in equatorial rainforest climates (Af), like Singapore [45,54], UHI peaks tend to align with the monsoon period and can be especially pronounced in dense commercial areas. These differences suggest that seasonality plays a more dominant role in Aw climates, where thermal contrasts between wet and dry seasons amplify UHI effects, whereas Af climates exhibit more stable but humidity-amplified UHI patterns, often tied to anthropogenic heat and built density. Several studies reinforce the role of seasonal variation. For instance, Correa et al. [55] found stronger UHI and SUHI intensities during spring and summer in Vitória, Brazil. Similarly, Setiawati et al. [56] observed how vegetation scenarios could mitigate Universal Thermal Climate Index (UTCI) values in Surabaya (−0.84 °C), while paradoxically increasing thermal discomfort in Denpasar and Medan (+3.1 °C), illustrating the complex relationship between climate, urban form, and green infrastructure. Overall, fixed meteorological stations provide a critical long-term view of UHI dynamics. While they require substantial investment and maintenance, their continuous records spanning years or even decades enable researchers to track seasonal and interannual trends. These data are essential not only for quantifying UHI intensity, but also for evaluating the effectiveness of mitigation strategies over time. Moreover, the ability to assess climate-specific UHI responses is particularly valuable in the tropics, where distinct patterns emerge across different Köppen classifications.

3.3. Measured parameters and outdoor thermal comfort

The characterization of UHI effects requires measuring various environmental parameters that influence thermal conditions. Fig. 6 illustrates the distribution of the most common parameters measured in UHI studies. Air temperature (T_{air}) is the most widely studied parameter, followed by relative humidity (RH), surface temperature (T_{surf}), and air velocity (V_{air}). Despite these common measurements, only a few studies have considered additional parameters such as radiation, typically measured using global irradiance (G_i) sensors or the mean radiant temperature (MRT), which accounts for both long-wave and short-wave radiation from all directions. MRT has been measured in some studies [47,50,51,57–59] but remains underused compared to other parameters.

In this review, we distinguish between air temperature, typically recorded at 2–3 m above ground in ventilated shelters, and surface temperature, measured directly on urban surfaces using thermocouples or infrared sensors. While T_{air} reflects ambient thermal conditions relevant to human exposure, T_{surf} provides insight into the storage and emission of heat by materials. Air temperature remains the primary parameter for characterizing UHI intensity. Numerous studies, such as Roth et al. [54], Manik and Syaikat [60], Zhang and Wu [61], Adebayo [62], Teo et al. [63], have focused on air temperature as the main metric for UHI. Additionally, several studies also measure surface temperature to account for the heat retention of materials in the urban environment, as seen in Tso [64], C.T. et al. [65], Maskulrath et al. [66], Amorim et al. [67], Al-ameri et al. [68]. Surface temperature is an important complement to air temperature, adding for a more comprehensive understanding of the heat dynamics within cities.

In addition to temperature, 24 studies have emphasized the importance of humidity in mitigating UHI effects. Studies such as Amorim

[69], Best et al. [70] have incorporated humidity levels into their UHI analysis, acknowledging the significant role that moisture in the air plays in thermal comfort, especially in tropical climates. This approach has allowed researchers to analyze contrasts between wet and dry seasons in terms of humidity and to demonstrate its impact on thermal comfort during the wet season and high humidity rate [42,71].

Similarly, air velocity has been studied in only 13 works including Wong et al. [72], Lindén and Holmér [73], Rajagopalan et al. [74], where the role of ventilation in moderating the impact of UHI has been emphasized.

While air temperature is essential for understanding UHI, it does not fully capture the thermal comfort of urban residents, particularly in tropical environments where other factors, like humidity and solar radiation, can significantly impact human comfort. A more comprehensive approach to UHI studies involves assessing outdoor thermal comfort (OTC), which considers multiple factors, including temperature, humidity, radiation, and air movement. However, only 19 studies in the literature combine UHI analysis with thermal comfort evaluation as illustrated in Fig. 7.

Among the OTC indicators used in UHI studies, Mean Radiant Temperature is one of the most crucial, as it accounts for both long-wave and short-wave radiation from all directions. MRT is essential for calculating more advanced OTC indicators like the Physiological Equivalent Temperature (PET) by Höppe [75], Walther and Goetschel [76], which was applied in studies such as Acero et al. [52], Sun et al. [77], Rajan and Amirtham [78]. The UTCI developed in Jendritzky et al. [79], Bröde [80], another important OTC indicator, has been used in 7 studies, including Setiawati et al. [56], Sun et al. [77], Dutta et al. [81], to assess thermal stress in urban environments.

Other OTC indicators, such as the Standard Effective Temperature (SET), have been used to evaluate UHI and thermal comfort in studies like Huang and Chen [82], while the Thermohygrometric Index (THI) has been employed in Balogun et al. [71], Doan et al. [83]. The Humidex index, which combines temperature and humidity, was used in Obe et al. [84], and the Thom's Discomfort Index (TDI) was applied in Silva et al. [85].

4. UHI characterization: Remote sensing

4.1. Remote sensing techniques for UHI analysis in tropical climates

Remote sensing from satellite and aerial platforms is a valuable tool for analyzing UHI patterns, particularly at large spatial scales. However, in tropical regions, persistent cloud cover, especially during the wet season, can limit the availability and reliability of satellite imagery, particularly for thermal infrared observations. Despite this, early studies by Tso [64], Nichol [86] using Landsat data in Singapore and Kuala Lumpur highlighted how variations in solar azimuth influence surface temperature patterns, underscoring the distinct radiative dynamics of tropical cities. This pioneering work demonstrated that satellite-derived surface temperatures can still serve as useful indicators of daytime UHI intensity, when cloud-free conditions are available.

Today, researchers regularly employ remote sensing tools to investigate SUHI dynamics, leveraging the accessibility and resolution of satellite imagery to analyze urban thermal behavior across diverse tropical cities. Two key satellite systems, Landsat and MODIS, are widely used in SUHI research, each offering unique advantages depending on spatial resolution and temporal coverage. Landsat, with its higher spatial resolution, is well-suited for detailed urban-scale studies but is limited by its 16-day revisit cycle. It enables precise comparisons between urban and rural areas, helping to identify spatial patterns and intensity variations in surface temperatures [87]. MODIS, on the other hand, provides daily coverage at a coarser resolution of approximately 1 km, making it more suitable for regional or national-scale observations [88]. The superior temporal frequency of MODIS data facilitates seasonal and regional SUHI analysis. For instance, Ayanlade

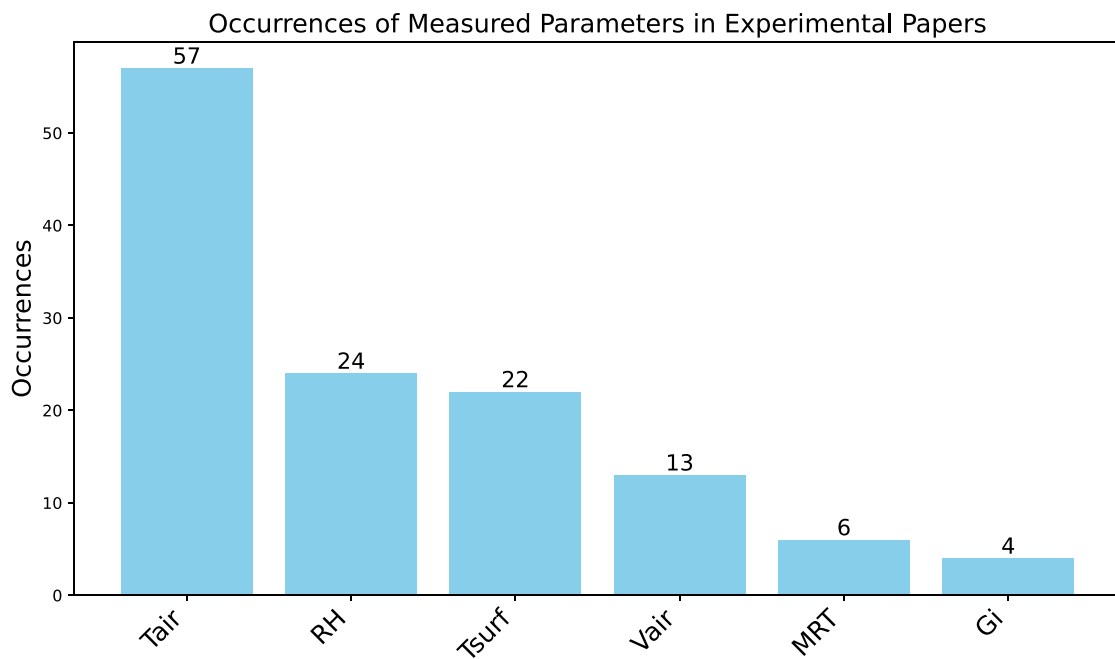


Fig. 6. Occurrences of measured parameters in experimental papers.

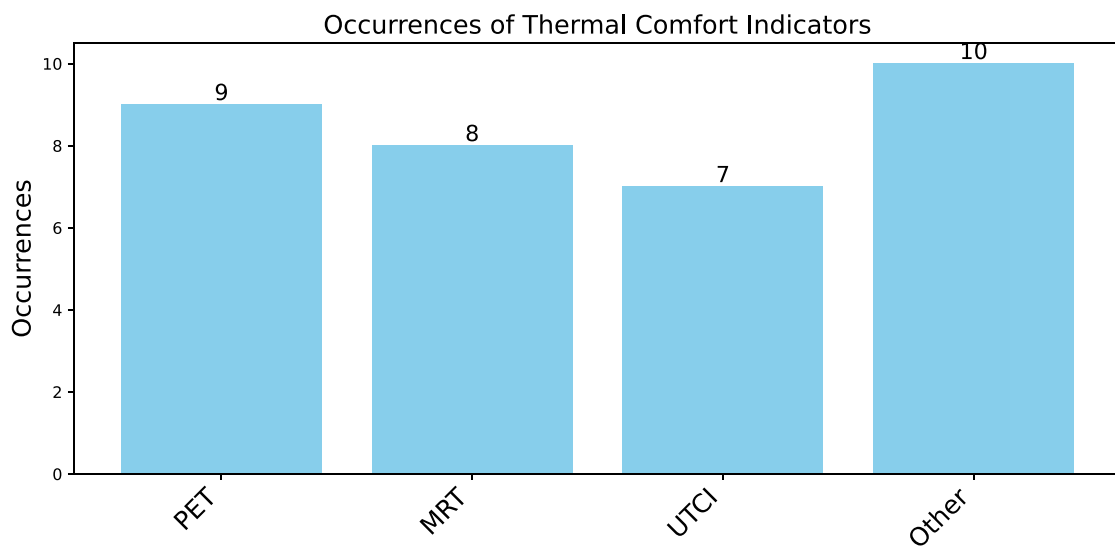


Fig. 7. Occurrences of outdoor thermal comfort indicators used in UHI studies.

[89] analyzed SUHI variations in Lagos, Nigeria, using MODIS data from 2002 to 2013. Their findings revealed stronger surface nighttime UHI intensities during the dry season, emphasizing the role of seasonal fluctuations and the thermo-hydrological contrast between urban and rural areas, particularly when vegetation is dry and cooling capacity is reduced. This aligns with previous work who highlighted the influence of vegetation moisture on early-morning land surface temperature patterns in tropical humid cities [90].

Methodologically, remote sensing combined with GIS has proven invaluable for UHI studies in tropical climates. Research in Malaysia, for example, addressed the challenges posed by frequent cloud cover to improve LST mapping [91].

4.2. Urbanization and land cover changes as UHI drivers

Urbanization and land cover transformation are major drivers of the UHI effect in tropical regions. Rapid population growth and unregulated urban expansion often result in the loss of vegetation and

the proliferation of impervious surfaces, both of which amplify urban temperatures. Numerous studies have documented this phenomenon across tropical cities, revealing substantial increases in LST and UHI intensity over relatively short periods.

In Jakarta, for instance, a 50% decline in green areas between 2000 and 2012 caused a 3.2 °C rise in urban temperatures [92], with similar trends in Lagos [93] and Rio de Janeiro [94]. Accra and Kumasi, Ghana, also exhibited elevated land surface temperatures due to urban sprawl [9,95]. A study on the Bhubaneswar-Cuttack twin cities in India further revealed divergent patterns: while Bhubaneswar maintained localized cooling through vegetation cover, Cuttack experienced stronger UHI effects due to denser urbanization [96]. In Taiwan, land conversion in Tainan between 2007 and 2021 led to a 1.1 °C increase in LST, emphasizing the long-term thermal impact of urban growth [97]. In Nigeria, studies in Lagos [98–100], Ibadan, and Umuahia [101,102] show significant daytime and nighttime UHI increases driven by urban expansion. Similarly, in Southeast Asia, Kota Kinabalu, Malaysia,

Table 2
Comparative summary of impact of urbanization on UHI in tropical cities.

Study	City, Country/Köppen climate	Population size	Period studied	Land cover change	Method used	Δ LST/UHI intensity
Acero and González-Asensio [90]	San Salvador, El Salvador/Aw	2.4 million	2000–2015	Urban expansion	Landsat	+0.5 °C SUHI
Buo et al. [9]	Kumasi, Ghana/Aw	3.0 million	2002–2017	Urban expansion	Landsat	+2.0 °C
Sethi et al. [96]	Bhubaneswar-Cuttack, India/Aw	1.0 million	2001–2020	Urban expansion	MODIS	+0.75 °C SUHI
Satheendran et al. [105]	Kerala, India/Am	0.2 million	1988–2018	+21% built-up	Landsat	+7 °C
Carrillo-Niquete et al. [104]	Merida, Mexico/Aw	1.2 million	2000–2018	–5413 ha vegetation	Landsat	+2.36–3.94 °C
Fashae et al. [101]	Ibadan, Nigeria/Aw	3.6 million	1984–2019	+179 km ² urban	Landsat	+21 °C
Ayanlade and Jegede [98], Bassett et al. [99]	Lagos, Nigeria/Am	14.8 million	1984–2016	+310 km ² built-up	Landsat	+2.3 °C SUHI
Adewale and A [93]	Osogbo, Nigeria/Aw	0.7 million	1986–2015	+51% impervious	Landsat	+4.6 °C
Felix and Ottah [102]	Umuahia, Nigeria/Am	0.4 million	1986–2017	–60% vegetation	Landsat	+4.5 °C
Ranagalage et al. [106]	Kandy City, Sri Lanka/Af	0.13 million	1996–2017	– vegetation, + impervious	Landsat	+2.3 °C

experienced heightened UHI intensity from 1991 to 2018 due to urbanization [103]. Latin America reflects comparable impacts, with San Salvador recording a 0.5 °C SUHI rise from 2000 to 2015 [90], and Mérida, Mexico, experiencing up to 3.94 °C increases from vegetation loss [104]. India's Kerala region and Kandy City, Sri Lanka, also reported intensified thermal environments [105,106]. Kampala, Uganda, offers a unique perspective: although urban land cover doubled from 1995 to 2016, SUHI intensity decreased from 2.2 °C to 1.9 °C by 2017, demonstrating how integrating green spaces can mitigate UHI effects [107,108]. On a broader scale, satellite-based analysis across the African continent showed a sharp increase in nighttime heatwaves from 1981 to 2020, with urbanization being a key contribution [24]. Likewise, a 20-year analysis in Kolkata, India, linked vegetation loss to UHI intensification and emphasized sustainable urban planning [109].

Table 2 provides a comparative summary of selected cities, highlighting their urbanization trajectories, methodological approaches, and observed thermal responses to clarify existing disparities and enhance cross-city comparisons. These examples collectively underscore how urbanization drives UHI intensification in tropical environments, often within just a few decades. However, drawing direct comparisons between cities such as Bhubaneswar and Lagos must be approached cautiously. These cities differ in population size, socio-economic development, urban morphology, and climatic conditions, all of which influence both the trajectory of land cover change and the nature of the UHI response. Additionally, the criteria used to define “urban” and “rural” areas are often study-specific, which can distort UHI estimates. Without standardized assessment frameworks, drawing robust, generalizable conclusions about the relationship between urbanization and UHI across tropical cities remains challenging. To address these limitations, future research should strive to adopt comparable land cover classification schemes and standardized metrics (e.g., surface temperature thresholds or land use typologies), such as the Local Climate Zones (LCZ) framework. This would enhance consistency across studies and allow more reliable cross-city comparisons, as advocated in recent multi-city reviews and comparative UHI assessments [110].

4.3. The role of vegetation in UHI mitigation

In tropical climates, vegetation plays a crucial role in moderating the UHI effect by providing shade, increasing evapotranspiration, and

reducing surface temperatures. Remote sensing studies, such as NDVI analyses in São Paulo and Rio de Janeiro, confirm that green areas significantly lower temperatures in urban settings [111]. Similarly, in Southeast Asia, urban greening is a key strategy for UHI mitigation. In Bangkok, tree planting is recommended to counteract the loss of vegetation due to urbanization [8], while in Ho Chi Minh City, urban parks effectively reduce land surface temperature and mitigate heat stress [112].

The cooling benefits of vegetation are also evident in Indonesia, where research demonstrates that incorporating green infrastructure into urban planning can counteract rising urban temperatures [113]. In South Asia, UHI intensification due to vegetation loss is well-documented. For instance, in Kerala, India, LST increased from 26.5 °C to 28.1 °C between 1988 and 2019, a trend directly linked to urban expansion and declining green cover [114]. Similarly, a recent study of tropical megacities such as Chennai, Dhaka, and Kolkata found that large urban parks and high-albedo surfaces were particularly effective in reducing surface temperatures, emphasizing the importance of both vegetation and material design in UHI mitigation [115].

However, while vegetation is generally associated with cooling effects, it is important to recognize that its thermal benefits are not uniform across all tropical settings. In hot-humid climates, excessive or poorly planned vegetation can sometimes worsen nighttime thermal conditions. This occurs when dense canopies block radiative heat loss to the sky and increase atmospheric moisture levels, potentially intensifying the UHI effect during the night. Moreover, recent studies indicate that standalone trees may have limited impact on air temperature reduction, particularly under tropical conditions with already high humidity and low wind speeds [52]. These complex interactions highlight the importance of climate-sensitive greening strategies that consider not only vegetation type and spatial distribution but also local microclimatic factors such as humidity, cloud cover, and nighttime cooling needs.

Tropical cities face unique challenges in maintaining vegetation due to high population growth, land pressure, and deforestation for urban expansion. Unlike temperate regions, where seasonal temperature variations are more pronounced, tropical cities experience year-round high temperatures, making continuous vegetation cover even more critical for heat mitigation. These considerations will be further discussed in detail in the section dedicated to UHI mitigation solutions Section 6.

4.4. Seasonal variability in UHI intensity

Seasonal changes significantly influence UHI intensity in tropical climates, where rainfall patterns, atmospheric moisture, and vegetation cycles play a central role. In Lagos, Nigeria, nighttime UHI intensity peaks during the dry season due to reduced humidity and lower evapotranspiration rates [89]. Similar seasonal fluctuations are observed in Rayong, Thailand [116], and Kerala, India [105], where variations in vegetation cover during wet and dry periods influence temperature dynamics.

In Latin America, seasonal UHI variations are particularly evident in Brazilian cities. In Brasília, differences in vegetation density and urban morphology affect LST fluctuations throughout the year [117]. Meanwhile, in Presidente Prudente, UHI intensity peaks during the rainy season, illustrating how cloud cover, rainfall, and thermal properties of urban materials interact to shape heat patterns [118]. A study in another Brazilian city found that UHI intensities were highest during the hot, rainy summer, driven by high urban density, building materials, and reduced vegetation cover [119].

Beyond Brazil, similar trends emerge in Central America. In San Salvador, El Salvador, the SUHI intensity increased by 0.5 °C between 2000 and 2015, with a 16 °C amplitude in LST observed during mid-morning warming periods [90]. In Bangkok, Acero et al. [120] demonstrated how urban heat patterns fluctuate across the year, with spatial differences linked to land use and monsoonal influences. In East Africa, a large-scale study in the Horn of Africa revealed that persistent drought conditions and vegetation loss amplify seasonal overheating in urban areas [121]. In Asia, a study of 1449 cities in China found that humid tropical and subtropical regions experience the most intense SUHI during the rainy season, while arid zones exhibit weaker effects due to limited evapotranspiration [26]. Likewise, Mughal et al. [122] investigated the role of sea surface temperature in modulating urban climate in coastal tropical cities, showing that ocean–atmosphere interactions can significantly alter thermal dynamics during wet and dry seasons.

A comparative study of medium-sized cities in continental tropical and temperate climates, including Presidente Prudente (Brazil) and Rennes (France), highlighted fundamental differences in UHI dynamics. Unlike temperate cities, where daily temperature variations are more pronounced, tropical urban environments tend to experience more sustained heat retention, driven not only by consistently warm conditions but also by reduced nocturnal ventilation. The study further revealed that vegetation significantly reduces both air and surface temperatures, particularly at night when atmospheric heat islands are most intense [65].

These findings emphasize the urgent need for urban policies that integrate seasonal climate variability into planning strategies. As tropical cities continue to expand, understanding the seasonal behavior of UHI effects is crucial to developing adaptive measures, such as targeted tree planting campaigns and green infrastructure projects that align with regional climate patterns.

Furthermore, combining data from multiple satellite platforms enhances the ability to evaluate UHI patterns over time. The integration of Landsat and MODIS data allows for a more comprehensive analysis of urban and rural thermal differences [123], while long-term studies in tropical cities worldwide underscore the urgent need for sustainable urban planning strategies to mitigate UHI effects.

5. Modeling the urban heat island in the tropics

Fig. 8 highlights the most commonly employed modeling tools in tropical UHI studies. These tools are categorized into three primary groups: complex thermal simulation tools that incorporate urban canopy models across various scales, simpler empirical and statistical approaches, and emerging machine learning techniques that offer new perspectives on UHI analysis. Table 6 in Appendix B presents a comparative summary of these tools, outlining their scale of application, main outputs, and key advantages, which are discussed in more detail in the following sections.

5.1. Thermal simulation in the urban canopy

As noted in previous review papers [124,125], a wide range of simulation tools exists for modeling urban microclimates and analyzing UHI dynamics. Despite their global applicability, only a limited number of these tools have been specifically developed, validated, or extensively applied in tropical regions. The choice of numerical tools is influenced by the spatial scale of the research, as UHI modeling can be conducted at varying scales, from the city to the building scale.

5.1.1. At the city scale

At the city scale, the Weather Research and Forecasting (WRF) model is the most extensively used numerical tool in tropical studies for evaluating urban climates. Among the studies reviewed, 20 applied WRF at various spatial resolutions depending on the study objectives, often ranging from 1 km down to a few hundred meters. This flexibility makes WRF particularly suitable for mesoscale urban climate simulations [126]. Originally developed by the National Center for Atmospheric Research, WRF is widely used in both research and operational meteorology for simulating key atmospheric variables such as temperature, wind, humidity, and precipitation [127]. When coupled with the Urban Canopy Model (UCM), WRF provides comprehensive insights into UHI dynamics. According to Zhu and Ooka [126], three UCMs are currently integrated into WRF:

1. Single-Layer Urban Canopy Model (SLUCM),
2. Multi-Layer Urban Canopy Model (MLUCM), also referred to as Building Effect Parameterization (BEP),
3. BEP + Building Energy Model (BEP+BEM).

These UCMs enhance urban microclimate analysis by incorporating the interactions between urban structures and atmospheric conditions. Additionally, coupling WRF with the Noah Land Surface Model allows researchers to model interactions between urban surfaces and ecological processes, capturing the effects of vegetation, hydrology, and artificial materials on urban climates.

Unlike temperate regions, tropical cities often undergo unplanned and extensive urban expansion, significantly altering land–atmosphere interactions. WRF has been instrumental in assessing the impacts of rapid urbanization on local climates, particularly on temperature and humidity distribution. Studies in Ho Chi Minh City [83] and Malaysia [128–130] highlight how land-use heterogeneity influences local climate conditions, affecting planetary boundary layer height and sensible heat flux. In India, WRF-based studies in Bhubaneswar [131] and Chennai [132] reveal that urbanization significantly alters boundary-layer dynamics, contributing to localized heating and disrupted wind patterns. Rath et al. [133] further demonstrated that urbanization over Kolkata stimulates boundary-layer development, enhancing localized convection, nighttime UHI, and altering rainfall patterns.

In addition to urban expansion and land cover changes, WRF has been widely employed to study heat stress and extreme weather events, which pose unique challenges in tropical climates. Tropical cities experience year-round high temperatures, making them more vulnerable to compounding heat stress due to climate change and urbanization. High-resolution WRF simulations in Lagos, Nigeria, revealed pronounced spatial variations in heat stress, highlighting the compounded effects of urban expansion and climate change [84]. In the tropical Andes, WRF coupled with chemical transport models assessed air pollution impacts on urban microclimates [134]. Additionally, Chew et al. [135] explored UHI-heatwave interactions, showing that tropical cities, projected to face severe heat stress, require further investigation.

Several studies have utilized WRF to evaluate UHI mitigation strategies in tropical cities. WRF simulations demonstrated that increasing vegetation cover and implementing cool roofs reduce UHI intensity [136–139], while anthropogenic emissions exacerbate urban

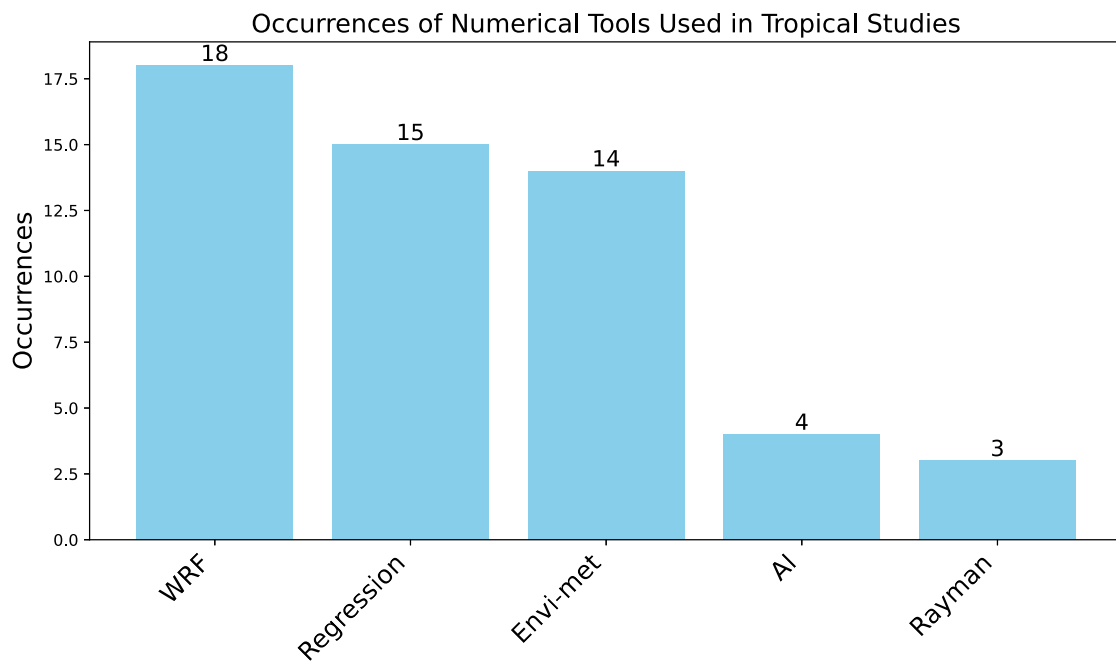


Fig. 8. Occurrences of numerical tools used in UHI studies.

heating [18,140]. Sensitivity analyses of WRF physical schemes optimized urban cooling strategies, such as reflective coatings [141]. Singh et al. [142] found that combining cool roofs, water bodies, and mixed forest patches was most effective in mitigating industrial heat islands in Angul-Talcher, highlighting the need for integrated scientific, economic, and policy considerations.

These findings emphasize that urbanization-induced surface heterogeneity amplifies UHI effects in tropical cities, making expansion a significant risk factor. WRF analyses of heat stress and extreme weather in tropical cities remain understudied compared to temperate regions, underscoring the need for targeted research and adaptation strategies. WRF, particularly when coupled with UCMs and land surface models, provides critical insights into UHI mitigation, urbanization impacts, and extreme weather in tropical environments. Its validated application in Southeast Asia with in situ observations [83] highlights its reliability for climate adaptation planning in rapidly urbanizing tropical cities.

Building on these WRF-based insights, other modeling tools have also been employed at the city scale to further investigate UHI effects in tropical environments characterized by persistent high temperatures and humidity. The Urban Weather Generator (UWG) [143] is one such model, adapted to simulate the complex interactions of urban surfaces and tropical atmospheric conditions. Litardo et al. [144] employed UWG for exploratory UHI simulations in Duran City, Ecuador, where tropical wet climates amplify the intensity of UHI effects. Using clustering techniques and sensitivity analysis, they identified key UHI drivers, particularly in informal settlements with high anthropogenic heat emissions, a common feature in rapidly growing tropical cities. The model's accuracy was validated by comparing simulated urban temperatures with in situ measurements across the city. Additionally, building cooling demands, analyzed using TRNSYS v.17, revealed that UHI significantly increases cooling-related energy consumption by 30%–70% in residential buildings and 10%–20% in commercial buildings, underscoring the severe energy and public health challenges posed by UHI in tropical coastal cities like Duran.

Similarly, the ADMS-Urban model [145] has demonstrated its efficacy in tropical settings by capturing the nuanced dynamics of UHI and outdoor thermal comfort. For instance, Aktas et al. [146] applied ADMS-Urban to evaluate thermal comfort and building energy use potential across various land-use types in Kuala Lumpur. The study

highlighted the model's capability to simulate thermal environments in tropical cities, accounting for local microclimatic interactions and the role of humidity in shaping heat perception.

Further enhancing the suite of models tailored to tropical conditions, the t-TEB model developed by Karam et al. [147], as an extension of the TEB scheme by Masson and V [148], specifically addresses the unique characteristics of tropical urban climates. Marked by high temperatures, intense humidity, and frequent heavy rainfall, tropical environments pose distinct challenges that t-TEB effectively manages through its localized scaling framework. This framework accounts for the pronounced free convection typical of tropical regions, enabling more intense heat diffusion. Additionally, its limited urban drainage system captures the critical factor of water accumulation on city roads, a recurrent issue in tropical cities prone to sudden and heavy downpours. Applied to model the surface energy balance of Rio de Janeiro in 2007, t-TEB demonstrated enhanced accuracy in capturing annual surface variable trends, with results consistently within one standard deviation of observed hourly averages across the metropolitan area.

Expanding beyond mesoscale analyses, some studies focus on localized impacts at the neighborhood scale, providing a more granular understanding of urban microclimates and mitigation strategies. This approach allows for the assessment of highly detailed interventions, such as the coupling of WRF with microclimate modeling tools like Envi-met or PALM-4U [149,150]. For instance, Wai et al. [151] utilized this combination to evaluate the effectiveness of water spraying systems in cooling high-density urban areas. Their study, set in Hong Kong under projected tropical conditions for 2050, offers valuable insights into innovative cooling strategies for densely populated tropical cities, reinforcing the importance of multi-scale modeling in developing tailored climate adaptation measures.

5.1.2. At the neighborhood scale

The neighborhood scale provides a detailed framework for analyzing the impact of urban morphology on UHI intensity. At this level, Computational Fluid Dynamics (CFD) solutions are widely used, offering insights into optimizing urban forms for improved thermal comfort. Adjustments to building heights and spacing, for example, influence prevailing airflow patterns, which can enhance outdoor thermal comfort.

Among CFD tools, Envi-met is the most commonly used model for UHI studies in tropical climates, as shown in Fig. 8, with 14 studies among the reviewed papers employing it. Developed by Bruse and Fleer [152], Envi-met is a three-dimensional, dynamic CFD software specifically designed to simulate the complex interactions between buildings, vegetation, and the atmosphere, particularly within urban canyons. Its foundation on thermodynamics and fluid dynamics, incorporating Navier–Stokes equations with a first-order turbulence model, enables realistic urban microclimate simulations essential for tropical settings where high temperatures, humidity, and dense urban fabrics prevail. For example, Huang and Chen [153] applied Envi-met to explore UHI mitigation strategies in Kaohsiung City, Taiwan, where tropical conditions exacerbate heat retention in built environments. Similarly, Shahidan et al. [154] assessed cooling effects through strategic tree placements and ground material modifications in Malaysia, highlighting the importance of vegetation in mitigating heat in humid tropical cities. In Colombo, Sri Lanka, Herath et al. [155,156] utilized Envi-met to evaluate green infrastructure as an adaptive strategy to urban heat, with model outputs validated against in-situ measurements, demonstrating its reliability in tropical contexts. Additionally, Swamy et al. [21] investigated the interplay between air pollution and UHI intensity in Chennai, revealing that low wind speeds typical of tropical regions (0.2 to 5 m/s) further aggravate UHI effects due to reduced convective cooling. Kotharkar et al. [157] Envi-met was used to test different scenarios solutions (a) Cool roof as a strategy works better for higher urban densities as compared to sparse settlements (b) Greening proves to be very beneficial as a cooling strategy and comfort enhancer at pedestrian level. (c) Vegetation planted along the streets, that is, spread out across the entire area imparts better results than the same amount of vegetation planned in an allocated green area. (d) Greening, though more the better, keeping its applicability in mind, a GAR of 25% is appropriate for an LCZ 9 type growth as it could impart cooling by up to 2.7 °C in the day time. The effectiveness of these interventions, depends upon the urban density and built characteristics of a particular neighborhood and shall be correctly chosen in context to a particular growth. The conclusions drawn from the study could extend an important insight in shaping the growth of other sparse neighborhoods belonging to LCZ 9, a sparse settlement which is developing over the time into LCZ 3 typology.

Envi-met also offers specialized capabilities for analyzing outdoor thermal comfort, which is particularly relevant for studying tropical climates due to its holistic approach that incorporates key factors such as humidity and solar radiation. This feature integrates individual-specific parameters, such as metabolic rates and clothing insulation, to provide key thermal comfort indices. For instance, the UTCI was applied in studies such as Raya et al. [158], which focused on spatial planning in Jakarta's transit-oriented development areas. Similarly, the PET has been widely utilized [34,159] used it to evaluate biomimicry-based urban designs, while Arif and Yola [160] analyzed both Mean Radiant Temperature and PET. Additionally, Chatterjee et al. [12], Acero et al. [161] employed PET in their assessment of outdoor thermal comfort. These indicators, alongside metrics like MRT, highlight the robustness of Envi-met in modeling and interpreting thermal comfort in tropical urban environments.

At the neighborhood scale, additional tools have been employed to study urban microclimates and optimize urban designs, with some models specifically tailored for tropical environments. The STEVE tool [162], an empirical model developed based on tropical urban data from Singapore, is particularly suited for microclimatic analysis in tropical cities. Unlike models designed for temperate regions, STEVE accounts for the persistent high temperatures, humidity, and unique urban morphologies found in tropical areas. It calculates maximum, minimum, and average air temperatures within a 50-meter radius, making it highly effective for detailed thermal assessments in dense tropical urban settings. Ignatius et al. [163] utilized STEVE to explore

how urban texture, including physical density and building form, influences external heat gain, ambient temperature, urban ventilation, and outdoor thermal comfort in Singapore's hot and humid climate. A comparison with Envi-met, conducted by Wong et al. [164], highlighted that STEVE, being calibrated with tropical data, predicted higher and more realistic urban temperatures than Envi-met, which is primarily developed for temperate climates. Simulations of empty land using both tools showed that Envi-met tended to under-predict temperatures by 2–3 °C due to its assumptions based on ideal conditions, while STEVE's predictions, grounded in empirical data from tropical environments, provided a more accurate representation of the thermal realities in tropical cities. This underscores the importance of using models specifically designed for tropical climates to ensure accurate microclimate analysis and effective urban planning in these regions.

Other CFD tools, such as ANSYS Fluent, OpenFOAM, and CRADLE by scSTREAM, have also been applied to study tropical urban microclimates. For instance, Adelia et al. [165] used ANSYS Fluent to analyze the interaction between airflow and heat fluxes emitted by high-rise residential buildings in the tropical context of Singapore, emphasizing how the positioning of heat emission sources and building porosity significantly influence the removal of anthropogenic heat from narrow street canyons, an essential factor in tropical cities where heat dissipation is critical due to persistent high temperatures and humidity. OpenFOAM, employed by Mughal et al. [166], assessed the UTCI and investigated the effects of vegetation on tropical microclimates. While vegetation is often perceived as a cooling solution, this study highlighted that in tropical settings, vegetation can increase ambient humidity and reduce already low wind speeds, both of which are critical parameters for thermal comfort in tropical climates. Additionally, Ill Kim [167] utilized CRADLE by scSTREAM to optimize building forms for natural ventilation in Singapore's tropical office buildings, demonstrating the potential of CFD tools in enhancing both thermal comfort and energy efficiency through climate-responsive design. These CFD tools, tailored to the specific challenges of tropical environments, complement Envi-met by offering alternative approaches for improving microclimatic conditions in tropical urban neighborhoods, where the interplay of heat, humidity, and ventilation is particularly complex and demanding.

Envi-met and other CFD tools offer valuable insights into urban airflow and temperature dynamics. However, a recurring methodological limitation in many CFD studies is the assumption of steady-state inflow boundary conditions. This simplification, though convenient, does not reflect the highly variable wind conditions typical of tropical cities, where gusts, turbulence, and shifting microclimates play a major role in shaping urban ventilation and heat dispersion. To address this gap, more recent studies have proposed the use of time-varying inflow conditions to better capture real-world airflow variability. For instance, Zhang et al. [168] developed a practical methodology to simulate unsteady wind inputs and demonstrated their importance in reproducing realistic airflow patterns within dense urban canyons. These advances underscore the need to move beyond idealized conditions and toward more dynamic CFD modeling approaches in future UHI studies, particularly in complex tropical environments.

5.1.3. At the building scale

At the microscale, tools such as Rayman are commonly utilized to study radiative exchanges and microclimates at the individual level, particularly in tropical urban environments where intense solar radiation is a predominant factor influencing thermal discomfort. Rayman is particularly effective for quantifying outdoor thermal comfort indicators such as MRT by accurately capturing the impact of solar exposure, a critical aspect in tropical climates.

In tropical regions, Rayman has been employed to highlight the significant influence of solar radiation on outdoor thermal comfort. In Cuba, guez Algeciras et al. [169] demonstrated that courtyard aspect ratios and orientations directly affect thermal conditions due to

high solar irradiance, showing that designing courtyards with aspect ratios between 1 and 3 enhances ventilation and minimizes solar heat accumulation. This design strategy reduced MRT by up to 15.7 °C when avoiding East-West orientations, underlining the importance of solar management in tropical settings. In Hong Kong, Fung and Jim [170] used Rayman to evaluate PET, emphasizing that tree configurations provide crucial shading and mitigate the intense tropical solar radiation, thereby enhancing outdoor comfort. Similarly, Simath and Emmanuel [27] in Colombo, Sri Lanka, highlighted that combining natural ventilation with strategic vegetation placement is essential in managing high solar radiation and maintaining thermal comfort. Arif and Yola [160] in Jakarta further illustrated that optimizing the Sky View Factor (SVF) to increase shading effectively reduces MRT and PET, demonstrating Rayman's capacity to address the unique challenge of solar radiation management in tropical urban environments.

Another radiative model, DART (Discrete Anisotropic Radiative Transfer), has been applied to investigate the interaction between vegetation and urban radiative budgets specifically designed for the tropical climate of Singapore. For instance, Dissegna et al. [171] utilized DART to reconstruct a 3D urban landscape and analyze how varying leaf area density influences the radiation absorbed by urban surfaces. This work was further validated through field measurements in Dissegna et al. [172], demonstrating the model's accuracy in simulating the effects of vegetation on urban radiation balance in the tropical context of Singapore.

EnergyPlus has also been employed in microscale studies to assess building-level interventions for mitigating UHI, particularly in tropical climates where solar radiation plays a key role. In Singapore, Yang et al. [173] used EnergyPlus to evaluate green and cool roofs, showing that while green roofs help mitigate UHI, their performance is influenced by high moisture levels due to frequent tropical rains. Cool roofs, however, offered higher mitigation potential by reflecting solar radiation without adding latent heat from evapotranspiration, making them more suitable for Singapore's tropical conditions. Similarly, Koranteng et al. [174] demonstrated the thermal efficiency of green roofs in Ghana's tropical climate, highlighting EnergyPlus's robustness in simulating building thermal performance under high solar irradiance and humidity.

These tools highlight the importance of microscale modeling in understanding the interplay between building design, vegetation, and radiative dynamics. However, while Envi-met is widely used for outdoor microclimate simulations in tropical settings, it is rarely coupled with building energy simulation tools to assess indoor-outdoor thermal dynamics. However, such coupling is essential for integrated assessments of UHI mitigation strategies, particularly in dense tropical urban environments where outdoor conditions directly impact cooling energy demand. For example, Lauzet et al. [175] propose a chaining method that links Envi-met outputs to EnergyPlus inputs, allowing a detailed evaluation of how microclimatic conditions, such as solar radiation, wind, and surface temperatures, affect building thermal loads. Moreover models like PALM-4U have integrated urban canopy, building energy, and atmospheric dynamics into a single framework [176,177]. This type of model integration remains largely underexplored in tropical UHI studies, despite its potential to inform both architectural design and energy-efficient urban planning. Future research should explore such hybrid modeling frameworks to better capture the complex interactions between urban form, vegetation, and building energy use in tropical climates.

5.2. Empirical and statistical models

Beyond specialized thermal simulation tools, empirical or statistical models have been developed to locally predict thermal comfort or UHI effects, particularly in tropical contexts. These models leverage observed data and statistical techniques, such as regression analysis, to establish relationships between urban parameters and microclimatic outcomes.

In Singapore, several studies have explored such approaches. For instance, Richards et al. [178] investigated the differential cooling performance of various urban vegetation types, highlighting their impact on localized air temperatures. Similarly, Jin et al. [179] assessed the effects of urban morphology parameters, such as building density and height, on microclimate regulation, identifying strategies to control UHI. Additionally, Yu et al. [40] conducted a temporal analysis of urban morphology's influence on outdoor air temperatures, using a campus as a case study, to highlight the evolving impact of urban design over time.

In India, empirical models have also been widely applied. Khan and Chatterjee [180] utilized data from 25 field observation sites in Kolkata, combining numerical simulations with observational data to analyze UHI intensity across urban and suburban surfaces. Similarly, Das et al. [181] quantified the cooling effect of urban green spaces in a tropical metropolitan area, employing correlation and regression analysis to examine the relationship between greenness parameters and thermal conditions. Additionally, Mohammad and Goswami [182] used multiple linear regression to explain the diurnal and seasonal variation of Surface UHI intensity across Indian cities, incorporating remote sensing data to identify the determinants of these variations.

Empirical approaches have also been applied outside Asia. In Merida, Mexico, Palafox-Juárez et al. [183] used regression analysis to explain the relationship between Land Surface Temperature and the NDVI, demonstrating a positive correlation. Similarly, in Kampala, Uganda, Kabano et al. [184] utilized regression analysis to investigate the spatiotemporal dynamics of temperature, humidity, and heat index during the wet-dry season transition, providing valuable insights into the city's urban climate.

These empirical and statistical models offer cost-effective and adaptable methods for understanding and managing urban microclimatic challenges, complementing simulation-based approaches in tropical environments.

5.3. Machine learning approach

Although still emerging in the field, machine learning and deep learning methods are being increasingly employed to model microclimates and UHI effects. In this review, only four studies utilized machine learning approaches to address these challenges, highlighting their growing but limited adoption in tropical urban studies. Mohite and Surawar [185] employed a Random Forest Regressor to predict thermal comfort in Nagpur, India, leveraging the Rayman model to evaluate microclimatic conditions. This approach demonstrated the utility of machine learning in accurately modeling complex thermal comfort parameters based on diverse environmental inputs. In Hong Kong and Singapore, Jia et al. [186] adopted a hybrid method combining Geographically Weighted Regression and Deep Neural Networks. This multiscale approach explored the relationships between green infrastructure cooling effects and their influencing factors at the district level, providing insights into green solutions for urban climate mitigation. Zhou et al. [187] applied a Genetic Algorithm in Sanya, China, to optimize urban green space layout. By integrating field data into the optimization process, this study demonstrated how machine learning can enhance decision-making in urban planning to reduce UHI intensity effectively. Lastly, Garzón et al. [188] utilized a remote sensing approach combined with machine learning algorithms to model Surface UHI in a tropical Colombian city. This study highlighted the potential of regression analysis and machine learning in analyzing remote sensing data to predict and manage UHI patterns. These applications underscore the potential of machine learning to complement traditional simulation and statistical methods, offering novel ways to model and mitigate microclimatic issues in tropical urban contexts.

5.4. From simulation to implementation

The modeling approaches discussed in this review, from mesoscale simulations to neighborhood-scale CFD models and microscale tools, not only provide insights into the physical processes underlying UHI, but also serve as decision-support tools for testing and optimizing mitigation strategies before they are implemented in real environments. Indeed, many of the studies employing numerical models do so with the explicit goal of evaluating the effectiveness of various UHI countermeasures under realistic tropical conditions. For instance, Envi-met, WRF-UCMs, and EnergyPlus are frequently used to simulate the thermal impacts of vegetation, cool roofs, or urban design modifications, enabling researchers and urban planners to anticipate the cooling effects of proposed interventions and assess their cost-effectiveness, scalability, or limitations. Model outputs, such as localized temperature reductions or changes in thermal comfort indices, offer a powerful means of translating theoretical mitigation strategies into context-specific, evidence-based urban planning decisions. In tropical cities, where rapid urbanization often outpaces climate adaptation, the ability to test solutions virtually is a crucial asset for proactive and sustainable UHI management.

6. Solutions to mitigate urban heat islands

A significant portion of the reviewed studies, accounting for 43 of the total papers, focuses on testing solutions to mitigate UHI, particularly in tropical climates. These solutions are primarily implemented at the microscale, such as at the level of individual buildings or streets, and involve the validation of interventions tailored to tropical contexts. Four main categories of mitigation measures emerge from these studies: green solutions, blue solutions, gray solutions and reducing Anthropogenic Heat (AH). Blue and green solutions are collectively referred to as Nature-Based Solutions (NBS), as they leverage ecological processes to improve thermal comfort and urban resilience. In contrast, gray solutions often involve technological or structural interventions such as high-albedo materials, cool pavements, reflective paints, or urban morphology optimization. Some solutions also include measures to reduce anthropogenic heat emissions, such as promoting public transport, electrification of mobility, improving building insulation, and optimizing the use of air conditioning systems. Building on the modeling approaches discussed in the previous section, which provide essential insights into the effectiveness and feasibility of UHI mitigation strategies, this section reviews real-world interventions tested or proposed in tropical urban contexts. Many of these strategies have been evaluated using simulation tools, reinforcing the role of modeling in bridging scientific research and practical urban climate adaptation.

6.1. Green solutions: Vegetation-based interventions

In tropical climates, vegetation remains active year-round, particularly in humid equatorial zones (Af), where dense foliage provides continuous shading and cooling. This natural advantage makes vegetation-based strategies highly effective for mitigating UHI effects by reducing the amount of solar radiation absorbed by urban surfaces and enhancing cooling through evapotranspiration. However, this mechanism can be limited under conditions of extreme heat or drought, when stomatal closure in plants restricts transpiration to conserve water, thus reducing cooling efficiency [52,189].

Moreover, in these climates, the high levels of precipitation and humidity generally facilitate the maintenance of urban greenery, making it a sustainable and relatively low-cost intervention compared to other cooling strategies. Yet, seasonal rainfall variability also influences thermal comfort in parks, as shown by Acero et al. [190], who found that rain events impact air temperature and humidity levels, modifying the microclimatic benefits of urban green spaces.

Green solutions include street trees, urban parks, green roofs, and vertical greening systems, each contributing differently to UHI mitigation. Studies have shown that green roofs, extensively analyzed in tropical cities, can significantly reduce surface and air temperatures [23,173,174,191,192]. Similarly, Rupasinghe and Halwatura [193] demonstrated that vertical greening systems in Sri Lanka could lower surface temperatures effectively, while Ruiz-Valero et al. [194] confirmed the cooling potential of living walls in the Dominican Republic. However, in highly humid environments, challenges such as plant maintenance and structural durability must be addressed to ensure long-term efficiency.

Beyond buildings, urban green spaces and street trees play a fundamental role in regulating temperatures. In Singapore, Richards and Edwards [195] assessed the cooling impact of street trees using Google Street View, demonstrating their contribution to thermal comfort. The importance of species selection was further highlighted in recent studies by Acero et al. [52,53], which evaluated the performance of different tree types under tropical conditions. These works emphasize how leaf transmissivity and diffuse radiation affect thermal regulation in tropical urban parks. Additionally, Tan et al. [196] examined ten plant species for their effectiveness in UHI mitigation, providing valuable insights for species selection in tropical cities. Large-scale green space configurations were also studied by Li et al. [197], revealing optimal layouts for urban cooling in tropical megacities such as Dhaka, Kolkata, and Bangkok. The importance of private gardens was highlighted by Silveira et al. [198], while Anak Kemarau [199] showed a strong correlation between urban green space coverage and reduced land surface temperatures in Malaysia.

Urban design models integrating vegetation have further demonstrated their potential in dense tropical environments. The “shadow umbrella” concept proposed by Emmanuel [200] illustrates how tree canopies and green structures can enhance thermal comfort in high-density tropical cities. In Kuala Lumpur, Harun et al. [201] analyzed urban vegetation patches and confirmed their effectiveness in reducing local temperatures through a combination of shading and evapotranspiration. However, in the case of isolated or standalone trees, recent field measurements indicate that their temperature-reduction effect may be minimal, particularly under tropical weather conditions [52]. Meanwhile, Irvine et al. [202] introduced the Agrihood concept in Bangkok, which integrates urban greenery with food production and ecosystem services, contributing to both cooling and biodiversity conservation.

The case studies in Table 3 illustrate the diverse range of vegetation-based interventions applied in tropical settings, from rooftop greening to urban forests. Notably, the cooling effects reported are often substantial, some exceeding 10 °C in surface temperature reduction, especially where vegetation is dense, strategically located, and well maintained. Nonetheless, these impacts can vary significantly depending on plant physiological traits and local microclimatic conditions.

However, the implementation of certain vegetation-based strategies faces challenges in drier tropical climates (Aw, As), where pronounced dry seasons limit plant survival without supplementary irrigation. For example, vertical greenery systems (VGS) may face specific difficulties in tropical climates due to extreme weather conditions, as noted by Senalankadhikara et al. [203], Acero et al. [204]. Their successful implementation requires careful material selection, interdisciplinary maintenance strategies, and continuous technological adaptation to ensure their long-term viability in tropical urban landscapes. In such regions, alternative mitigation approaches, such as blue (water-based) and gray (built infrastructure) solutions, may be required to complement vegetation-based cooling efforts.

6.2. Blue solutions: Water-based interventions

Blue solutions leverage water features such as lakes, fountains, and wetlands to mitigate urban heat by converting sensible heat into latent heat through processes like evaporation. Studies have demonstrated

Table 3
Summary of vegetation-based UHI mitigation strategies in tropical cities.

Study	City, Country/Köppen	Green solution	Scale	Method	Cooling effect	Main findings/notes
Koranteng et al. [174]	Kumasi, Ghana/Aw	Green roofs	Building	EnergyPlus simulation	-1.5 °C (indoor)	Larger Leaf Area Index and deeper soil improve cooling efficiency.
Pragati et al. [23]	Chennai, India/As	Green roofs and walls	Building	DesignBuilder simulation	-10.5% energy; -13% cooling demand	Urban greenery improves comfort and reduces building energy use.
Rupasinghe and Halwatura [193]	Moratuwa, Sri Lanka/Af	Vertical greening systems	Building	Field + simulation	-10.16 °C (surface), -2.11 °C (indoor)	Living walls + <i>Axonopus compressus</i> plant effective; maintenance critical.
Ruiz-Valero et al. [194]	Santo Domingo, Dominican Rep./Aw	Living wall system	Façade	Field measurements	-5.3 °C (air), -3.3 °C (day)	lowers outdoor air temperature during hot months.
Richards et al. [178]	Singapore/Af	Urban vegetation (trees, shrubs)	Neighborhood	Monitoring + modeling	Varies (max in secondary forest)	Secondary forest provides best air temperature reduction.
Tan et al. [196]	Singapore/Af	Turf, shrubs, climbers	Rooftop	Infrared thermography	-11 °C vs. artificial materials	Shade plays a critical role; plants cool more than materials.
Li et al. [197]	Dhaka, Kolkata, Bangkok/Aw	Urban green space	City	Remote sensing (MODIS)	-4.83 °C to -8.07 °C	Optimal park size: 0.37-0.77 ha; shape and NDVI influence cooling.
Silveira et al. [198]	Rio de Janeiro, Brazil/Aw	Private gardens	Parcel	Spatial analysis	Not quantified	Spatial configuration of gardens influences UHI mitigation.
Harun et al. [201]	Kuala Lumpur, Malaysia/Af	Mixed vegetation & water	Urban patch	Field observations	-6 °C (night), -4 °C (day cool island)	Vegetation and water combined most effective at night.
Irvine et al. [202]	Bangkok, Thailand/Aw	Agrihood (green + food production)	Peri-urban	Ecosystem valuation	Not quantified	Integrates urban greenery with food systems and resilience.

the cooling potential of urban water bodies in tropical contexts. For instance, research by Le Phuc et al. [205] showed that urban lakes in Hue, Thailand, act as cooling islands, significantly reducing surrounding temperatures. Similarly, Kemarau and Eboy [206] highlighted the role of wetlands in lowering land surface temperatures in tropical climates, emphasizing their importance in mitigating urban heat effects. Comparative analyses have also explored the relative effectiveness of water features and vegetation. In Malaysia, the garden city concept was evaluated by Morris et al. [139], revealing that vegetated areas generally provided greater cooling effects compared to waterbodies. However, waterbodies were found to contribute to localized warming during certain times of the day, particularly in the mornings and evenings, underscoring the nuanced impact of water features on urban microclimates in tropical settings with already high level of humidity.

6.3. Gray solutions: Material-based interventions

Material-based strategies play a crucial role in mitigating UHI by enhancing surface reflectivity, optimizing thermal resistance, and improving water retention. These solutions are based on several principles: improving solar reflectance and increasing albedo, reducing thermal accumulation, and enhancing water evaporation at the surface. The goal is to promote the use of “cool” or “heat-reflective” materials for pavements, rooftops, and façades to reduce urban overheating and, consequently, the intensity of UHI [207,208].

In the tropical context, these strategies are particularly relevant because of the consistently high solar radiation, elevated ambient temperatures, and often high humidity levels. Materials tested in tropical climates must demonstrate not only high thermal performance but also durability under intense solar exposure, heavy rainfall, and moisture. Moreover, the year-round heat load in tropical cities makes passive cooling approaches – such as reflective surfaces and thermally resistant construction materials – an essential component of climate-sensitive urban design. Table 4 provides a comparative overview of recent studies evaluating gray UHI mitigation strategies specifically designed or tested in tropical environments. These include innovative coatings, reflective pavements, insulating construction materials, and passive cooling roofing systems. By focusing on real-world conditions and region-specific challenges, these interventions demonstrate direct applicability and replicability in other tropical urban contexts.

In Malaysia, experimental studies demonstrated the effectiveness of waste tile aggregate coatings in improving the thermal performance of cool pavements [209,215]. High-albedo paints, such as barium sulfate

and calcium carbonate-based coatings, have also been shown to provide subambient cooling in tropical conditions [210]. Similarly, Malet-Damour et al. [216] evaluated the effectiveness of a nano-structured ceramic coating applied to rooftops, showing a surface temperature reduction of over 50 °C compared to conventional materials, and a heat flux attenuation of more than 70%. A full-scale experiment in Singapore further highlighted the role of cool surface materials in regulating urban microclimates [211].

Building envelope materials significantly influence UHI intensity. In Bandung, Indonesia, an analysis of common construction materials, including brick, aerated concrete, insulated wood, and reinforced concrete, revealed their varying thermal properties and impacts on heat accumulation [212]. Innovative solutions, such as the “Pakis-Stem Blocks” system, offer additional benefits by utilizing convective airflow for passive cooling, making them well-suited for tropical urban environments [213].

Pavement materials also contribute to UHI dynamics, with color and texture playing key roles in surface temperature regulation. A study in a tropical climate assessed 27 pavement setups, showing that gray and red pavers maintained surface temperatures 4.2–4.5 °C lower than black pavers during peak hours. Additionally, smoother textures retained less heat, with red jagged pavers achieving the lowest recorded surface temperature of 42.9 °C [214]. These findings highlight the potential for optimized pavement design to reduce urban heat stress with specific solutions tested in tropical environment.

6.4. Reducing anthropogenic heat through transport and energy transitions

While material-based solutions target passive control of surface heat gain, reducing AH emissions is another critical dimension of UHI mitigation. Key sources of AH include building cooling systems, industrial activity, and especially road transport.

In tropical cities, the widespread use of private vehicles equipped with air conditioning results in a dual heat burden: waste heat is released directly into the urban environment, and energy demand increases at the grid level. The impact of such emissions was quantified in Singapore by Singh et al. [217], who found that road transportation and power generation significantly contribute to local UHI intensification. To mitigate this, recent studies have investigated the potential of electrifying vehicle fleets. Electric vehicles (EVs) produce less waste heat during operation, particularly when powered by cleaner electricity sources. A modeling study in Singapore showed that widespread EV adoption could moderately reduce urban temperatures and help alleviate UHI effects, especially in dense traffic corridors [218]. These

Table 4
Summary of material-based UHI mitigation strategies in tropical cities.

Study	Location/Köppen	Material solution	Scale	Method	Cooling effect	Main findings/notes
Anting et al. [209]	Johor Bahru, Malaysia/Af	Cool pavement using waste tile aggregates	Street surface	Outdoor experiment (14 days)	-6.4 °C (FBP), -4.3 °C (PG)	FBP and Monoporosa tiles had best thermal reduction; PG less effective
Joseph et al. [210]	Kuala Lumpur, Malaysia/Af	High-albedo paints	Building materials	Lab + field tests	Subambient cooling	Reflective paints reduce heat gain and energy demand in tropical conditions
Donthu et al. [211]	Singapore/Af	Cool surfaces on roofs, walls, and pavements	Street canyon	Full-scale field experiment	-2 °C (air), -1.5 °C (UTCI)	Cool-coated canyon lowered ambient temp and improved pedestrian comfort
Wonorahardjo et al. [212]	Bandung, Indonesia/Am	Wall materials: brick, aerated concrete, insulated composites	Building envelope	Lab + Energy2D simulation	ΔT indoor: 0.32 °C	Insulated sandwich walls limited heat gain better than massive wall types
Mintorogo and Ahmad [213]	Surabaya, Indonesia/Aw	Pakis-Stem Block roofing system	Rooftop	Conceptual + testing	Not quantified	Convective airflow + eco-materials reduce rooftop heat passively
Senevirathne et al. [214]	Moratuwa, Sri Lanka/Af	Colored	textured concrete pavers	Pavement surface	Field experiment (27 setups)	Up to -4.5 °C (gray/red vs. black)

findings highlight the dual benefit of EVs in tropical contexts: lowering greenhouse gas emissions and mitigating near-surface heat accumulation due to reduced localized AH.

Thus, alongside gray infrastructure and passive cooling materials, transitioning to low-emission mobility and reducing AH at its source is an important, yet often overlooked, component of UHI mitigation strategies in tropical cities.

7. Discussion and future perspectives

UHI research has rapidly expanded over the past two decades, yet tropical climates, characterized by persistent warmth, high humidity, and monsoonal dynamics, remain comparatively underexplored and often treated with tools or methodologies designed for temperate regions. While UHI intensities can indeed be high globally, the mechanisms, seasonal expressions, and human impacts in the tropics are distinct. Notably, substantial heterogeneity exists within tropical zones themselves: equatorial rainforest climates (Af), tropical savanna (Aw), and tropical monsoon (Am) exhibit divergent thermal behaviors, influencing both the formation and mitigation of UHIs. This section highlights priorities for advancing UHI research in diverse tropical settings.

7.1. Expanding research to understudied tropical cities

Despite the prevalence of UHI research in tropical cities, its geographic distribution remains heavily skewed toward highly instrumented, affluent urban centers, particularly in Af climates, such as Singapore and Kuala Lumpur. This concentration limits the generalizability of findings across the broader tropical belt. By contrast, smaller and mid-sized cities in Aw (tropical savanna) and Am (monsoon) climates, such as those in West Africa, parts of India, or coastal Latin America, remain significantly underrepresented [36], even though Aw is the most widespread tropical climate type globally in terms of land area.

This imbalance is problematic because the seasonality and thermal regimes differ substantially across tropical subtypes. In Aw climates, intense dry seasons lead to strong daytime surface heating and pronounced nocturnal UHI peaks, particularly in low-rise, sprawling cities with limited vegetation [7,42]. In contrast, Af climates often exhibit more stable diurnal temperature ranges, but urban heat stress is amplified by persistently high humidity and reduced nocturnal ventilation due to weak winds and dense built environments. Am climates fall between these extremes: their monsoonal rainfall reduces UHI in wet months but intensifies it in dry periods when evapotranspiration is suppressed.

Such climatic distinctions directly influence the timing, magnitude, and health impacts of UHI in the tropics. Failing to account for them, by aggregating all tropical cities under a single category, risks developing mitigation strategies that are either ineffective or counterproductive. Expanding UHI studies to better represent Aw and Am regions is therefore not only a matter of spatial equity but also of scientific accuracy.

7.2. Climatic differentiation in experimental design

The choice of observation methods and interpretation of results must be contextualized within the specific tropical climate zone. In Af cities, where humidity rarely drops below 70% and vegetation persists year-round, surface temperatures alone often underestimate human heat exposure, emphasizing the need for radiation and humidity, sensitive indices like UTCI or PET. Conversely, in Aw settings, rapid surface drying during the dry season causes higher ground-level heat storage and stronger UHI contrasts between urban and rural zones. Fixed measurements in these cities capture strong diurnal and seasonal amplitudes, but may miss micro-spatial variability exacerbated by informal settlement patterns.

Therefore, field methods should be tailored to each tropical subtype's thermal behavior. Studies in Am climates, such as coastal India or parts of Southeast Asia, must also account for shifting wind patterns and seasonal albedo changes due to monsoon precipitation. Very few experimental studies currently do so explicitly, resulting in inconsistent data comparability across regions.

A combined approach, integrating fixed and mobile measurement techniques, should be prioritized to increase both temporal depth and spatial resolution across tropical climate zones. Fixed stations provide essential long-term data for tracking UHI evolution, while mobile transects offer fine-scale spatial insights into intra-urban variability. Together, these methods enable a more robust understanding of UHI dynamics in tropical cities and should be systematically deployed across Af, Am, As and Aw zones to support comparative and context-specific urban climate research [34,219].

7.3. A holistic approach to experimental UHI studies

Most experimental UHI studies in tropical regions focus primarily on air temperature, often neglecting key microclimatic parameters such as humidity, wind speed, radiation, and Mean Radiant Temperature, all of which significantly influence outdoor thermal comfort. Given the high humidity and intense solar radiation typical of tropical cities, temperature-based assessments alone fail to capture the full extent of urban heat stress [220]. While UHI effects are often most pronounced at night, OTC concerns tend to peak during the day when high temperatures and strong sunlight exacerbate discomfort. Despite the growing use of OTC indicators, studies rarely measure all critical parameters simultaneously, limiting the accuracy of urban climate analyses. To develop effective mitigation strategies and better understand UHI impacts on human well-being, future research should adopt a more holistic approach, integrating metrics such as Mean Radiant Temperature, PET, and UTCI or Outdoor Thermal Comfort Autonomy (OTCA) [221] which allows for more climate-responsive urban design evaluations. Such approaches have been successfully applied in tropical cities like Singapore, where outdoor thermal comfort has been modeled in complex high-rise environments [161]. These expanded metrics are essential for

accurately capturing both daytime discomfort and nighttime heat stress under tropical conditions.

Low-cost meteorological sensor networks present an opportunity to overcome the financial constraints often associated with experimental research. Despite their affordability, these networks remain underutilized in tropical settings [222–224]. Expanding these systems with high-resolution sensors could enhance data collection efforts, enabling more precise microclimate modeling. Additionally, standardizing methodologies [14,225] is crucial for enhancing data comparability and fostering cross-regional analyses. In this context, the adoption of low-cost and wearable sensing technologies, such as miniaturized loggers and personal microclimate trackers [226–228] offers promising solutions for widening data collection in underrepresented regions, particularly in tropical Africa or small island states where scientific resources are scarce. Wearable devices enable individual-level exposure assessments and can support mobile transect studies with real-time, high-frequency data across diverse urban morphologies. These compact systems are particularly valuable for capturing pedestrian-scale variations in thermal stress and can be deployed with minimal infrastructure, making them suitable for resource-constrained contexts. Their integration into citizen science initiatives or community-based monitoring could further democratize climate data collection while enhancing public engagement.

Another critical yet often overlooked factor in tropical UHI studies is anthropogenic heat emissions. Air conditioning, a dominant cooling strategy in tropical cities, paradoxically exacerbates UHI effects by releasing excess heat into the urban environment, creating a self-reinforcing feedback loop [229,230]. Despite its significance, only few studies in the reviewed literature explicitly examined AH contributions [217,218]. Given the increasing reliance on air conditioning and motorized transport in tropical regions, further research is needed to quantify AH emissions across diverse urban settings. Incorporating anthropogenic heat sources into UHI models would provide a more comprehensive understanding of urban heating dynamics and support the development of more effective, climate-adapted mitigation strategies [18,145].

7.4. Advancing numerical modeling for tropical contexts

While numerous numerical models have been developed for UHI simulation, their applicability to tropical climates remains limited. Most of these tools, such as Envi-met, were originally calibrated for temperate environments and often fail to capture the distinct heat and moisture dynamics found in tropical cities. In equatorial rainforest climates (Af), for instance, high humidity and persistent evapotranspiration are frequently underrepresented, while in tropical savanna (Aw) and monsoon (Am) zones, models struggle to replicate the pronounced seasonality of surface heat fluxes and soil moisture. Tropical-specific models such as t-TEB [147] have begun addressing these issues, but their application remains rare and typically restricted to case studies in a single city or climate zone. Overall, large-scale experimental validation of urban climate models in tropical settings is still lacking, especially under extreme conditions of solar radiation, convective activity, and anthropogenic heat emissions. As is commonly done in temperate contexts, tropical UHI modeling would benefit from systematic calibration against field measurements, tailored to each climatic subtype (Af, Aw, Am), to improve accuracy and support the development of context-appropriate mitigation strategies.

Additionally, artificial intelligence and machine learning approaches, though increasingly used for UHI prediction, remain largely adapted to temperate climates [231]. Existing AI models struggle to account for the distinct urban microclimate interactions present in tropical environments, such as reduced nocturnal cooling due to lower wind speeds [145]. Developing machine learning models trained on tropical-specific datasets could significantly improve predictive capabilities and support data-driven urban planning decisions.

Hybrid modeling approaches, which integrate AI with traditional numerical simulations, offer promising avenues for improving UHI research in tropical settings. However, their effectiveness hinges on the availability of high-quality, standardized data. Given the rapid urbanization in Southeast Asia, where UHI intensification is projected to increase urban temperatures by up to 4 °C by 2050 [232], investing in robust data acquisition frameworks will be critical for advancing UHI modeling efforts.

7.5. Study scales and their implications for urban planning

In tropical cities understanding the UHI effect requires methodological approaches tailored to both climatic and urban realities. However, most existing studies are still conducted at broad spatial scales (city-wide or regional), relying predominantly on satellite-based remote sensing or sparse in-situ measurements with urban-rural station comparisons. While useful for detecting macro-level heat patterns, these approaches often overlook the pronounced microclimatic variability that exists within tropical urban fabrics.

Remote sensing technologies, such as MODIS and Landsat, have been instrumental in capturing land surface temperature and urban land cover changes in tropical regions. Yet, their limitations make them poorly suited for analyzing short-term diurnal variability, which is critical in the tropics where cloud cover and heat exposure fluctuate rapidly throughout the day [233]. Moreover, satellite-derived surface temperatures do not necessarily correspond to human thermal exposure at the pedestrian level, especially in heterogeneous environments such as informal settlements or vegetated zones.

To address these limitations, multi-scale strategies are urgently needed. Integrating remote sensing with fine-resolution in-situ air temperature monitoring, CFD simulations, and microclimate models can offer a more accurate picture of UHI intensity and outdoor thermal comfort [161]. This is particularly important in tropical cities, where localized phenomena such as vegetation evapotranspiration, anthropogenic heat release, and low wind speeds play a disproportionately large role in shaping thermal conditions.

Neighborhood-scale studies are especially relevant for evaluating targeted interventions such as green roofs, reflective surfaces, street shading, and water-based cooling systems [154]. Yet, such studies remain extremely limited, as evidenced by the fact that only seven reviewed papers employed mobile measurements, underscoring the broader lack of fine-scale spatial analysis of urban climate in tropical regions. While more resource-intensive, such fine-scale investigations can directly inform urban design policies adapted to tropical microclimates. However, this level of analysis remains rare in many tropical regions, most notably in tropical Africa.

In African cities within Aw climates, where population growth and unplanned urban expansion are accelerating, UHI research remains largely confined to coarse-scale remote sensing [65]. There is a lack of detailed thermal characterization in dense urban districts, particularly informal or peripheral neighborhoods where vulnerability to heat is highest. This underrepresentation significantly hinders efforts to design effective, equitable cooling strategies. Expanding microclimate-focused research in these regions, through mobile transects, sensor networks, CFD modeling, or participatory sensing, represents a critical avenue for advancing climate-responsive urban design.

Incorporating socioeconomic variables [25] and local urban morphologies into both remote sensing analyses and microclimate simulations would further enhance the relevance of UHI research for tropical planning. Additionally, advances in high-resolution satellite data, machine learning, and urban digital twins open new opportunities for capturing intra-urban thermal disparities and identifying vulnerable zones. Ultimately, developing tropical-specific, multi-scale, and data-integrated frameworks will be key to enabling effective and context-sensitive urban climate adaptation in the Global South. In this regard, the development of fine-scale early warning systems (EWS)

should be prioritized in tropical contexts [234]. While most UHI studies emphasize long-term spatial patterns or mitigation planning, fewer address short-term forecasting. Yet, tropical cities increasingly face frequent and severe extreme heat events, exacerbated by UHI effects and limited infrastructure. EWS at neighborhood scale, supported by high-resolution thermal and health data, could help authorities issue timely alerts and deploy cooling measures, especially for vulnerable populations in informal settlements or areas with low green cover.

Beyond spatial resolution, it is equally important to consider the reciprocal usefulness of the main methodological approaches used to investigate UHI: ground-based characterization, satellite-derived SUHI analysis, and numerical modeling. Fixed and mobile stations offer high temporal granularity and enable direct assessment of air temperature and thermal comfort. Remote sensing, in contrast, provides broad spatial coverage and valuable long-term data on surface temperature and land cover evolution, though it does not capture human thermal perception [90]. Numerical models serve as a crucial bridge between these observational approaches, enabling the simulation of both physical processes and the testing of mitigation scenarios. For instance, LST data can inform urban canopy models, while in-situ air temperature observations are essential for validation. However, cross-scale modeling comes with limitations: mesoscale models may overlook fine urban morphology or vertical stratification, while microscale models often lack accurate initial conditions or localized parameters for tropical environments [149,151]. These mismatches can hinder the transferability of findings across cities or climate zones. Stronger integration of field measurements, remote sensing, and numerical simulations is therefore essential. When combined, they offer a powerful and complementary toolkit for characterizing urban heat, designing interventions, and informing planning decisions in a spatially explicit way especially critical in fast-urbanizing tropical regions.

8. Conclusion

This review has highlighted both the strengths and gaps in the scientific literature on UHI in tropical climates, a region marked by persistent high temperatures, extreme humidity, and rapid urban growth. It underscores the critical role of intense solar radiation and high humidity in shaping urban climate dynamics, beyond the well-documented influence of urbanization itself. As a result, some studies have begun to adopt a more holistic approach by analyzing both UHI intensity and outdoor thermal comfort at city or neighborhood scales. Expanding this integrated perspective across all tropical UHI studies would enhance our understanding of urban overheating and its implications for human well-being. Future research should prioritize multi-parameter analyses and refine numerical models to better capture local conditions, including anthropogenic heat sources like air conditioning, and tropical-specific processes such as limited nocturnal cooling, evapotranspiration under high humidity, and convective rainfall events.

This review highlights the urgent need for more climate-sensitive approaches to UHI research in the tropics. Grouping tropical cities together under a single umbrella obscures important variations across Af (tropical rainforest), Am (tropical monsoon), and Aw (tropical savanna) climates, each defined by distinct rainfall seasonality, cloud cover regimes, and evapotranspiration patterns, which in turn shape UHI intensity and duration. To advance the field, future studies must embrace these distinctions, both in experimental design and model selection. Many UHI models and mitigation strategies originate from temperate regions and may not translate effectively to tropical contexts, where solar angles, vegetation responses, and building ventilation practices differ significantly. By doing so, researchers can develop more precise, equitable, and climate-resilient strategies to mitigate urban heat in a region that is both rapidly urbanizing and highly vulnerable to climate change.

While research has predominantly focused on large metropolitan areas, smaller and mid-sized tropical cities remain underexplored, despite experiencing significant UHI effects. Extending investigations to these urban areas, especially in Aw (tropical savanna) climates, is essential to ensure equitable and effective mitigation strategies, particularly in rapidly urbanizing regions facing increasing climate vulnerability. Bridging the gap between large-scale remote sensing studies and local-scale urban interventions remains another challenge. High-resolution, multi-scale approaches, combining satellite data with detailed in-situ measurements, are essential for developing targeted, effective strategies. Strengthening interdisciplinary collaboration between researchers, urban planners, and policymakers will be crucial to designing cities that are more resilient to climate change.

By integrating diverse methodologies, improving data resolution, and tailoring models to tropical environments, future research can provide actionable insights for sustainable urban planning. Addressing these challenges will be key to ensuring that tropical cities, which are experiencing rapid population growth, remain livable and adaptive in an era of rising temperatures.

CRediT authorship contribution statement

A. Lefevre: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **B. Malet-Damour:** Writing – review & editing, Supervision, Funding acquisition. **H. Boyer:** Writing – review & editing, Supervision. **G. Rivière:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Summary of fixed measurement studies

The table below synthesizes key UHI findings from fixed-station measurement studies across tropical cities.

Appendix B. Summary of numerical tools for UHI modeling in the tropics

Table 6 presents a comparative summary of the most commonly used numerical tools for UHI modeling in tropical climates. These tools are categorized by their application scale, typical outputs, and key advantages, highlighting their relevance for addressing the unique challenges of urban climate modeling in hot and humid environments.

Table 5
Summary of fixed measurement UHI studies in tropical regions.

Study	City, Country/Köppen	Scale	Station network	Param measured	Key findings/notes
Ramakreshnan et al. [48]	Kuala Lumpur, Malaysia/Af	City	2 fixed stations (PJ and SUB)	Tair, RH, Vair, Patm, Rain	UHI max: 1.71 °C (PJ), 1.29 °C (SUB). More intense at night during dry monsoon. Variable correlations with RH and wind.
Amorim and Dubreuil [7]	Presidente Prudente, Brazil/Aw	City	2 fixed stations	Tair, RH	Stronger UHI at night (tropical winter), lower during the day.
Zhang and Wu [61]	Sanya, China/Aw	City	2 stations	Tair	During Chinese New Year, tourism enhances UHI: +0.66 °C (max), +0.42 °C (min).
Adebayo [62]	Ibadan, Nigeria/Aw	City	3 urban + 1 rural stations	Tair	UHI stronger at night (1 °C in dry season), weak daytime effect.
Balogun [42]	Akure, Nigeria/Aw	City	Fixed measurements	Tair, RH	Nocturnal UHI: up to 4 °C (dry season), 2 °C during day (wet season).
Amorim [69]	Presidente Prudente, Brazil/Aw	City	26 points	Tair, RH	Spatial distribution of UHI analyzed by season. Greater intensity during dry season.
Roth et al. [54]	Singapore/Af	City	20 stations (6 years)	Tair	Avg nocturnal UHI: 2.8–3.7 °C. Seasonal effect observed.
Amorim et al. [67]	Presidente Prudente, Brazil/Aw	City	Fixed stations	Tsurf, Tair	UHI also strong in medium-sized cities. Temporal intensity analysis performed.
Best et al. [70]	Paramaribo, Suriname/Am	City	16 fixed stations	Tair, RH	Cooling up to –2.5 °C in green zones.
Correa et al. [55]	Vitória, Brazil/Aw	Region	Fixed stations	Tair, Tsurf	UHI: +0.9 °C. UHI more intense in spring/summer.
Setiawati et al. [56]	Medan, Surabaya, Denpasar/Aw	Region, City	4 stations in Medan, 2 in Surabaya, 2 in Denpasar	Tsurf, RH, sunshine duration, UTCI	High UTCI in urban centers. Vegetation scenarios reduce UTCI in Surabaya (–0.84 °C), increase it in Medan/Denpasar (+3.1 °C).
Sharmin et al. [47]	Dhaka, Bangladesh/Aw	Street	Not specified	Tair, RH, MRT, Vair	Temperature differences of 1–3.8 °C depending on urban form. More diverse forms (parcel size, height) improve thermal comfort.
Weitz et al. [49]	Kolkata, India/Aw	Street	Mini-sensors worn by 130 urban + 180 rural residents	Tair, RH	Indoors hotter than outdoors in cities, especially at night. Urban residents 4.3× more exposed to Heat Index > 45 °C. Rural women more exposed than men.
Rajapaksha et al. [230]	Darwin, Australia/Aw	Street	Measurements + surveys	Tair, RH, Radiation	Anthropogenic Heat Emissions: buildings = 87%–95%; traffic = 4%–13%; human metabolism = 0.5%. UHI reinforced by human activity.
Chow and Roth [45]	Singapore/ Af	Street, neighborhood	6 fixed	Tair, Vair	UHI max 7 °C in commercial zone during monsoon (May–Aug), 3–4 h after sunset.
Ahmed et al. [41]	Putrajaya, Malaysia/Af	Street, neighborhood	10 fixed points in one neighborhood	Tair, Radiation, Vair, Tsurf, RH	Average nocturnal UHI of 2 °C, negligible during daytime. Street orientation and vegetation strongly affect surface temperature.

Table 6
Common numerical tools used for UHI modeling in tropical regions.

Tool	Scale	Typical outputs	Key advantages in tropical context
WRF (with UCMs)	City/Region	Air temperature, humidity, wind, UHI, heat stress	Captures mesoscale dynamics and seasonal UHI variation; validated in Southeast Asia; sensitive to land use heterogeneity and anthropogenic heat.
UWG (Urban Weather Generator)	City/Neighborhood	UHI intensity, building energy demand	Accounts for high anthropogenic heat in informal settlements; effective for energy impact assessments in hot-humid cities.
ADMS-Urban	City/Neighborhood	Thermal comfort, building energy use	Well-adapted to persistent humidity and low ventilation; integrates land use and pollution for urban comfort analysis.
t-TEB	City	Surface energy fluxes, temperature, drainage impact	Calibrated for tropical convection and poor drainage; accurately models tropical rainfall and free convection.
Envi-met	Neighborhood	Air temperature, MRT, PET, UTCI, wind, solar radiation	Most popular CFD tool in tropical UHI studies; highly detailed for urban greening, tree shade, and ventilation effects.
STEVE	Neighborhood	Mean/max/min air temperature	Empirical model designed with tropical data; outperforms temperate-based tools for tropical conditions.
ANSYS Fluent, OpenFOAM, CRADLE	Neighborhood/Building	Airflow, heat fluxes, UTCI	Flexible CFD platforms; suitable for dense tropical cities; analyze building porosity effects.
Rayman	Building/Individual	MRT, PET, thermal comfort indices	Excellent for solar radiation analysis; widely used in tropical courtyard and vegetation shading studies.
EnergyPlus	Building	Building cooling load, indoor temperatures	Evaluates passive strategies (green/cool roofs); responsive to tropical rainfall and latent heat; ideal for indoor-outdoor coupling.
DART	Building/Urban Patch	Radiative balance, vegetation interaction	3D radiation transfer for vegetation shading; captures urban canopy complexity in tropical greenery studies.

Data availability

No data was used for the research described in the article.

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