FORUM GEOGRAFI
ISSN: 0852-0682 | E-ISSN: 2460-3945

HTTPS://JOURNALS.UMS.AC.ID/INDEX.PHP/FG/

Review article

Local Climate Zones in Tropical Urban Environments: A Review

Jamal Harimudin, Lam Kuok Choy*, Frankie Marcus Ata

Geography Program, Centre for Research in Development, Social & Environment, Faculty of Social Sciences & Humanities, Universiti Kebangsaan Malaysia, Bangi, Malaysia.

*) Correspondence: lam@ukm.edu.my

Citation:
Harimudin, J., Choy, L. K., & Ata, F. M. (2026). Local Climate Zones in Tropical Urban Environment: A Review. Forum Geografi. 40(2), xx-xx.

Article history:
Received: 20 November 2025
Revised: 16 March 2026
Accepted: 21 May 2026
Published: 26 May 2026

Abstract

Local climate zones (LCZs) were originally proposed to redefine the rural–urban dichotomy, while providing a standardised framework for urban heat island (UHI) studies worldwide. The UHI phenomenon, characterised by rising land surface temperature (LST), particularly in urban areas, has become a global urban environmental issue. At the same time, experts project that cities in tropical macroclimate regions will experience UHI effects more rapidly. Therefore, this literature review examines the development of the LCZ framework and identifies future research directions to address global climate change, particularly within tropical urban environments. The study employs the PRISMA framework within the Scopus database, identifying 51 documents suitable for further analysis. Descriptive analysis indicates that LCZ studies are distributed across 60 cities, with Nagpur (India) being the most prominent. Meanwhile, the publication frequency fluctuates, with 2024 recording the highest number. A bibliometric analysis of authors revealed that at least 10 of the most productive researchers originated from different countries, institutions and disciplines. In addition, a bibliometric analysis of keywords identified 18 terms with the highest co-occurrence rates, which constitute the themes of current LCZ research. Remote sensing (RS)-based methods, employing supervised pixel-based analysis with a random forest classifier developed within the WUDAPT project, dominate LCZ mapping approaches, alongside expert-based and geographic information system (GIS)-based methods. Based on a thematic analysis, the applications of LCZ across various fields include the UHI effect and its mitigation, surface temperature monitoring, heat risk, heat stress and heat hazards, thermal comfort, energy consumption and balance, urban climate modelling, urban planning, and other applications such as urban health and air quality. In the future, LCZ in tropical macroclimate regions is likely to become a highly complex field of study, requiring the involvement of multidisciplinary approaches.

Keywords: heat island; literature review; LCZs; tropics; urban environment.

1. Introduction

By 2018, more than half of the world's population was living in urban areas. Urbanisation has nearly doubled, reaching 55 per cent, up from 30 per cent in 1950, and is projected to reach 68 per cent by 2050 (United Nations, 2019). Over the last few decades, the growth of the global population has boosted urbanisation, triggering massive development across the world (Asnawi *et al.,* 2024). In addition to uncontrolled growth, urbanisation results in significant changes to the form, order, structure and metabolism of the landscape, ultimately altering the local climate of the region (Xue *et al.,* 2020). Dense building structures, impervious surfaces, limited vegetation and anthropogenic heat emissions can cause urban air temperatures to rise above those of surrounding areas (Wellinger *et al.,* 2024). This phenomenon, referred to as the urban heat island (UHI), has become a serious challenge for the global urban environment. At present, more pronounced regional warming is occurring in many parts of the world. It is estimated that between 20 and 40 per cent of the world's population has experienced an increase in air temperature exceeding 1.5 °C during at least one season in the region where they reside (Allen *et al.,* 2022).

The UHI phenomenon (Figure 1) is defined as the temperature difference between urban and rural areas, generally caused by rising temperatures in city centres (McCarthy & Sanderson, 2011). It is generally categorised into surface urban heat islands (SUHI), canopy urban heat islands (CUHI) and boundary layer urban heat islands (BUHI) (Fernandes *et al.,* 2023; Dewan *et al.,* 2021; Voogt & Oke, 2003). However, in much of the literature, SUHI has become the primary focus of research and has often been equated with the term UHI itself.

Although research on the UHI effect has advanced significantly, experts have only recently realised that the definitions of "urban" and "rural" remain ambiguous. In numerous studies, the descriptions of such areas in one region differ from those in another (Xue et al., 2020), leading to biased definitions of the two terms. As a result, inconsistencies arise in UHI intensity when employed as a parameter for measurement. To address these challenges, Stewart and Oke (2012) introduced the concept of local climate zones (LCZs), defined as areas characterised by similar surface cover, structure, materials and human activities, ranging from hundreds of metres to several kilometres in horizontal scale.

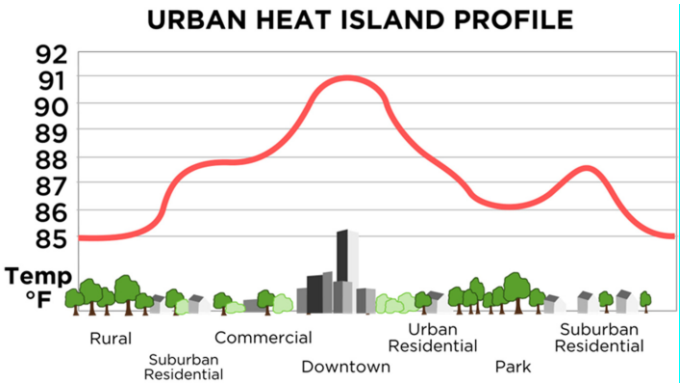

Figure 1. Illustration of an urban heat island (UHI) (Fernandes *et al.*, 2023).

Implicitly, this definition encompasses three elements: the local scale, the climatic nature and the reflection of zones. The primary objective of the LCZs framework is to standardise urban temperature observations in order to support UHI research globally. The LCZs classification system consists of 17 standard classes: LCZ classes 1 to 10, representing "building" types, and LCZ classes A to G, representing "land cover" types (Figure 2). All LCZ types can represent "heat islands", which refer to the urban canopy layer, where heat is measured at a height of 1–2 metres above the ground. The urban canopy layer is quantified using urban canopy parameters (UCPs), comprising ten parameters based on geometric, thermal, radiative and metabolic properties, as defined in Table 1. Therefore, each LCZ class corresponds to a specific UCP value.

Figure 2. Local climate zones (LCZs) classified into built types and land-cover types (Demuzere *et al.,* 2020).

To date, LCZ studies have been conducted on every continent apart from Antarctica (Wang *et al.,* 2024), including investigations into the relationship between LCZ, land surface temperature (LST) and the UHI effect. However, the warming effect is strongly dependent on the macroclimatic conditions of each city (Stewart & Oke, 2012). A study by Zhang *et al.* (2024a) found that

tropical regions are the most vulnerable to increases in LST due to population and road network density. At the same time, developing countries, which are generally situated in tropical regions, have experienced the most rapid population growth and unsystematic developmental activities, which have often led to the changes in land use and land cover experienced in recent years (Roth, 2007; Choy et al., 2020). Furthermore, the IPCC projects that tropical regions will undergo substantial temperature increases during the twenty-first century (Marcotullio *et al.,* 2021; IPCC, 2014). Therefore, this study presents a literature review of LCZs, with a particular focus on cities situated within the tropical macroclimate regions.

Table 1. Definitions of UCP based on geometric, thermal, radiative and metabolic LCZ properties (Stewart & Oke, 2012).

No	Parameter	Definition
Geometric properties and surface coverage		
1	Sky view factor	Ratio of the amount of sky hemisphere visible from ground level to that of an unobstructed hemisphere.
2	Aspect ratio	Mean height-to-width ratio of street canyons (LCZs 1–7), building spacing (LCZs 8–10), and tree spacing (LCZs A–G).
3	Building surface fraction	Ratio of building plan area to total plan area (%).
4	Impervious surface fraction	Ratio of impervious plan area (paved, rock) to total plan area (%).
5	Pervious surface fraction	Ratio of pervious plan area (bare soil, vegetation, water) to total plan area (%).
6	Height of roughness elements	Geometric average of building heights (LCZs 1–10) and tree/plant heights (LCZs A–F) (m).
7	Terrain roughness class	Davenport et al. (2000) classification of effective terrain roughness (Z0) for city and country landscapes.
		Thermal, radiative and metabolic properties
8	Surface admittance	Ability of surface to accept or release heat (Jm–2 s–1/2 K–1).
9	Surface albedo	Ratio of the amount of solar radiation reflected by a surface to the amount received by it.
10	Anthropogenic heat output	Mean annual heat flux density (W m−2) from fuel combustion and human activity (transportation, space cooling/heating, industrial processing, human metabolism).

The objective of the study is to review the development of the LCZs scheme, both in terms of mapping methods and its applications within tropical macroclimate regions. To achieve these objectives, three sub-objectives were developed: (1) to describe the spatial, temporal and statistical distribution of all articles considered; (2) to examine the development of LCZs mapping and classification methods; and (3) to analyse the development of applications of the LCZs scheme.

2. Methods

Literature reviews expand the scope of knowledge on a specific research topic (Jahan *et al*., 2016) and are an effective method for comprehensively evaluating knowledge in a particular field, determining future research priorities, and answering individual study questions (Zhang *et al*., 2024b). In this literature review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was employed to identify and analyse relevant articles. PRISMA provides technical guidelines for reporting, designed to enhance the completeness, transparency and scientific value of systematic reviews and meta-analyses (Hutton *et al*., 2015). The guidelines comprise a four-stage flowchart that explains how articles are identified, screened, assessed for eligibility, and selected for inclusion in the review (Selçuk, 2019). Each stage of the review is described in detail and synthesised in a flowchart, as presented in Figure 3.

Stage 1: Identification. The Scopus database was selected as the primary database because it undergoes a rigorous peer-review process on various multidisciplinary topics. The search strings TITLE-ABS-KEY (local climate zone OR local climate zones OR LCZ) were used on September 13, 2025, resulting in 11,545 articles.

Inclusion and exclusion criteria, as outlined in Table 2, were applied at this stage and during the screening process. Consequently, several filters were applied. The first filter, document type, was restricted to articles, yielding a total of 9,521. The second filter, restricted to final publications, identified 9,471 articles, while the third, source type, was restricted to journals, resulting in 9,360 articles. The fourth filter, language used in the articles, was restricted to English, which yielded 8,750 articles, while the fifth, publication year, was restricted to the period 2012 to 2025, and resulted in 7,251 articles. The final filter was keywords. To achieve the objective, keywords were selected directly related to LCZ and tropical regions. Consequently, the keywords were limited to local climate zone, local climate zones, tropics, and tropical regions, yielding 838 articles. All documents that met the criteria based on the applied filters were selected to proceed to the next stage.

Stage 2: Screening. At this stage, a screening of articles that were not relevant to the theme of LCZs was conducted. This involved a thorough review of each title, abstract and keywords to determine their relevance to LCZ research. A total of 336 articles deemed irrelevant were identified at this stage, while 502 articles progressed to the subsequent phase.

In addition, a filter based on study location was applied. This was done to exclude studies conducted in non-tropical regions that had not been identified in the previous stage. Therefore, each study area accessed at https://datacatalog.worldbank.org/infrastructure-data/search/dataset/0038272/world-bank-official-boundaries was combined with the Köppen-Geiger world climate classification map. The data source was obtained from the climate map, which was reanalysed by Rubel *et al*. (2017) with higher resolution (accessed at https://koeppen-geiger.vu-wien.ac.at/present.htm) and 51 articles were found.

Table 2. Inclusion and Exclusion Criteria.

No	Criterion	Inclusion	Exclusion
Source: Scopus Database			
1	Document type	Article	Conference paper, review, book chapter, book, conference review, data paper, note, editorial, letter, erratum, short survey
2	Publication stage	Final	Article in press
3	Source type	Journal	Conference proceeding, book series, trade journal
4	Language	English	Non-English
5	Years	2012–2025	Year/s not mentioned
6	Keywords	Local climate zone, local climate zones, tropics, tropical regions	Keywords not mentioned
Source: World Map of Köppen-Geiger Climate Classification			
7	Location	Tropical area (Af, Am, As, Aw)	Non-tropical area

Stage 3: Eligibility. At this stage, all 51 documents identified were reviewed in their entirety for text suitability. Once this was completed, their relevance to LCZs was re-evaluated, with all 51 documents deemed suitable to proceed to the final stage.

Stage 4: Included. This is the final stage in the PRISMA flowchart. Each article was re-examined to ensure that all 51 were directly related to the LCZs framework and concerned tropical climate regions. Subsequently, all articles were declared to have passed the review.

The selected articles were then analysed. ArcGIS 10.8 software was employed to map the spatial distribution based on the study area of each article. Additionally, VOS Viewer and Microsoft Office Excel were used for bibliometric analysis and analysis of temporal dynamics, author bibliographies, and keywords. The final step was to conduct a thematic analysis to describe LCZ performance across all articles, based on mapping themes and application of the LCZ framework.

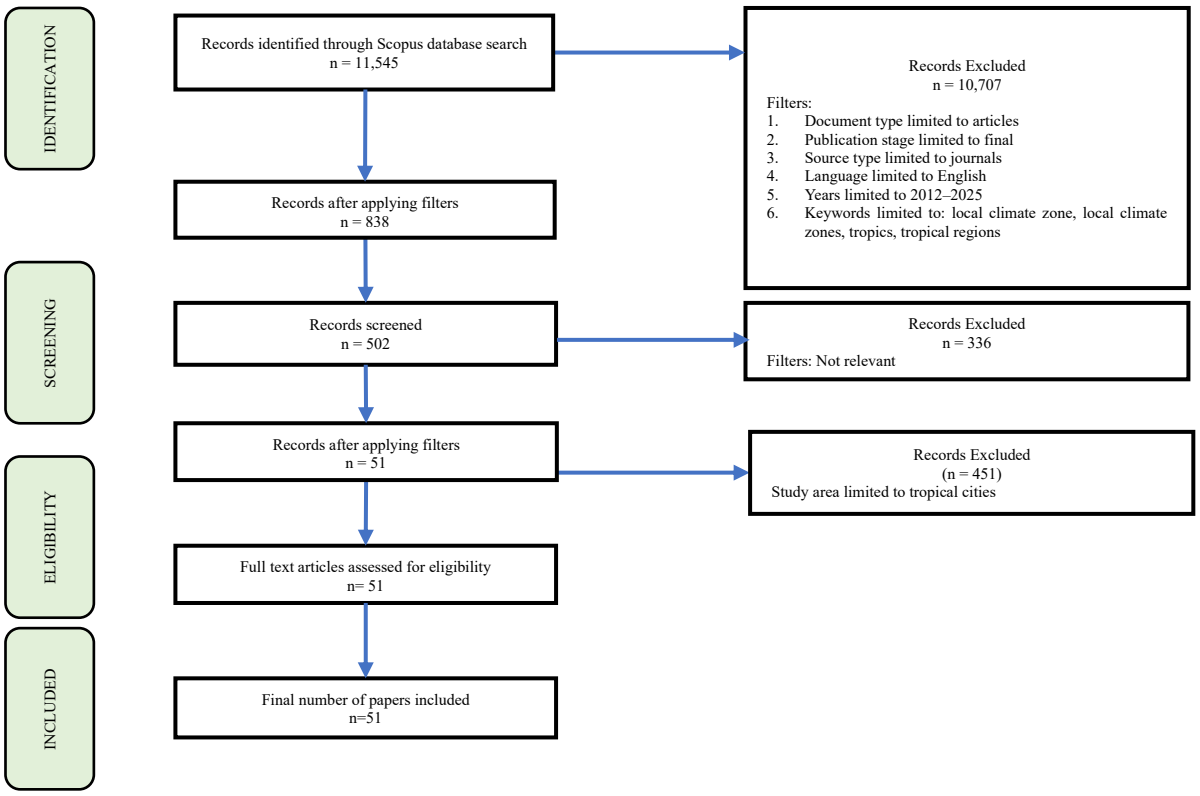

Figure 3. Article search strategy based on the PRISMA flowchart using keywords in the Scopus database.

3. Results and Discussion

3.1. Spatial and Temporal Assessment of the Selected Articles

Spatially, the distribution of sites from the 51 selected articles is dispersed across various cities, countries and continents. Each article focuses on a singular location, with the exception of that of Brousse *et al.* (2020a), which encompasses nine locations as its study area. Figure 4 illustrates the spatial distribution of study areas, which are spread across 32 sites, 20 countries and three continents, with varying frequencies.

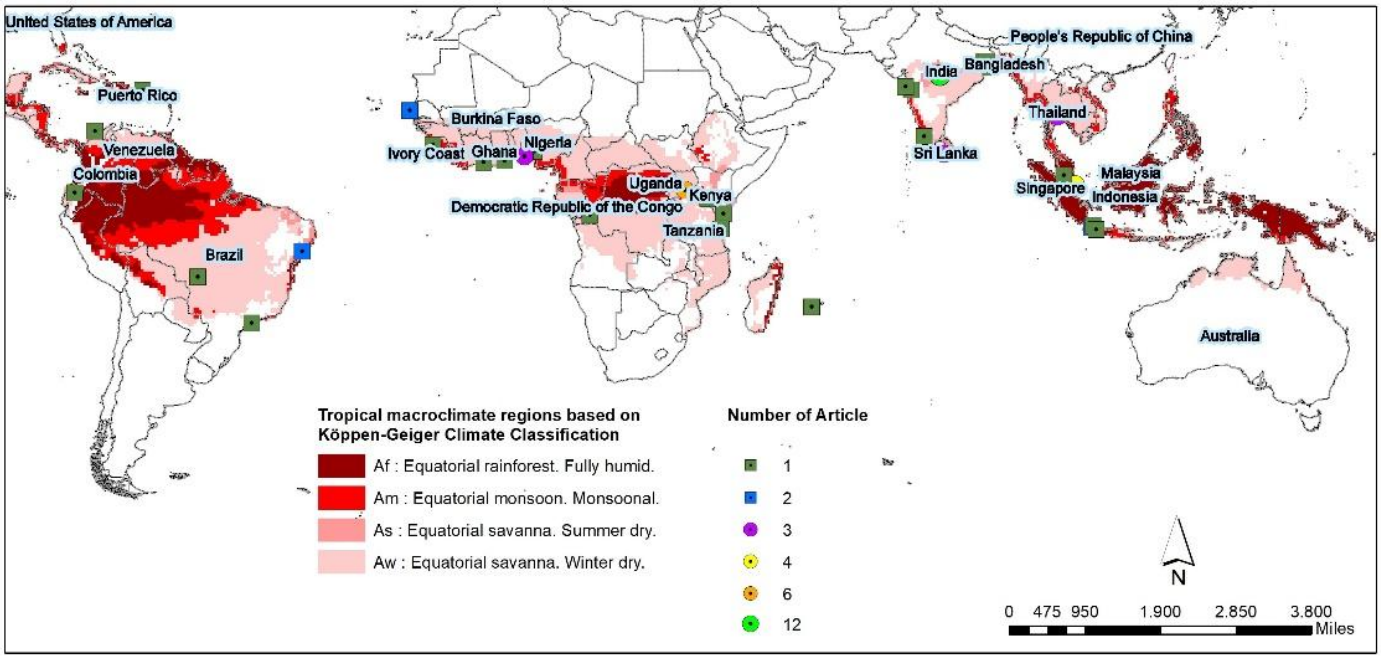

Figure 4. Spatial distribution of study areas (cities and countries) in LCZ themed articles identified within the tropical macroclimate regions (modified from Rubel *et al.* (2017)).

Asia dominates the number of published articles, with 60% of the 60 study locations on this continent. India and Uganda are the two most frequently studied countries, with 24 articles published. Although they each contributed only four articles, Brazil, Indonesia, Nigeria and Singapore were the third-largest contributors after India and Uganda. Similarly, Nagpur in India and Kampala in Uganda were the two most selected cities for study. Other cities, including Singapore, Bangkok, Colombo and Lagos, made similar number contributions after Nagpur and Kampala.

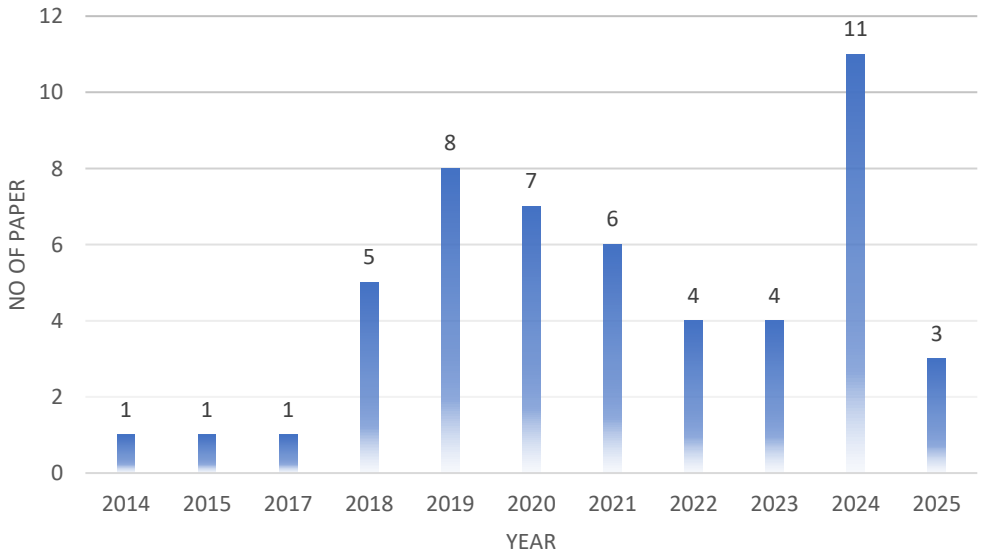

Figure 5. Temporal distribution of articles with LCZ themes identified within the tropical macroclimate regions.

Temporally, the publication of LCZ-based articles in the tropical macroclimate regions commenced in 2014, subsequently exhibiting a relatively fluctuating frequency (Figure 5). The number remained unchanged until 2017, with only one article published each year, although none in 2016. Subsequently, there was an increase in the frequency of publications in 2018 and 2019, followed by a tendency to decline until 2023. The peak frequency of articles occurred in 2024, with a total of 11 published. By September 2025, three articles relating to LCZ in the tropical macroclimate regions had been published in 2025.

3.2. Bibliographic Assessment of Authors and Keywords

Figure 6 shows a bibliometric analysis based on the networks of authors who have produced three or more articles. A total of 161 authors have contributed to LCZ research in the tropical macro climate regions, originating from various countries, with the most productive coming from India, Belgium, Singapore and Thailand. Among them is Rajashree Kotharkar, who collaborates closely with Anurag Bagade, Aveek Ghosh and Ravindra Keskar. All four are from the Visvesvaraya National Institute of Technology, India. Furthermore, there is cross-national collaboration involving Oscar Brousse from KU Leuven, Belgium, who works closely with Matthias Demuzere from Ghent University, Belgium, Matthias Roth from the National University of Singapore, Hendrik Wouters from KU Leuven, Belgium and Wim Thiery from Vrije Universiteit Brussel (Belgium). Another author id Dararat Khamchiangta from Khon Kaen University, Thailand. The papers written by the authors listed above have been published in renowned international journals such as Urban Climate, Sustainable Cities and Society, Building and Environment, Landscape and Urban Planning, Atmosphere, Energy & Buildings, Environmental Research Letters, International Journal of Biometeorology, International Journal of Climatology, International Journal of Geo-Information and Sustainability.

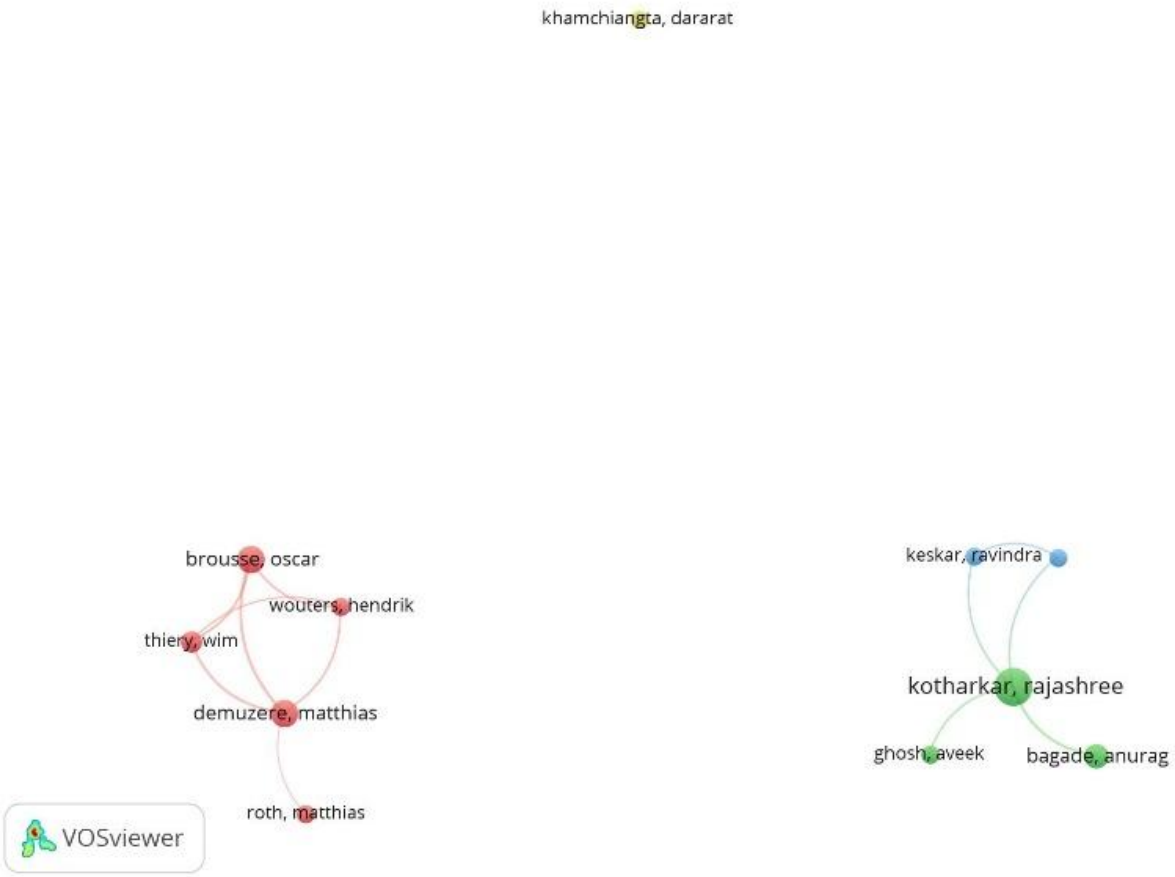

Figure 6. Productivity and networks of authors (Note: larger circles indicate more productive authors).

A bibliometric analysis based on keywords was conducted by grouping them according to their co-occurrence, as shown in Figure 7. The aim was to illustrate the evolution of and current trends in LCZ research. The connections and distances between keywords demonstrate the strength of the relationships between keywords within the LCZ topic. Furthermore, the results of the keyword analysis can were used for thematic analysis in the literature review.

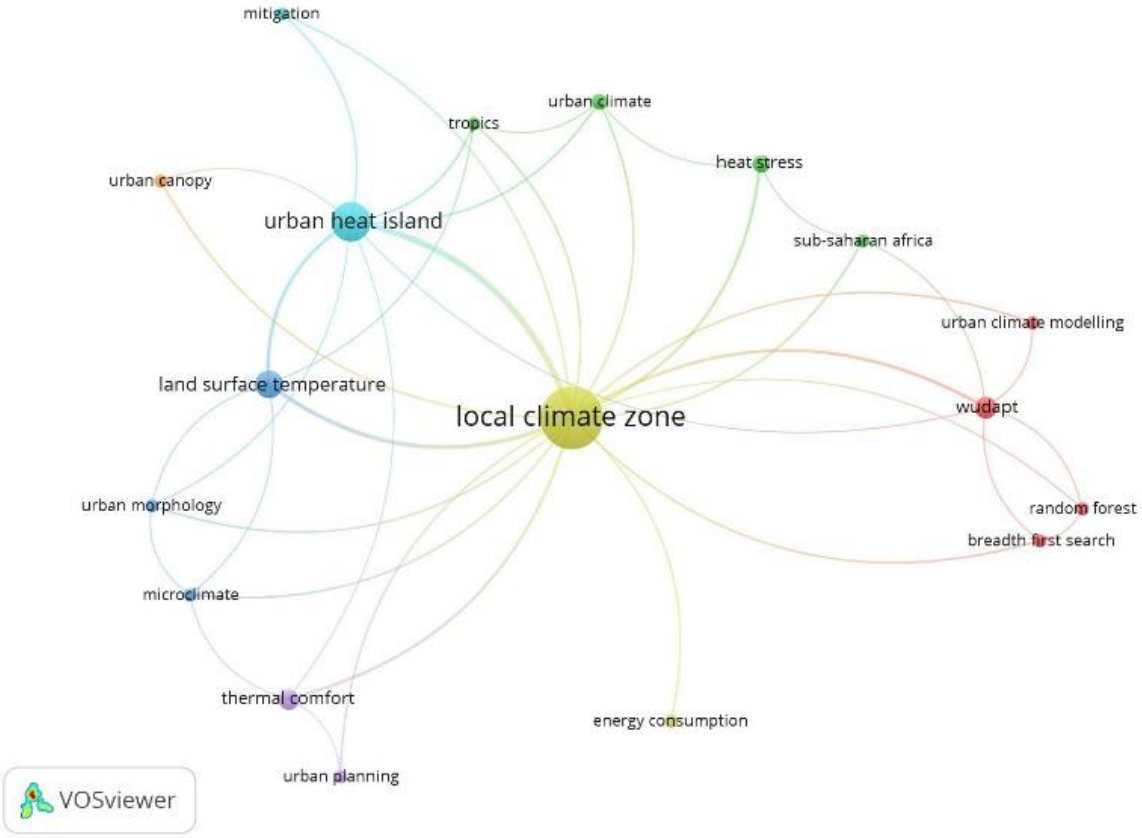

Figure 7. Keyword co-occurrence with a frequency of at least three occurrences.

The results of the analysis show that, out of the 166 keywords identified, 18 appeared together at least three times. The five keywords with the highest frequency were “local climate zone”, “urban heat island”, “land surface temperature”, “wudapt” and “thermal comfort (outdoors)”. The occurrence of these five keywords provides a preliminary indication that LCZ study in the tropical macroclimate regions has progressed in line with its original objectives for urban climate research, namely in relation to land surface temperature and the urban heat island effect. In subsequent developments, LCZ studies began to expand their focus to other important themes, such as heat stress, energy consumption and urban climate modelling. From the perspective of LCZ classification, it appears that the WUDAPT procedure using the random forest (RF) classifier still dominates the theme of LCZ mapping. Finally, recent developments in LCZ studies are moving towards climate-based mitigation strategies and urban planning.

3.3. LCZ Mapping

3.3.1. Expert Based Method

Expert-based methods are essentially based on authors’ local expertise and knowledge of specific urban areas, or on general urban surface calculations that are not described in detail in the publication (Lehnert *et al.,* 2021). This method adapts the guidelines set out by Stewart and Oke (2012), which includes collecting site metadata, defining the thermal source area and selecting the local climate zone. Consequently, in some cases, the identification of LCZs utilises Google Earth and Bing Maps.

As found in the literature review, an expert-based method was employed by Thomas *et al.* (2023) to identify land use within the LCZ scheme in the city of Kochi, India. In addition, Villadiego and Velay-Dabat (2014) mapped LCZs in the city of Barranquilla, Colombia, using Google Earth and Bing Maps, combining in-depth knowledge of urban morphology with field studies to observe and verify the information. Morris *et al.* (2015) took the same approach, identifying LCZs based on expert knowledge with the aid of Google Earth in Putrajaya, Malaysia. In contrast, Paula *et al.* (2025) deployed 91 observation stations to identify LCZs in the city of Cuiabá, Brazil. Overall, it appears that this method is a traditional one; effective in smaller scale studies, but impractical when applied on a large urban scale.

3.3.2. Geographic Information System (GIS)-Based Method

In principle, LCZ mapping using GIS-based methods utilises urban canopy parameters (UCPs), as defined in Table 1. This approach was introduced by Lelovics *et al.* (2014), who defined seven of the 10 UCPs, namely the sky view factor (SVF), building surface fraction (BSF), pervious surface fraction (PSF), impervious surface fraction (ISF), height of roughness elements (HRE), terrain roughness class (TRC) and surface albedo (SAL).

These parameters are obtained from various sources, such as satellite and aerial images, 3D building databases, CORINE land cover databases, road databases and maps (Gál *et al.,* 2015). The method relies heavily upon GIS data, which is not always available in various urban areas, and follows six key steps (Quan & Bansal, 2021), as presented in Figure 8.

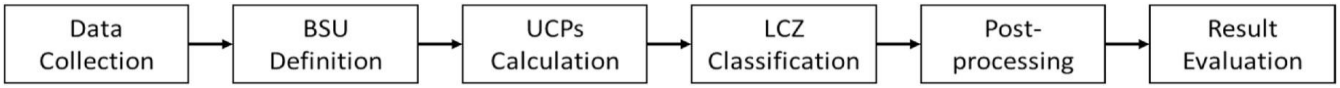

Figure 8. Workflow of the GIS-based LCZ mapping method (Quan & Bansal, 2021).

In the GIS method, vector-based GIS data collection, such as building footprint data and road cover/path data, is used to generate urban canopy parameters (UCPs), including the sky view factor (SVF), aspect ratio (AR) and roughness element height (HRE) (Quan & Bansal, 2021). The resulting UCP values are then translated into basic spatial units (BSUs) that refer to a specific spatial scale. This procedure is followed by the quantification of each UCP into BSUs based on the LCZ scheme. Post-processing is aimed at collecting units for simplification and size adjustment (Han *et al.,* 2024).

Quan and Bansal (2021) grouped LCZ classifiers in GIS-based methods as 1) standard rule-based classifiers; 2) modified standard rule-based classifiers; 3) fuzzy rule-based classifiers; and 4) other classifiers. The standard rule-based classifier is based on the UCP value range proposed by Stewart and Oke (2012). The method was employed by Perera and Emmanuel (2018), who mapped the LCZs using fish-eye lens photographs, field surveys, detailed maps and Google Earth to identify UCPs in the city of Colombo, Sri Lanka. The LCZ map they produced was also utilised by Emmanuel *et al.* (2023).

The method was also used by Ekanayaka *et al.* (2025), who identified LCZs using building data, NDWI and NDVI to extract UCP also in the city of Colombo. A modified standard rule-based classifier adjusts the range of UCP values if there is insufficient data to apply the original UCP range. A fuzzy rule-based classifier is based on fuzzy rules designed to address the limitations of standard rule-based classifiers, while, 'other classifiers' also aim to address the limitations of standard rule-based classifiers. This other classifiers was employed by Kotharkar and Bagade (2018a), who identified LCZs using Bhuvan land use and land cover maps from the NRSC, Google Maps, Landsat 7 ETM+ and a primary survey, by applying a new rule-based classifier that adopted standardised methods aligned with qualitative and descriptive parameters to extract UCPs in the city of Nagpur, India. Subsequently, the method was used as the LCZ base map by Kotharkar and Bagade (2018b), Kotharkar *et al.* (2019a), Kotharkar et al. (2019b), Kotharkar *et al.* (2020), Kotharkar *et al.* (2021), Kotharkar *et al.* (2022), Kotharkar *et al.* (2024a).

In terms of data sources, GIS streams mostly utilise vector-based GIS data combined with satellite imagery to construct UCP properties. In the literature review, SVF was interpreted through fish-eye lens photographs (Quan & Bansal, 2021; Perera & Emmanuel, 2018), while others UCPs were interpreted using Autodesk Auto-CAD format generated from vector data combined with Landsat 7 ETM+ satellite imagery (Perera & Emmanuel, 2018; Kotharkar & Bagade, 2018a). For accuracy assessment, Google Earth and field surveys are used to validate LCZ results.

Overall, this method performs relatively well compared to expert knowledge-based methods. However, it has limitations in terms of the availability of vector-based GIS data, which varies from region to region. In other words, the method is promising for regions with comprehensive vector data.

3.3.3. Remote Sensing-Based Method

The Remote sensing-based method is widely popular in LCZ classification due to its applicability, simplicity and availability of free data (Zhang *et al.,* 2024b). In our literature review, remote sensing-based methods are categorised into pixel-based and object-based methods (Table 3).

In the LCZ mapping repository, the pixel-based method with supervised classification has gained momentum since Bechtel *et al.* (2015) proposed the World Urban Database and Access Portal

Tools (WUDAPT) framework to address the limitations of information on the form and function of cities at various spatial resolutions. WUDAPT is a collection of urban canopy modelling and information infrastructure databases produced by the international community to facilitate research applications focused on urban climate, weather, air quality and energy use (Ching *et al*., 2018). Figure 7 presents the WUDAPT standard LCZ mapping workflow. Mills *et al*. (2015) categorised WUDAPT based on data collection into level 0 data, level 1 data and level 2 data. All three types use data from a two-dimensional medium scale to a three-dimensional detailed scale. In this literature review, the majority of studies used the WUDAPT level 0 framework.

Table 3. Remote sensing-based method (overview of methods, classifiers and procedures).

No	Author	Method	Classifier	Procedure
1	Anjos and Lopes (2017)	Pixel-Based	RF	WUDAPT
2	Pokhrel *et al.* (2019)	Pixel-Based	RF	WUDAPT
3	Mughal *et al.* (2019)	Pixel-Based	RF	WUDAPT
4	Ochola *et al.* (2020)	Pixel-Based	RF	WUDAPT
5	Patel *et al.* (2020)	Pixel-Based	RF	WUDAPT
6	Anjos *et al.* (2020)	Pixel-Based	RF	WUDAPT
7	Kabano *et al.* (2021)	Pixel-Based	RF	WUDAPT
8	Pereira *et al.* (2021)	Pixel-Based	RF	WUDAPT
9	Pathak *et al*. (2022)	Pixel-Based	RF	WUDAPT
10	Obe *et al.* (2024a)	Pixel-Based	RF	WUDAPT
11	Obe *et al.* (2024b)	Pixel-Based	RF	WUDAPT
12	Mancheno *et al.* (2024)	Pixel-Based	RF	WUDAPT
13	Lefevre *et al.* (2025)	Pixel-Based	RF	WUDAPT
14	Middel *et al.* (2018)	Pixel-Based	RF	WUDAPT
15	Brousse *et al.* (2020a)	Pixel-Based	RF	WUDAPT
16	Brousse *et al.* (2020b)	Pixel-Based	RF	WUDAPT
17	Van de Walle *et al.* (2021)	Pixel-Based	RF	WUDAPT
18	Van de Walle *et al.* (2022)	Pixel-Based	RF	WUDAPT
19	Roth *et al.* (2022)	Pixel-Based	RF	WUDAPT
20	Sanchez *et al.* (2023)	Pixel-Based	RF	WUDAPT
21	Choudhury *et al.* (2021)	Pixel-Based	RF	WUDAPT
22	Das *et al.* (2020)	Pixel-Based	RF	WUDAPT
23	Brousse *et al.* (2019)	Pixel-Based and Object-Based	RF and segmentation	WUDAPT and GEOBIA
24	Simanjuntak *et al.* (2019)	Pixel-Based and Object-Based	RF and segmentation	WUDAPT and OBIA
25	Vaidya *et al.* (2024a)	Pixel-Based	RF, deep learning (3DNN and 1D-CNN), subset ensemble	WUDAPT and others
26	Vaidya *et al.* (2024b)	Pixel-Based	RF, deep learning (3DNN and 1D-CNN), subset ensemble	WUDAPT and others
27	Vaidya *et al.* (2024c)	Pixel-Based	RF, deep learning (3DNN and 1D-CNN), subset ensemble	WUDAPT and others
28	Khamchiangta and Dhakal (2019)	Pixel-Based	MLC	WUDAPT
29	Khamchiangta and Dhakal (2021)	Pixel-Based	MLC	WUDAPT
30	Khamchiangta and Yamagata (2024)	Pixel-Based	MLC	WUDAPT
31	Kotharkar *et al.* (2024b)	Pixel-Based	MLC	WUDAPT
32	Gupta *et al.* (2024)	Pixel-Based	MLC	WUDAPT
33	Fardani *et al.* (2024)	Pixel-Based	RF	Others
34	Nurwanda and Honjo (2018)	Pixel-Based	MLC	Others
35	Daramola and Balogun (2019)	Pixel-Based	Others	Others
36	Wibowo *et al.* (2023)	Pixel-Based	Others	Others

Notes: RF = random forest; MLC = maximum likelihood classification; 3DNN = 3-layer deep neural network; 1D-CNN = 1D convolutional neural network; WUDAPT = World Urban Database and Access Portal Tools.

The WUDAPT procedure starts with raster processing involving the cropping of the area of interest (ROI) and resampling of the image data into a uniform grid of Landsat 8 OLI-TIRS satellite imagery as raster data. SAGA–GIS software is recommended for the satellite image processing. In addition, Demuzere *et al*. (2021) developed the LCZ Generator (https://lcz-generator.rub.de) to run the overall WUDAPT framework process.

The next step is to digitise homogeneous surface training data, with a 50% training area and 50% validation area (Bechtel *et al*., 2018) and a minimum polygon area of 1 km² (Verdonck *et al*., 2017) using the Google Earth platform. The quality of the resulting LCZ map is highly dependent

on the quality of the training area created (minimum average accuracy > 50%), therefore local knowledge is essential in this process. The overall process sequence within the WUDAPT framework is followed by an accuracy assessment. Bechtel *et al*. (2018) divided the three approaches to accuracy assessment in WUDAPT into cross-validation, manual review and cross-comparison with other data. In the literature review, the combination of cross-validation and manual review was seen to be the most commonly used approach in LCZ mapping. Cross-validation is calculated using a confusion matrix, which will produce an overall accuracy (OA). The literature review identified that accuracy was assessed using a confusion matrix, and all articles reported LCZ mapping with an overall accuracy of >60%, meeting expectations by Bechtel *et al*. 2018.

The final step is the application of random forest classification. The random forest algorithm introduced by Breiman (2001) is the best-performing machine learning method for WUDAPT-based LCZ mapping (Bechtel & Daneke, 2012; Bechtel *et al*., 2018).

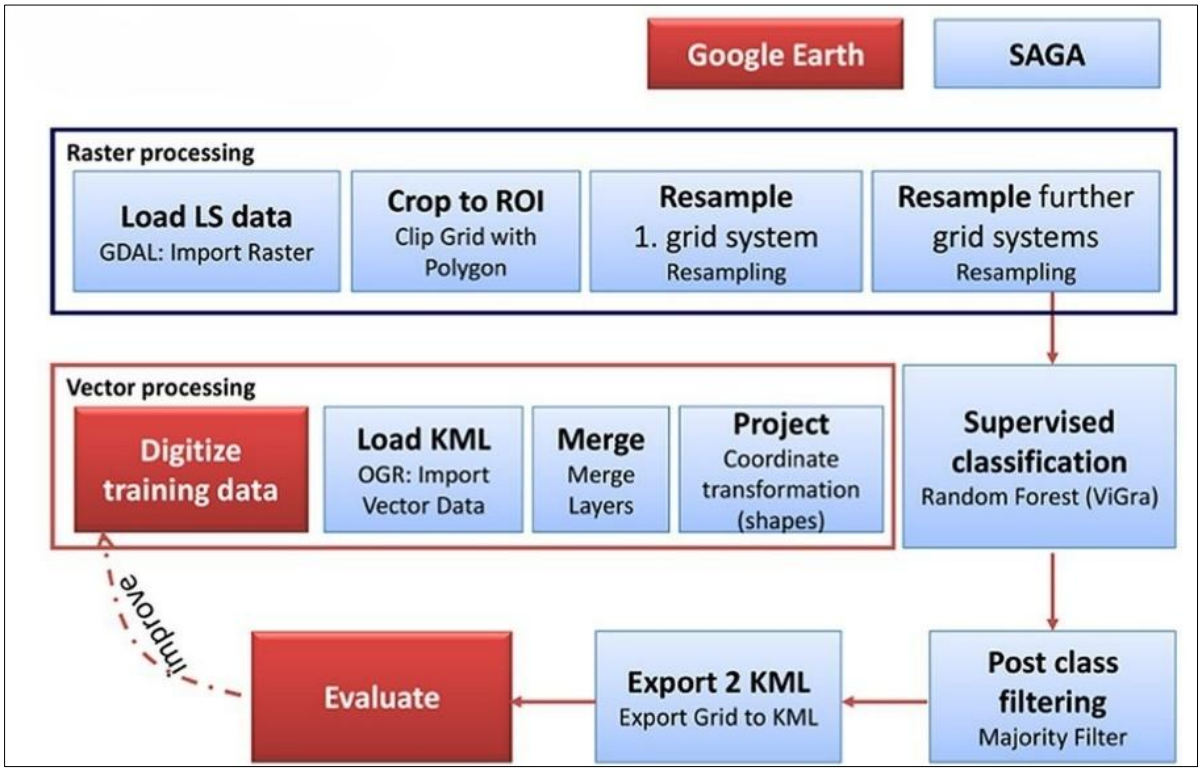

Figure 9. WUDAPT standard LCZ mapping workflow (Bechtel *et al*., 2015).

Although the series of steps outlined above may appear complicated, they are in line with the project's ambition to provide a global LCZ database quickly and cost-effectively; the availability of the LCZ generator enables local urban experts without experience in RS and GIS to perform LCZ classification within their urban environments.

In the literature review, the standard WUDAPT procedure developed by Bechtel et al. (2015) was the most widely used classification system and was employed in the majority of articles. In summary, this procedure is characterised by: 1) pixel-based classification; 2) the use of SAGA GIS software, the LCZ Generator and the Google Earth Engine platform as processing tools; 3) the use of freely available Landsat datasets; and 4) the use of random forest (RF) classifiers. The overall standard procedure results in moderate accuracy, with an overall accuracy (OA) ranging from 50–60% (Bechtel *et al.,* 2018), the accuracy of the built-up type being lower than that of land cover.

Several notes are detailed below based on the previous description.

a. *Basics of classification*. As previously mentioned, the WUDAPT procedure is a pixel-based LCZ classification system. Consequently, most of the documents in this study utilise the standard WUDAPT procedure with a pixel-based classification method to map LCZs. Pixel-based LCZ mapping is constrained by the need to resample to a grid size of 50–200 m (typically 100 m), which results in smaller pixel sizes for identifying LCZ types (Ma *et al*., 2021). For example, in a Landsat dataset with a pixel size of 30 m, a single pixel is too small to represent a single type of LCZ. Consequently, resampling was conducted to a 100 m grid to accommodate the definition of an LCZ as 'several hundred metres or kilometres horizontally', which

generally resulted in a fragmented LCZ classification. Therefore, Brousse *et al*. (2019) tested the mapping of LCZs using object-based image analysis (OBIA) in cities across sub-Saharan Africa. This approach was also followed by Simanjuntak *et al*. (2019), who used the OBIA method to map the LCZ in the city of Bandung, Indonesia. Ma *et al*. (2021) and Yan *et al*. (2022) propose that OBIA could be a promising method for future LCZ mapping practices. In addition, in the studies of Fardani *et al*. (2024), who mapped LCZs in the city of Bekasi, Indonesia; Nurwanda and Honjo (2018), who mapped LCZs in Bogor, Indonesia; Daramola and Balogun (2019), who mapped LCZs in the city of Akure, Nigeria; and Wibowo *et al*. (2023), who mapped LCZs in the city of Bogor, Indonesia none of the four followed the WUDAPT procedure for LCZ classification.

b. *Datasets and software.* Following standard WUDAPT procedures, most of the documents in the literature review utilised the Landsat dataset series (Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI/TIRS, Landsat 9 OLI/TIRS) for the identification of single LCZs and the detection of LCZ changes. Pleiades and SPOT-6 were selected for the OBIA method. Meanwhile, SAGA GIS software, the LCZ Generator platform, and the Google Earth Engine platform are the most popular software options, in line with standard WUDAPT procedures. Therefore, most studies following standard WUDAPT procedures used this software, with the exception of Choudhury *et al*. (2021), who mapped the LCZ in the Asansol-Durgapur Development Area (ADDA), India; Khamchiangta and Dhakal (2019), who mapped the LCZ in Bangkok, Thailand; and Kotharkar *et al*. (2024), who used ArcGIS 10.X software to map the LCZ in the city of Nagpur, India. Meanwhile, the classification of LCZ using the OBIA method utilises R software and eCognition software, whilst other LCZ classifications use Quantum GIS and ArcGIS Pro software.

c. *Classifier.* Bechtel *et al*. (2012) tested several classifiers within pixel-based methods and due to its robustness recommended the random forest (RF) method for use as the classifier in the standard WUDAPT procedure. Consequently, the RF classifier has become popular, and was commonly found in this literature review, alongside the traditional maximum likelihood classification (MLC) used by Khamchiangta and Dhakal (2019), Kotharkar *et al*. (2024) and Gupta *et al*. (2024). The RF classifier is also used in the OBIA method. Other documents that did not follow the standard WUDAPT procedure did not specify which LCZ classifier was used. Several strategies have been employed to improve the accuracy of WUDAPT standard mapping, including those of Vaidya *et al*. (2024), who utilised deep learning (3DNN and 1D-CNN) and a subset ensemble, which proved capable of improving the overall accuracy (OA) of LCZ mapping compared to a RF classifier.

Overall, the remote sensing-based method in the WUDAPT classification system performs better than the GIS-based method, particularly in spatial and temporal resolution and in its ability to rapidly generate LCZ maps on a global scale. In addition, the OBIA method, which is gaining popularity, can provide new insights into LCZ mapping.

Despite its advantages, the RS-Based method has limitations, particularly regarding transferability, spatial and temporal resolution, the quality of cloud-free data (especially in tropical regions), and sample quality; it also requires specialist expertise in remote sensing to operate.

3.4. Application of LCZ for Urban Temperature Research

The LCZ framework has attracted the interest of researchers and shown rapid development worldwide. It has brought many benefits to various topics related to urban temperature studies and proved to be an input to urban climate simulations. Studying the urban climate and other related factors is necessary to learn more about consequences of urbanisation (Rendana *et al.,* (2023). Researchers are in the process of understanding temperature dynamics in cities, which can lead to serious problems in the urban environment. In this section, the LCZ application theme for urban heat island research is based on the results of a bibliometric analysis using keywords. Lehnert *et al.* (2021) revealed that temperature detection within the LCZ framework can be pursued in several ways, based on field measurements, mobile measurements, satellite image interpretation and simulation. In the literature review, temperature detection was dominated by field measurements and the interpretation of satellite imagery; a combination of the two; or a combination of one of these with other methods. Temperature data from field measurements generally come from direct measurement installations or data from measurement stations owned by local meteorological agencies. In addition, temperature data from satellite image interpretation is obtained from Landsat dataset and MODIS land surface temperature data that provide thermal bands. Procurement of temperature data through field measurements is not only used as primary data, but also for validation based on satellite image interpretation, and for simulation and modelling.

3.4.1. Urban Heat Islands (UHIs)

UHI studies dominate many literature reviews, which is expected, given that the LCZ scheme was originally designed as a standardised classification system for UHI research (Xue *et al.,* 2020). UHIs are commonly measured by UHI magnitude/UHI intensity, as discussed by Stewart and Oke (2012). In our literature review, this method was applied to study the appearance of UHIs based on the distribution of air temperatures in each LCZ class.

Our review included several UHI studies conducted by various researchers. Morris *et al.* (2015) studied the UHI in Putrajaya (Malaysia) by integrating several LCZ observation points into a Weather Research and Forecasting (WRF) simulation and found the UHI intensity to range from 1.9 to 3.1 °C. On the other hand, Anjos and Lopes (2017) mapped the LCZs and linked it to UHI intensity, combined with park cool island (PCI) intensity, to study the dynamics of both in Aracaju (Brazil). They found that the UHI intensity was in the range of 1.5–2°C. A UHI study was also conducted by Kotharkar and Bagade (2018) in Nagpur (India), which examined the relationship between different types of LCZs and UHIs, finding that UHI intensity during the winter season ranged from 1.76 to 4.09 °C. Roth *et al.* (2022) measured the UHI magnitude for each type of LCZ in Singapore and found that the average range of night-time UHI intensity across seven built-up LCZ types ranged between 1.8 and 3.5°C, with the highest temperatures observed in LCZ 3 (compact lowrise) and LCZ 8 (large lowrise). Sanchez *et al.* (2023) used the diagnostic equation proposed in Theeuwes *et al.* (2017) to detect the maximum canopy-layer urban heat island (CL-UHI) in Singapore and found that the equation was effective for UHI detection. Gupta *et al.* (2024) applied Moran's I clustering method to study the dynamics of the UHI in Kolkata (India) and found that, between 2003 and 2014, there was an increase in UHI intensity of up to 4°C. In addition, Paula *et al.* (2025) conducted a study in Cuiabá (Brazil) and identified an average UHI intensity across all seasons ranging from 0.013°C to 0.53°C. Together with the combination of methods, UHI intensity has also been studied to provide recommendations; for example by Lafevre *et al.* (2025) in relation to urban planning on Réunion Island (France), with a difference in UHI intensity of up to 4.14 °C found between urban and natural areas.

Besides detecting the UHI effect based on LCZ type, some researchers have also studied UHI thermal characteristics in relation to the 'urban' and 'rural' dichotomy in order to recommend the most effective mitigation measures to slow down the effects of climate change. A study conducted by Kotharkar *et al.* (2019a) using regression analysis with the lmtest package in the R statistical software in Nagpur (India) found that there had been a reduction in UHI intensity, influenced by distance dynamics from the CBD (DI), surface albedo (AL), aspect ratio (AR) and vegetation density ratio (VDR). Kotharkar *et al.* (2020) also evaluated strategies involving the installation of cool roofs and pavements using the ENVI-Met model to mitigate the urban heat island effect in Nagpur.

Overall, the use of LCZs for UHI studies in macro-tropical climates is well established. By integrating temperature data from satellite image analysis, field measurements, and mobile measurements, researchers can obtain more precise data, whilst gaining comprehensive understanding of the UHI effect in tropical macroclimate regions. UHI intensity appears to vary across cities. This observation requires more detailed analysis to provide a comprehensive description of the nature of such intensity in the tropical macroclimate regions, thereby aiding decision-making regarding future climate change adaptation.

3.4.2. Surface Temperature Monitoring

Understanding the spatial and temporal dynamics of temperature in the context of LCZs is crucial in formulating urban thermal quality improvement strategies (Feng & Liu, 2022). Therefore, this theme has attracted much research, in addition to that on UHIs. Surface temperature monitoring generally concerns the relationship between LCZ and land surface temperature (LST) based on remote sensing methods utilising Landsat datasets (Landsat 5 TM, Landsat 7 ETM+ and Landsat 8 OLI-TIRS), which have thermal bands for surface temperature identification. The utilisation of multi-temporal satellite imagery has become a cornerstone of researchers' efforts to understand the linkages between LCZ changes and their impact on LST changes. In this literature review, urban expansion through such a linkage was conducted by Nurwanda and Honjo (2018) in Bogor (Indonesia) during the period 1990-2017 and by Khamchiangta and Dhakal (2021) in Bangkok (Thailand) over the period 1991-2016, and estimated until 2026. In addition, Simanjuntak *et al.* (2019) monitored changes in LST due to the development of the city of Bandung (Indonesia) during the period 2013-2016, while Fardani *et al.* (2024) conducted a similar study in relation to Bekasi (Indonesia) for the period 1993-2023, as did Vaidya *et al.* (2024) for Nagpur (India) over the summer and winter periods in 2019-2020. A variation to such studies was conducted by

Khamchiangta and Dhakal (2019), who evaluated the physical and non-physical factors of urban Bangkok (Thailand) that triggered LST changes during the period March to April, 2016. Moreover, Ochola *et al.* (2020) analysed Nairobi (Kenya) urban hotspot management through LCZ differentiation at various LSTs during the period 2013-2018. Likewise, Ekanayaka *et al.* (2025) studied the impact of urban ventilation corridors on LST and wind in Colombo (Sri Lanka) in 2017 and 2020, while Kabano *et al.* (2021) studied the relationship between LST, vegetation phenology and LCZ during the period 2013–2015 in Kampala (Uganda). Finally, Choudhury *et al.* (2021) investigated thermal behaviour patterns (TBPs) in the industrial Asansol-Durgapur development area in India.

Overall, the majority of studies conclude that there is a strong link between LCZ and LST. Furthermore, changes in LCZ have led to an increase in LST over time. This scientific evidence can assist in future urban planning.

3.4.3. Heat Risk, Heat Stress and Heat Hazards

In addition to UHI studies and LST monitoring, researchers have begun to consider other topics related to the LCZ relationship and the spatial and temporal dynamics of temperature, such as heat risk, heat stress and heat disasters. All three conditions can provide early warning of the dangers of increasing urban temperatures. Emmanuel *et al.* (2023) defined heat risk as the occurrence of high/extreme temperatures (hazard), mediated by urban morphology including buildings, shade, vegetation, and various types of infrastructure (exposure), applying the concept in Colombo (Sri Lanka). Heat stress is defined as the discomfort and physiological burden of exposure to extreme heat (Wills, 2016) and has been studied using several methods. Kotharkar *et al.* (2021) and Kotharkar *et al.* (2024b) in Nagpur (India) and Van de Walle *et al.* (2022) in Kampala (Uganda) assessed heat stress through heat stress by heat index, while Obe *et al.* (2024b) in Lagos (Nigeria) ran a WRF-urban scheme simulation to assess such stress. In addition to these topics, Wibowo *et al.* (2023) investigated the urban heat hazard, considered as the occurrence of extreme temperatures (exceeding 30°C) in the urban area of Bogor that can endanger humans.

Overall, several studies addressing the topics of heat risk, heat stress and heat hazards have demonstrated a relationship between LCZ and threats of heat, that can affect anyone. It is therefore important to take these various hazards into account in all decision-making, particularly with regard to the sustainability of the urban environment.

3.4.4. Thermal Comfort

Thermal comfort is defined as a subjective assessment of human comfort in relation to the surrounding thermal environment (Feng & Liu, 2022) and is achieved by several methods. The parameters generally vary spatially in urban areas as a result of the dynamics of surface energy balance and radiation in different LCZs (Xue *et al.,* 2020). Thermal comfort has been shown to indirectly affect the quality of life in urban areas (Han *et al.,* 2024).

In our literature review, thermal comfort was assessed using common methods such as comparing objective thermal conditions (temperature measurement) and subjective thermal conditions (comfort questionnaires); use of a thermal comfort index; and simulation using SOlar and Long Wave Environmental Irradiance Geometry (SOLWEIG) and ENVI-met. Thermal comfort analysis of tropical regions was pioneered by Villadiego and Velay-Dabat (2014), who assessed outdoor thermal comfort in Barranquilla (Colombia), while Kotharkar *et al.* (2019b) and Kotharkar and Dongarsane (2024a) investigated outdoor thermal comfort in Nagpur (India) using different methods. In addition, Das *et al.* (2020) assessed outdoor thermal comfort in the Sriniketan-Santiniketan Planning Area (India); Anjos *et al.* (2020) analysed sea breeze front and outdoor thermal comfort in Aracaju (Brazil); and Pereira *et al.* (2021) examined socio-spatial inequality and its correlation to thermal (dis)comfort in Santos (Brazil).

In short, although thermal comfort studies generally cover a limited area, the representation of each location within different LCZ types can provide an overview of thermal sensations at each study site, whilst also aiding the design of future cities that are climate adaptive.

3.4.5. Energy Consumption and Balance

Globally, nearly 75% of energy supplies are consumed in urban areas, which are home to 55% of the world's population (Kotharkar *et al.,* 2022). Since urban morphology and energy use are related to the interaction between urban form and microclimate, LCZ can be an alternative typology for analysing both (Wang *et al.,* 2024). In addition to energy consumption, knowledge of surface energy distribution, especially in urban areas, is also of interest to researchers, due to its important role in regulating the exchange between land surface and atmospheric energy. Therefore, our

review addresses both topics. Kotharkar *et al.* (2022) studied the energy consumption of the building sector with the LCZ approach using building models for energy simulation in Nagpur (India). Likewise, Pokhrel *et al.* (2019) built a scenario of building cooling load reductions for sustainable energy with building effect parameterisation and building energy model (BEP-BEM) simulation schemes in the San Juan Metropolitan Area (Puerto Rico). Similarly, Daramola and Balogun (2019) and Obe et al. (2024a) focused on investigating surface energy flux by simulating the surface energy balance algorithm for land (SEBAL) and surface urban energy and water balance scheme (SUEWS) models in the cities of Akure and Lagos (Nigeria).

Overall, various studies conducted in different locations indicate that LCZs are effective in monitoring energy consumption (particularly built-up types) with a view to creating cities that are resilient to climate change.

3.4.6. Urban Climate Modelling

In addition to field observations and satellite monitoring, the integration of regional climate models (RCMs) and urban canopy parameters (UCPs) in specific regions is an important method for urban environmental research (Wang *et al.,* 2024). Urban climate modelling can help describe current and future urban climate conditions while urban climate simulation has been partially discussed in relation to topics such as UHI, thermal comfort and energy. In the literature review, in general urban climate modelling is performed to understand overall urban climate conditions. Mughal *et al.* (2019) utilised the Weather Research and Forecast (WRF) model to understand the urban climate conditions of Singapore during the hot period of April 2016; Mancheno *et al.* (2024) used the same model to simulate the meteorological conditions of Quito (Ecuador); while Patel *et al.* (2020) also employed the model to predict very heavy rainfall events in Mumbai (India). In addition, Brousse *et al.* (2020b) utilised the COSMO-CLM model to assess and understand the impact of recent urbanisation on the (surface) urban heat island ((S)UHI) under clear-sky conditions in Kampala (Uganda). Similarly, Van de Walle *et al.* (2021) used the model to illustrate the influence of urban parameters on urban climate formation in Kampala (Uganda).

In general, the simulation models developed by the researchers mentioned above indicate that LCZs can serve as tools for predicting future urban climate dynamics. This is important in order to provide input to decision-makers so that they do not overlook climate-related factors that could contribute to multi-hazard risks.

3.4.7. Urban Planning

The various climate-related issues in the tropical macroclimate regions described above would not pose a serious problem if climate-inclusive urban planning were implemented from the outset. Recognising this, researchers need to consider climate-resilient urban planning solutions to ensure the sustainability of cities in the future. Therefore, local characteristics (natural and cultural landscapes) must be taken into account when planning a city. In this literature review, a study of the prospects of LCZs in urban planning was conducted by Perera and Emmanuel (2018) in Colombo, Sri Lanka, who demonstrate how the LCZ framework can be utilised to improve urban planning. Although only one relevant urban planning study was identified, the co-occurrence of the keyword "urban planning" more than three times suggests that the various themes addressed in the different studies will contribute to climate-resilient urban planning.

3.5. Other LCZ Applications

The results of the bibliometric analysis based on keywords have provided an overview of current research trends regarding the LCZ scheme in the tropical macroclimate regions. However, several other themes emerged in a number of studies. These included urban health, air quality and a specific study by Pathak *et al.* (2022), which investigated the presence of the urban heat island effect using the LCZ method for the placement of meteorological measurement sensors in Pune (India).

Heat stress as a cause of death, vector-borne diseases, and air quality issues are some of the health problems caused by urban climate issues (Xue *et al.,* 2020). Therefore, researchers have become interested in assessing the urban climate dynamics influenced by LCZ distribution that impact health issues. Brousse *et al.* (2019) demonstrated that the LCZ scheme can be correlated with temperature (using an urban climate model) to study urban health issues, particularly malaria. Furthermore, Brousse *et al.* (2020a) predicted vector behaviour and malaria prevalence based on LCZ.

Air quality monitoring based on LCZs is another topic that is beginning to attract attention. For example, Thomas *et al.* (2023) investigated the uneven influence on air quality due to lockdown policies during Covid-19 in urban Kochi (India). In addition, Khamchiangta and Yamagata (2024)

mapped urban carbon emissions in the building sector in the context of LCZs in Bangkok (Thailand). The emergence of several new themes in LCZ studies may point the way for future research into the field.

3.6. Discussion

Since it was first proposed by Stewart and Oke, the LCZ framework has attracted researchers' interest in applying it to sites or cities in various parts of the world, including cities in the tropical macroclimate regions. Our study comprises a literature review on the progress of the framework in the region. The contributions of LCZ frameworks in tropical environmental studies can be viewed in several ways.

First, LCZ mapping; there is no denying that such mapping using RS-based methods pioneered by the WUDAPT project has dominated LCZ studies for over a decade. Furthermore, although GIS-based methods have not seen significant development, they remain relatively promising. However, both encounter the same problem: data availability and accuracy. In the WUDAPT scheme, the use of pixel-based analysis and free datasets with medium pixel size (such as the Landsat and Sentinel data series) – which are claimed to be user-friendly and accessible to non-experts – has yet to yield optimal results. Therefore, the OBIA method could serve as an alternative for mapping the LCZs in the future.

The case study on the use of the OBIA method in this literature review has been shown to improve overall accuracy. However, it is important to note that the use of medium-resolution data, transferability and the type of classifier need to be carefully tested in the OBIA method. Furthermore, the application of machine learning and deep learning can expand insights into the future prospects of LCZ mapping. A hybrid method (combining RS and GIS) could also serve as a new mapping alternative to improve the accuracy of LCZ mapping. Furthermore, the scope of the LCZ study could be extended to cities with high rates of urbanisation, which, according to United Nations (2019) projections, are expected to have a population of over 5 million by 2030, with a view to expanding the scope of LCZ application whilst testing the transferability of LCZ mapping. Studies conducted in cities across the world, such as those by de Moraes *et al.* (2024), Chen *et al.* (2024), Falah *et al.* (2024), Xie *et al.* (2024), Ding and Chen (2022), Hu *et al.* (2021), Aslam *et al.* (2021), Yeung *et al.* (2020), Brousse *et al.* (2020b) and Li *et al.* (2015) provide sufficient evidence of how uncontrolled urbanisation rates lead to the large-scale conversion of land into various LCZ classes (particularly built-up types) and changes to the physical structure of cities, triggering rises in air temperature, posing dangers and even resulting in mortality.

Second, the application of the LCZ framework in various fields; as described in Sections 3.4 and 3.5, these make a significant contribution to urban climate and urban environmental studies, particularly in tropical macroclimate regions. Current themes are very supportive of the original aim of introducing the LCZ, namely for urban temperature studies and UHI. Overall, each of the LCZ application areas reviewed focuses on the phenomena caused by the response to urban temperature dynamics resulting from human activities represented by the LCZ. In the future, the scope of various LCZ applications—such as monitoring surface temperatures and urban heat islands, heat risks, and thermal comfort—needs to be expanded in order to gain broader insights into mitigation efforts and best practices in urban planning. Other areas of application for LCZs include energy consumption (in buildings and transportation), which contributes to the energy crisis and deteriorating air quality, as well as urban climate modelling for improved urban planning, which is also conducted on a regular basis. In tropical contexts, the scope of LCZ applications can be expanded to address the following gaps:

1) Urban climate monitoring. Monitoring can be implemented in many cities to understand the characteristics of urban heat in tropical cities, including its influence based on the geographical location of cities, such as coastal or highland regions. This monitoring is important for studying urban climate behaviour, which is not limited to temperature alone, but can also cover other climate elements including rainfall, humidity and wind. Therefore, with various studies available, urban climate issues can be identified at an early stage, providing insights for policy-making aimed at improving urban living.

2) Tropical vegetation characteristics. The diversity of tropical vegetation and vegetation phenology could become a new field of application in LCZ studies. The type and density of vegetation in natural land cover types such as "dense trees" (LCZ A) and "scattered trees" (LCZ B) can provide a new perspective on climate-based urban planning, particularly in terms of their cooling effects and carbon storage capacity. This prospect could lead green infrastructure planning toward better future urban planning.

3) Urban environmental studies based on the LCZ from economic and socio-cultural perspectives. Uncontrolled urbanisation frequently results in uncontrolled demand for land. Furthermore, the massive urban expansion that is taking place often leads to regional disparities, resulting in economic and socio-cultural inequalities. Several studies in this literature review demonstrate how urban expansion can affect the urban environment, which in turn can lead to thermal discomfort—a factor that has been shown to correlate with socio-spatial inequalities. Therefore, LCZ studies could be expanded to examine the ability of LCZ to identify issues of environmental injustice that have an impact on economic and socio-cultural issues. LCZ studies can also be geared towards redefining sustainable economic development by examining the impact of economic activities on environmental degradation.

In short, LCZ studies in tropical climate regions can be highly complex and multi-disciplinary.

4. Conclusion

This study comprised a systematic literature review of 51 articles addressing the LCZ framework from spatial and temporal aspects; in relation to bibliometric authors and keywords; and in terms of methods and their application in tropical urban environments. To date, studies involving LCZ frameworks in tropical areas are spread across multiple sites, but concentrated in India. The frequency of publications has fluctuated, peaking in 2024. The authors, coming from various disciplinary backgrounds, reflect the prospects for research collaboration; LCZ has become a complex field involving a multi-disciplinary approach.

The RS-based LCZ mapping method with supervised pixel-based image analysis and random forest classifiers initiated in the WUDAPT project has become the most popular approach taken. Various methods of LCZ mapping continue to be refined in order to obtain the highest quality LCZ maps. Meanwhile, the application of LCZ shows an encouraging and developing trend. Themes include rising surface temperatures and the formation of UHIs, which have various consequences such as heat risk, heat stress and heat hazards, potentially reducing thermal comfort and affecting urban health. In addition, another impact is the increase in energy consumption, which can accelerate the formation of greenhouse gases due to air quality disruption, including an increase in carbon concentration in the air. Therefore, various simulations through urban climate modelling are expected to identify better urban planning formulations in the future.

The LCZ framework in tropical urban environments has been proven to contribute significantly to urban environmental studies and has promising prospects for future development, particularly for a better way of life for humans.

There are, however, limitations to our systematic review. The time lag involved in the publication of the studies means that some documents from subsequent years have not been included. Similarly, the selection of database was limited to Scopus, which means that this it was not possible to cover all the documents published on other databases during the same time period. Keyword selection in a search strategy that is not comprehensive can also lead to bias in the selection of articles. Nevertheless, this literature review is expected to provide insights that can help guide future research in the field of urban environmental studies in macro-tropical climates to tackle climate change issues.

Acknowledgements

The authors would like to thank all parties who contributed to this research and the completion of this manuscript, including supervisors, data providers, and supporting institutions.

Author Contributions

Conceptualization: Harimudin, J., Choy, L. K., Ata, F. M.; **methodology**: Harimudin, J., Choy, L. K.; **investigation**: Harimudin, J.; **writing—original draft preparation**: Harimudin, J.; **writing—review and editing**: Harimudin, J., Choy, L. K.; **visualization**: Harimudin, J. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Data is available upon Request.

Funding

This research received no external funding.

References

Allen, M.R., Dube, O.P., Solecki, W., Aragón-Durand, F., Cramer, W., Humphreys, S., Kainuma, M., Kala, J., Mahowald, N., Mulugetta, Y., Perez, R., Wairiu, M., Zickfeld, K. (2018). *Framing and Context. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (Masson-Delmotte, *et al.* (eds)). Cambridge University Press, Cambridge, UK and New York, NY, USA, 49-92. doi: 10.1017/9781009157940.003

Anjos, M. & Lopes, A. (2017). Urban Heat Island and Park Cool Island Intensities in the Coastal City of Aracaju, North-Eastern Brazil. *Sustainability*, 9, 1379. doi: 10.3390/su9081379

Anjos, M., Lopes, A., de Lucena, A. J., Mendonça, F. (2020). Sea Breeze Front and Outdoor Thermal Comfort during Summer in Northeastern Brazil. *Atmosphere*, 11, 1013. doi: 10.3390/atmos11091013

Aslam, A., Rana, I. A., Bhatti, S. S. (2021). The spatiotemporal dynamics of urbanisation and local climate: A case study of Islamabad, Pakistan. *Environmental Impact Assessment Review,* 91, 106666. doi: 10.1016/j.eiar.2021.106666

Asnawi, N. H., Choy, L. K., Rose, R. A., Widiawaty, M. A., Dede, M., Muhammad, F. N. (2024). Impacts of urban land use and land cover changes on land surface temperature in Kuala Lumpur, Malaysia. *Geografia-Malaysian Journal of Society and Space,* 20(1), 99-120. doi: 10.17576/geo-2024-2001-07

Bechtel, B. & Daneke, C. (2012). Classification of Local Climate Zones Based on Multiple Earth Observation Data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* 5, 1191-1202. doi: 10.1109/JSTARS.2012.2189873

Bechtel, B., Alexander, P. J., Böhner, J., Ching, J., Conrad, O., Feddema, J., Mills, G., See, L., Stewart, I. (2015). Mapping Local Climate Zones for a Worldwide Database of the Form and Function of Cities. *ISPRS Int. J. Geo-Inf.*, 4, 199-219. doi: 10.3390/ijgi4010199

Bechtel, B., Brousse, O., Alexander, P. J., Beck, C., Böhner, J., Hidalgo, J., Ching, J., Demuzere, M., Fonte, C., Gál, T., Hoffmann, P., Middel, A., Mills, G., Ren, C., See, L., Sismanidis, P., Verdonck, M-L., Xu, G., Xu, Y. (2018). Generating WUDAPT Level 0 data – Current status of production and evaluation. *Urban Climate,* 27, 24-45. doi: 10.1016/j.uclim.2018.10.001

Breiman, L. (2001). Random Forests. *Machine Learning* 45, 5–32. doi: 10.1023/A:1010933404324

Brousse, O., Georganos, S., Demuzere, M., Dujardin, S., Lennert, M., Linard, C., Snow, R. W., Thiery, W. (2020a). Can we use local climate zones for predicting malaria prevalence across sub-Saharan African cities? *Environ. Res. Lett.,* 15, 124051. doi: 10.1088/1748-9326/abc996

Brousse, O., Wouters, H., Demuzere, M., Thiery, W., Van de Walle, J., van Lipzig, N. P. M. (2020b). The local climate impact of an African city during clear-sky conditions—Implications of the recent urbanization in Kampala (Uganda). *Int J Climatol.,* 40, 4586 – 4608. doi: 10.1002/joc.6477

Brousse, O., Georganos, S., Demuzere, M., Vanhuysse, S., Wouters, H., Wolff, E., Linard, C., van Lipzig, N. P. M., Dujardin, S. (2019). Using Local Climate Zones in Sub-Saharan Africa to tackle urban health issues. *Urban Climate,* 27, 227–242. doi: 10.1016/j.uclim.2018.12.004

Chen, R., Zhou, S., Liu, S., Li, Z., Xie, J. (2024). Assessment of Urban Spatial Integration Using Human Settlement Environmental Geographic Dataset: A Case Study in the Guangzhou–Foshan Metropolitan Area. *Land*, 13, 1262. doi: 10.3390/land13081262

Ching, J., Mills, G., Bechtel, B., See, L., Feddema, J., Wang, X., Ren, C., Brousse, O., Martilli, A., Neophytou, M., Mouzourides, P., Stewart, I., Hanna, A., Ng, E., Foley, M., Alexander, P., Aliaga, D., Niyogi, D., Shreevastava, A., Bhalachandran, P., Masson, V., Hidalgo, J., Fung, J., Andrade, M., Baklanov, A., Dai, W., Milcinski, G., Demuzere, M., Brunsell, N., Pesaresi, M., Miao, S., Mu, Q., Chen, F., Theeuwes, N. (2018). WUDAPT An Urban Weather, Climate, and Environmental Modelling Infrastructure for the Anthropocene. *Bulletin American Meteorological Society*., 99, 1907–1924. doi: 10.1175/BAMS-D-16-0236.1

Choudhury, D., Das, A., Das, M. (2021). Investigating thermal behavior pattern (TBP) of local climatic zones (LCZs): A study on industrial cities of Asansol-Durgapur development area (ADDA), eastern India. *Urban Climate,* 35 100727. doi: 10.1016/j.uclim.2020.100727

Choy, L. K., Jaafar, M., Halime, L. A., Asnawi, N. H., Rose, R. A. (2020). Analysis of land use and land cover change of Sidon City, Lebanon. *Malaysian Journal of Society and Space,* 16(3), 108-120. doi: 10.17576/geo-2020-1603-09

Daramola, M. T. & Balogun, I. A. (2019). Local climate zone classification of surface energy flux distribution within an urban area of a hot-humid tropical city. *Urban Climate* 29 (2019) 100504. doi: 10.1016/j.uclim.2019.100504

Das, M., Das, A., Mandal, S. (2020). Outdoor thermal comfort in different settings of a tropical planning region: A study on Sriniketan-Santiniketan Planning Area (SSPA), Eastern India. *Sustainable Cities and Society,* 63, 102433. doi: 10.1016/j.scs.2020.102433

Davenport, A. G., Grimmond, S. B., Oke, T. R., Wieringa, J. (2000). Estimating the roughness of cities and sheltered country. *Preprints, 12th Conf. on Applied Climatology*, Asheville, NC, Amer. Meteor. Soc., 96–99.

de Moraes, S. L., Brousse, O., Simpson, C., Almendra, R., Barrozo, L. V., Heaviside, C. (2024). The potential burden from urbanisation on heat-related mortality in Sao Paulo, Brazil. *Urban Climate,* 57, 102104. doi: 10.1016/j.uclim.2024.102104

Demuzere, M., Hankey, S., Mills, G., Zhang, W., Lu, T., Bechtel, B. (2020). Combining expert and crowdsourced training data to map urban form and functions for the continental US. *Scientific Data* (2020), 7, 264. doi: 10.1038/s41597-020-00605-z

Demuzere, M., Kittner, J., Bechtel, B. (2021). LCZ Generator: A Web Application to Create Local Climate Zone Maps. *Front. Environ. Sci.* 9, 637455. doi: 10.3389/fenvs.2021.637455

de Paula, D. C. J., Santos, F. M. D. M., Valin Jr., M. D. O., Novais, J. W. Z., Ventura, T. M., Souza, N. S. (2025). The effects of urban morphology in a city with a tropical continental climate in the context of heat islands. *Urban Climate,* 61, 102381. doi: 10.1016/j.uclim.2025.102381

Dewan, A., Kiselev, G., Botje, D. (2021). Diurnal and seasonal trends and associated determinants of surface urban heat islands in large Bangladesh cities. *Applied Geography,* 135, 102533. doi: 10.1016/j.apgeog.2021.102533

Ding, W. & Chen, H. (2022). Urban-rural fringe identification and spatial form transformation during rapid urbanization: A case study in Wuhan, China. *Building and Environment,* 226, 109697. doi: 10.1016/j.buildenv.2022.109697

Ekanayaka, N., Kankanamge, N., Kangana, N., Goonetilleke, A. (2025). The Impact of Urban Ventilation Corridors on Land Surface Temperature: A Temporal Multisource Spatial Analysis of Colombo, Sri Lanka. *Environment and Urbanization ASIA,* 16(1) 41–69, 2025. doi: 10.1177/09754253251331938

Emmanuel, R., Jalal, M., Ogunfuyi, S., Maharoof, N., Zala, M., Perera, N., Ratnayake, R. (2023). Urban Heat Risk: Protocols for Mapping and Implications for Colombo, Sri Lanka. *Atmosphere*, 14, 343. doi: 10.3390/atmos14020343

Falah, N., Solis-Guzman, J., Falah, N. (2024). Thermal Footprint of the Urbanization Process: Analyzing the Heat Effects of the Urbanization Index (UI) on the Local Climate Zone (LCZ) and Land Surface Temperature (LST) over Two Decades in Seville. *Land*, 13, 1877. doi: 10.3390/land13111877

Fardani, I., Razak, F., Saraswati. (2024). Spatial-temporal analysis between landcover change and urban surface temperature of bekasi city, indonesia. *PLANNING MALAYSIA: Journal of the Malaysian Institute of Planners,* 22(1), 194 – 208. doi: 10.21837/pm. v22i30.1434

Feng, W. & Liu, J. (2022). A Literature Survey of Local Climate Zone Classification: Status, Application, and Prospect. *Buildings*, 12, 1693. doi: 10.3390/buildings12101693

Fernandes, R., Nascimento, V., Freitas, M., Ometto, J. (2023). Local Climate Zones to Identify Surface Urban Heat Islands: A Systematic Review. *Remote Sens.*, 15, 884. doi: 10.3390/rs15040884

Gál, T., Bechtel, B., Unger, J. (2015). Comparison of two different Local Climate Zone mapping methods. *ICUC9 – 9th International Conference on Urban Climate jointly with 12th Symposium on the Urban Environment.*

Gupta, A., Sadab., A., De, B. (2024). Assessment of critical thermal characteristics and land surface dynamics of an Indian metropolitan city. *Journal of Water and Climate Change,* 15(7), 3409. doi: 10.2166/wcc.2024.370

Han, J., Mo, N., Cai, J., Ouyang, L., Liu, Z. (2024). Advancing the local climate zones framework: a critical review of methodological progress, persisting challenges, and future research prospects. *Humanities and Social Sciences Communications*, 11, 538. doi: 10.1057/s41599-024-03072-8

Hu, J., Wang, Y., Taubenbock, H., Zhu, X. X. (2021). Land consumption in cities: A comparative study across the globe. *Cities,* 113 (2021) 103163. doi: 10.1016/j.cities.2021.103163

Hutton, B., Salanti, G., Caldwell, D. M., Chaimani, A., Schmid, C. H., Cameron, C., Ioannidis, J. P. A., Straus, S., Thorlund, K., Jansen, J. P., Mulrow, C., Lopez, F. C., Gotzsche, P. C., Dickersin, K., Boutron, I., Altman, D. G., Moher, D. (2015). The PRISMA Extension Statement for Reporting of Systematic Reviews Incorporating Network Meta-analyses of Health Care Interventions: Checklist and Explanations. *Ann Intern Med.*, 162, 777-784. doi: 10.7326/M14-2385

IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Pachauri, R.K. & Meyer, L.A. (eds.)). IPCC, Geneva, Switzerland, 151 pp.

Jahan, N., Naveed, S., Zeshan, M., Tahir, M. A. (2016). How to Conduct a Systematic Review: A Narrative Literature Review. *Cureus,* 8(11), e864. doi: 10.7759/cureus.864

Kabano, P., Lindley, S., Harris, A. (2021). Evidence of urban heat island impacts on the vegetation growing season length in a tropical city. *Landscape and Urban Planning,* 206, 103989. doi: 10.1016/j.landurbplan.2020.103989

Khamchiangta, D. & Dhakal, S. (2019). Physical and non-physical factors driving urban heat island: Case of Bangkok Metropolitan Administration, Thailand. *Journal of Environmental Management,* 248, 109285. doi: 10.1016/j.jenvman.2019.109285

Khamchiangta, D. & Dhakal, S. (2021). Future urban expansion and local climate zone changes in relation to land surface temperature: Case of Bangkok Metropolitan Administration, Thailand. *Urban Climate,* 37, 100835. doi: 10.1016/j.uclim.2021.100835

Khamchiangta, D. & Yamagata, Y. (2024). Mapping urban carbon emissions in relation to local Climate zones: Case of the building sector in Bangkok Metropolitan Administration, Thailand. *Energy and Built Environment,* 5, 337–347. doi: 10.1016/j.enbenv.2022.11.002

Kotharkar, R. & Bagade, A. (2018a). Local Climate Zone classification for Indian cities: A case study of Nagpur. *Urban Climate,* 24, 369–392. doi: 10.1016/j.uclim.2017.03.003

Kotharkar, R. & Bagade, A. (2018b). Evaluating urban heat island in the critical local climate zones of an Indian city. *Landscape and Urban Planning,* 169, 92–104. doi: 10.1016/j.landurbplan.2017.08.009

Kotharkar, R. & Dongarsane, P. (2024a). Investigating outdoor thermal comfort variations across Local Climate Zones in Nagpur, India, using ENVI-met. *Building and Environment,* 249, 111122. doi: 10.1016/j.buildenv.2023.111122

Kotharkar, R., Bagade, A., Agrawal, A. (2019b). Investigating Local Climate Zones for Outdoor Thermal Comfort Assessment in an Indian City. *Geographica Pannonica,* 23(4), 318–328. doi: 10.5937/gp23-24251

Kotharkar, R., Bagade, A., Ramesh, A. (2019a). Assessing urban drivers of canopy layer urban heat island: A numerical modelling approach. *Landscape and Urban Planning*, 190, 103586. doi: 10.1016/j.landurbplan.2019.05.017

Kotharkar, R., Bagade, A., Singh, P. R. (2020). A systematic approach for urban heat island mitigation strategies in critical local climate zones of an Indian city. *Urban Climate,* 34, 100701. doi: 10.1016/j.uclim.2020.100701

Kotharkar, R., Dongarsane, P., Ghosh, A., Kotharkar, V. (2024b). Numerical analysis of extreme heat in Nagpur city using heat stress indices, all-cause mortality and local climate zone classification. *Sustainable Cities and Society,* 101, 105099. doi: 10.1016/j.scs.2023.105099

Kotharkar, R., Ghosh, A., Kapoor, S., Reddy, D. G. K. (2022). Approach to local climate zone-based energy consumption assessment in an Indian city. *Energy & Buildings,* 259, 111835. doi: 10.1016/j.enbuild.2022.111835

Kotharkar, R., Ghosh, A., Kotharkar, V. (2021). Estimating summertime heat stress in a tropical Indian city using Local Climate Zone (LCZ) framework. *Urban Climate,* 36, 100784. doi: 10.1016/j.uclim.2021.100784

Lefevre, A., Malet-Damour, B., Bénard, F., Boyer, H., Rivière, G. (2025). Integrating urban heat island analysis for sustainable urban planning: Insights from Reunion Island. *Building and Environment,* 278, 112964. doi: 10.1016/j.buildenv.2025.112964

Lehnert, M., Savic, S., Milošević, D., Dunjic, J., Geletic, J. (2021). Mapping Local Climate Zones and Their Applications in European Urban Environments: A Systematic Literature Review and Future Development Trends. *ISPRS Int. J. Geo-Inf.*, 10, 260. doi: 10.3390/ijgi10040260

Lelovics, E., Unger, J., Gál, T., Gál, C. V. (2014). Design of an urban monitoring network based on Local Climate Zone mapping and temperature pattern modelling. *Clim Res,* 60, 51–62, 2014. doi: 10.3354/cr01220

Li, L., Chan, P. W., Wang, D., Tan, M. (2015). Rapid urbanization effect on local climate: intercomparison of climate trends in Shenzhen and Hong Kong, 1968−2013. *Clim Res.,* 63, 145–155, 2015 doi: 10.3354/cr01293

Ma, L., Zhu, X., Qiu, C., Blaschke, T., Li, M. (2021). Advances of Local Climate Zone Mapping and Its Practice Using Object-Based Image Analysis. *Atmosphere*, 12, 1146. doi: 10.3390/atmos12091146

Mancheno, G., Castro-Molinare, J., Jorquera, H. (2024). Predictive modeling the effect of Local Climate Zones (LCZ) on the urban meteorology in a tropical andean area. *Modeling Earth Systems and Environment*, 10, 6133–6153. doi: 10.1007/s40808-024-02121-0

Marcotullio, P. J., Keßler, C., Gonzalez, R. Q., Schmeltz, M. (2021). Urban Growth and Heat in Tropical Climates. *Front. Ecol. Evol.,* 9, 616626. doi: 10.3389/fevo.2021.616626

McCarthy, M. P. & Sanderson, M. G. (2011). *Urban Heat Island: Sensitivity of Urban Temperatures to Climate Change and Heat Release in Four European Cities* (Hoornweg, *et al*. (Eds)). Cities and Climate Change: Responding to an Urgent Agenda. The International Bank for Reconstruction and Development/The World Bank. Washington. doi: 10.1596/978-0-8213-8493-0

Middel, A., Lukasczyk, J., Maciejewski, R., Demuzere, M., Roth, M. (2018). Sky View Factor footprints for urban climate modelling. *Urban Climate,* 25, 120–134. doi: 10.1016/j.uclim.2018.05.004

Mills, G., Bechtel, B., Ching, J., See, L., Feddema, J., Foley, M., Alexander, P., O'Connor, M. (2015). An Introduction to the WUDAPT project. *ICUC9 – 9 International Conference on Urban Climate jointly with 12th Symposium on the Urban Environment. Toulouse, France.*

Morris, K. I., Salleh, S. A., Chan, A., Ooi, M. C. G., Abakr, Y. A., Oozeer, M. Y., & Duda, M. (2015). Computational study of urban heat island of Putrajaya, Malaysia. *Sustainable Cities and Society*, 19, 359-372. doi: 10.1016/j.scs.2015.04.010

Mughal, M. O., Li, X-X., Yin, T., Martilli, A., Brousse, O., Dissegna, M. A., Norford, L. K. (2019). High-Resolution, Multilayer Modeling of Singapore's Urban Climate Incorporating Local Climate Zones. *Journal of Geophysical Research: Atmospheres*, 124, 7764–7785. doi: 10.1029/2018JD029796

Nurwanda, A. & Honjo, T. (2018). Analysis of Land Use Change and Expansion of Surface Urban Heat Island in Bogor City by Remote Sensing. *ISPRS Int. J. Geo-Inf.*, 7, 165. doi:10.3390/ijgi7050165

Obe, O. B., Morakinyo, T. E., Mills, G. (2024a). A study of the impact of landscape heterogeneity on surface energy fluxes in a tropical climate using SUEWS. *Urban Climate,* 53, 101788. doi: 10.1016/j.uclim.2023.101788

Obe, O. B., Morakinyo, T. E., Mills, G. (2024b). An assessment of WRF-urban schemes in simulating local meteorology for heat stress analysis in a tropical sub-Saharan African city, Lagos, Nigeria. *International Journal of Biometeorology*, 68, 811–828. doi: 10.1007/s00484-024-02627-3

Ochola, E. M., Fakharizadehshirazi, E., Adimo, A. O., Mukundi, J. B., Wesonga, J. M., Sodoudi, S. (2020). Inter-local climate zone differentiation of land surface temperatures for Management of Urban Heat in Nairobi City, Kenya. *Urban Climate,* 31, 100540. doi: 10.1016/j.uclim.2019.100540

Patel, P., Karmakar, S., Ghosh, S., Niyogi, D. (2020). Improved simulation of very heavy rainfall events by incorporating WUDAPT urban land use/land cover in WRF. *Urban Climate,* 32, 100616. doi: 10.1016/j.uclim.2020.100616

Pathak, P., Pandya, P., Shukla, S., Sane, A., Sengupta, R. (2022). A Sensor Placement Strategy for Comprehensive Urban Heat Island Monitoring. *ISPRS Int. J. Geo-Inf.*, 12, 11. doi: 10.3390/ijgi12010011

Pereira, C. T., Masiero, É., Bourscheidt, V. (2021). Socio-spatial inequality and its relationship to thermal (dis)comfort in two major Local Climate Zones in a tropical coastal city. *International Journal of Biometeorology*, 65, 1177–1187. doi: 10.1007/s00484-021-02099-9

Perera, N. G. R. & Emmanuel, R. (2018). A "Local Climate Zone" based approach to urban planning in Colombo, Sri Lanka. *Urban Climate,* 23, 188–203. doi: 10.1016/j.uclim.2016.11.006

Pokhrel, R., Ramírez-Beltran, N. D., González, J. E. (2019). On the assessment of alternatives for building cooling load reductions for a tropical coastal city. *Energy & Buildings,* 182, 131–143. doi: 10.1016/j.enbuild.2018.10.023

Quan, S.J. & Bansal, P. (2021). A systematic review of GIS-based local climate zone mapping studies. *Building and Environment,* 196, 107791. doi: 10.1016/j.buildenv.2021.107791

Rendana, M., Idris, W. M., Rahim, S. A., Abdo, H. G., Almohamad, H., Al Dughairi, A. A., Al Mutiry, M. (2023). Relationships between land use types and urban heat island intensity in Hulu Langat district, Selangor, Malaysia. *Ecological Processes*, 12, 33. doi: 10.1186/s13717-023-00446-9

Roth, M. (2007). Review of urban climate research in (sub) tropical regions. *Int. J. Climatol.* 27, 1859–1873. doi: 10.1002/joc.1591

Roth, M., Sanchez, B., Li, R., Velasco, E. (2022). Spatial and temporal characteristics of near-surface air temperature across local climate zones in a tropical city. *Int J Climatol*., 1–23. doi: 10.1002/joc.7862

Rubel, F., Brugger, K., Haslinger, K., Auer, I. (2017). The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800–2100. *Meteorol. Z*., 26, 2017. doi: 10.1127/metz/2016/0816

Sanchez, B., Roth, M., Patel, P., Simón-Moral, A. (2023). Application of a Semi-Empirical Approach to Map Maximum Urban Heat Island Intensity in Singapore. *Sustainability*, 15, 12834. doi: 10.3390/su151712834

Selçuk, A. A. (2019). A Guide for Systematic Reviews: PRISMA. *Turk Arch Otorhinolaryngol*, 57(1), 57-8. doi: 10.5152/tao.2019.4058

Simanjuntak, R. M., Kuffer, M., Reckien, D. (2019). Object-based image analysis to map local climate zones: The case of Bandung, Indonesia. *Applied Geography,* 106, 108–121. doi: 10.1016/j.apgeog.2019.04.001

Stewart, I. D. & Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin American Meteorology Society*., 93, 1879–1900. doi: 10.1175/BAMS-D-11-00019.1

Theeuwes, N. E., Steeneveld, G.-J., Ronda, R. J., Holtslag, A. A. M. (2017). A diagnostic equation for the daily maximum urban heat island effect for cities in northwestern Europe. *Int. J. Climatol.,* 201737(1), 443–454. doi: 10.1002/joc.4717

Thomas, G., Thomas, J., Mathew, A. V., Devika, R. S., Krishnan, A., Nair, A. J. (2023). Non-uniform effect of COVID-19 lockdown on the air quality in different local climate zones of the urban region of Kochi, India. *Spatial Information Research*, 31, 145–155. doi: 10.1007/s41324-022-00481-2

United Nations. (2019). *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*. New York: United Nations.

Vaidya, M., Keskar, R., Kotharkar, R. (2024a). Classifying heterogeneous urban form into local climate zones using supervised learning and greedy clustering incorporating Landsat dataset. *Urban Climate,* 53, 101770. doi: 10.1016/j.uclim.2023.101770

Vaidya, M., Keskar, R., Kotharkar, R. (2024b). Quantifying the effect of surrounding spatial heterogeneity on land surface temperature based on local climate zones using mutual information. *Sustainable Cities and Society,* 107, 105455. doi: 10.1016/j.scs.2024.105455

Vaidya, M., Keskar, R., Kotharkar, R. (2024c). DEALB: A Post-classification Framework for Regionalizing Local Climate Zones in the Urban Environment. *Journal of the Indian Society of Remote Sensing,* 52(10):2293–2315. doi: 10.1007/s12524-024-01950-x

Van de Walle, J., Brousse, O., Arnalsteen, L., Brimicombe, C, Byarugaba, D., Demuzere, M., Jjemba, E., Lwasa, S., Misiani, H., Nsangi, G., Soetewey, F., Sseviiri, H., Thiery, W., Vanhaeren, R., Zaitchik, B. F., van Lipzig, N. P. M. (2022). Lack of vegetation exacerbates exposure to dangerous heat in dense settlements in a tropical African city. *Environ. Res. Lett.,* 17, 024004. doi: 10.1088/1748-9326/ac47c3

Van de Walle, J., Brousse, O., Arnalsteen, L., Byarugaba, D., Ddumba, D. S., Demuzere, M., Lwasa, S., Nsangi, G., Sseviiri, H., Thiery, W., Vanhaeren, R., Wouters, H., van Lipzig N. P.M. (2021). Can local fieldwork help to represent intra-urban variability of canopy parameters relevant for tropical African climate studies? *Theoretical and Applied Climatology*, 146, 457–474. doi: 10.1007/s00704-021-03733-7

Verdonck, M. L., Okujeni, A., van der Linden, S., Demuzere, M., De Wulf, R., Van Coillie, F. (2017). Influence of neighbourhood information on 'Local Climate Zone' mapping in heterogeneous cities. *Int J Appl. Earth Obs Geoinformation,* 62(2017) 102–113. doi: 10.1016/j.jag.2017.05.017

Villadiego, K. & Vellay-Dabat, M. A. (2014). Outdoor thermal comfort in a hot and humid climate of Colombia: A field study in Barranquilla. *Building and Environment* 75 (2014) 142-152. doi: 10.1016/j.buildenv.2014.01.017

Voogt, J. A. & Oke, T. R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment,* 86(2003) 370 – 384. doi:10.1016/S0034-4257(03)00079-8

Wang, R., Wang, M., Ren, C., Chen, G., Mills, G., Ching, J. (2024). Mapping local climate zones and its applications at the global scale: A systematic review of the last decade of progress and trend. *Urban Climate,* 57(2024), 102129. doi: 10.1016/j.uclim.2024.102129

Wellinger, N., Gubler, M., Müller, F., Bronnimann, S. (2024). GIS-based revision of a WUDAPT Local Climate Zones map of Bern, Switzerland. *City and Environment Interactions,* 21, 100135. doi: 10.1016/j.cacint.2023.100135

Wibowo, A., Abisha, N. R., Hernina, R., Kusratmoko, E., Saraswati, R. (2023). Urban Heat Hazard Model Based on Local Climate Zones. *International Journal of GEOMATE*, 24(103), 96-103. doi: 10.21660/2023.103.g12284

Wills, S. (2016). Extremes of Temperature: Hyperthermia. *Encyclopedia of Forensic and Legal Medicine,* 2 (2016) 476-485. doi: 10.1016/B978-0-12-800034-2.00175-0

Xie, J., Wei, N., Gao, Q. (2024). Assessing spatiotemporal population density dynamics from 2000 to 2020 in megacities using urban and rural morphologies. *Scientiic Reports* (2024), 14, 14166. doi: 10.1038/s41598-024-63311-5

Xue, J., You, R., Liu, W., Chen, C., Lai, D. (2020). Applications of Local Climate Zone Classification Scheme to Improve Urban Sustainability: A Bibliometric Review. *Sustainability* 2020, 12, 8083. doi: 10.3390/su12198083

Yan, Z., Ma, L., He, W., Zhou, L., Lu, H., Liu, G., Huang, G. (2022). Comparing Object-Based and Pixel-Based Methods for Local Climate Zones Mapping with Multi-Source Data. *Remote Sens*., 2022, 14, 3744. doi: 10.3390/rs14153744

Yeung, P. S., Fung, J. C-H., Ren, C., Xu, Y., Huang, K., Leng, J., Wong, M. M-F. (2020). Investigating Future Urbanization's Impact on Local Climate under Different Climate Change Scenarios in MEGA-urban Regions: A Case Study of the Pearl River Delta, China. *Atmosphere*, 11, 771. doi:10.3390/atmos11070771

Zhang, H., Bai, J., Zhao, J., Guo, F., Zhu, P., Dong, J., Cai, J. (2024b). Application and future of local climate zone system in urban climate assessment and planning—Bibliometrics and meta-analysis. *Cities* Volume, 150(2024) 104999. doi: 10.1016/j.cities.2024.104999

Zhang, L., Zhou, L., Yuan, B., Wang, B., Wei. W. (2024a). Multifactorial influences on land surface temperature within local climate zones of typical global cities. *Urban Climate,* 57 (2024) 102130. doi: 10.1016/j.uclim.2024.102130