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Advancing the local climate zones framework: a critical review of methodological progress, persisting challenges, and future research prospects

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The local climate zones (LCZs) classification system has emerged as a more refined method for assessing the urban heat island (UHI) effect. However, few researchers have conducted systematic critical reviews and summaries of the research on LCZs, particularly regarding significant advancements of this field in recent years. This paper aims to bridge this gap in scientific research by systematically reviewing the evolution, current status, and future trends of LCZs framework research. Additionally, it critically assesses the impact of the LCZs classification system on climate-responsive urban planning and design. The findings of this study highlight several key points. First, the challenge of large-scale, efficient, and accurate LCZs mapping persists as a significant issue in LCZs research. Despite this challenge, the universality, simplicity, and objectivity of the LCZs framework make it a promising tool for a wide range of applications in the future, especially in the realm of climate-responsive urban planning and design. In conclusion, this study makes a substantial contribution to the advancement of LCZs research and advocates for the broader adoption of this framework to foster sustainable urban development. Furthermore, it offers valuable insights for researchers and practitioners engaged in this field.

Introduction

Urbanization is an irreversible process that will continue to accelerate over the next three decades, resulting in a projected global urban population increase of up to 668 million (UN-Habitat 2022). While urbanization brings economic development, cultural exchange, and technological progress, it also concentrates people in cities, leading to higher greenhouse gas emissions and pollutants. These emissions contribute to air quality degradation, global warming, and climate change. Urban heat island (UHI), characterized by higher temperatures in urban areas compared to their surrounding rural areas, is a consequence of urbanization, driven by unique urban surfaces and anthropogenic heat release. UHI carries numerous

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Table 1 Current review articles for LCZs research.

Reference	Research theme	Differentiation from the proposed study
(Huang et al. 2023)	Bibliometric and critical review of LCZs mapping progress, challenges, and prospects based on literature from 2012 to 2021.	• Focus on LCZs mapping study, lack of description of LCZs application areas. • The bibliometric analysis has the limitation of time lag.
(Fan et al. 2023)	Bibliometric and critical review of research progress, focuses, and prospects of LCZs based on literature up to November 2022.	• Focus on bibliometric review of LCZs study, lack of in-depth critical analysis of LCZs research. • The bibliometric analysis has the limitation of time lag.
(Fernandes et al. 2023)	Systematical review of the scientific literature that uses the LCZs classification to study the LST and the SUHI phenomenon based on literature up to June 2020.	• Focus on review of SUHI study using LCZs framework, lack of analysis of LCZs mapping and LCZs application fields except SUHI. • The bibliometric analysis has the limitation of time lag.
(Aslam and Rana 2022)	Systematic review of data sources, methods, and themes of LCZs study based on literature up to July 2020.	• The bibliometric analysis has the limitation of time lag.
(Quan and Bansal 2021)	Systematic review of GIS-based LCZs mapping studies based on literature up to April 2020.	• Focus on review of GIS-based LCZs mapping study, lack of description of RS-based LCZs mapping, and LCZs application fields.
(Lehnert et al. 2021)	Systematic review of LCZs mapping and applications in European Urban Environments based on literature up to June 2020.	• Solely reflects developments of LCZs study in Europe. • The bibliometric analysis has the limitation of time lag.
(Ma et al. 2021)	Systematic review of LCZs mapping based on literature up to August 2021.	• Focus on LCZs mapping study, lack of description of LCZs application areas. • The bibliometric analysis has the limitation of time lag.
(Xue et al. 2020)	Bibliometric review of the applications of LCZs Classification Scheme based on literature up to July 2020.	• Focus on the application of LCZs framework, lack of description of LCZs mapping. • The bibliometric analysis has the limitation of time lag.
(Núñez Peiró et al. 2019)	Systematic review of the source area definition for LCZs studies based on literature before 2017.	• Lack of description of LCZs mapping and the application of LCZs framework. • The bibliometric analysis has the limitation of time lag.

adverse effects, including increased energy consumption, air pollution, degradation of living conditions, and elevated heat-related mortality rates. All of these challenges significantly impede sustainable development, underscoring the critical importance of identifying, mitigating, and adapting to UHI (Huang and Lu 2018).

The term "urban heat island" was first introduced by Balchin and Pye (1947), and it has since become a prominent research field within urban climate studies (Peng et al. 2022, Zhang et al. 2022, Mo et al. 2024). The central issue in UHI research revolves around quantifying urban heat island intensity (UHII) (Huang and Lu 2018). The conventional approach to UHI evaluation involves computing UHII by comparing the average temperature difference between urban and rural areas. However, this method encounters limitations due to the diverse nature of urban morphology, land cover, and human activities, leading to varying UHII results within urban areas. Consequently, UHI analysis and mitigation strategies based on these results lack precision. Another challenge with the urban-rural dichotomy lies in selecting suburban measurement points that are minimally affected by urbanization. With urbanization, the once-clear social, political, and economic boundaries between urban and rural areas have blurred. It is more accurate to describe the relationship between urban and rural areas as a continuous and dynamic system rather than a rigid dichotomy.

To address the shortcomings of the traditional "urban-rural dichotomy" in UHI research, the local climate zones (LCZs) classification system, introduced by Stewart and Oke (2012), offers a fresh research framework. This system has expanded its applications beyond UHI research and is now being employed in other domains related to sustainable urban development, including urban planning (Pradhesta et al. 2019, Kopp et al. 2021), building energy consumption (Yang et al. 2020a, 2022, Benjamin et al. 2021), and urban thermal comfort (Lau et al. 2019, Wu et al. 2022).

Table 1 lists the existing review articles on LCZs research. Many researchers in the domain of LCZs mapping have directed their attention to the current advancements in this area. For instance, Huang et al. (2023) offered a comprehensive review of LCZs mapping, providing detailed analyses of remote sensing (RS)-based and geographic information system (GIS)-based methods. They discussed RS-based methods in terms of feature sets, classification units, training areas, classification algorithms, and accuracy assessment, while GIS-based methods were elaborated based on LCZ parameters, basic spatial units (BSUs), classification algorithms, and accuracy assessment. Quan and Bansal (2021) summarized the general LCZs mapping processes in the reviewed studies, encompassing data collection, defining BSUs, calculating urban canopy parameters (UCPs), LCZs classification, post-processing, and performance evaluation. Ma et al. (2021) conducted a timely investigation into RS-based LCZs mapping applications. They analyzed and evaluated several aspects influencing LCZs mapping performance, including mapping units/scales, transferability, sample datasets, low accuracy, and classification schemes. Meanwhile, researchers have dedicated their focus to the field pertaining to the LCZs framework. For example, Lehnert et al. (2021) provided a comprehensive analysis of the application of the LCZs framework in European urban areas, demonstrating an increasing and widely recognized use of LCZs in climate research across European cities. Xue et al. (2020) explored the applications of LCZs schemes in various research fields such as meteorology, atmospheric science, environmental science, remote sensing, architectural technology, civil engineering, and ecology by conducting a bibliometric analysis of articles citing LCZs using CiteSpace. Additionally, most review studies utilize bibliometric analysis to review LCZs research. However, bibliometric analysis has the limitation of time lag due to the literature on which it is based, which can not sufficiently reflect the latest research progress.

The mentioned studies indicate the significant attention LCZs-related research has garnered within the academic community.

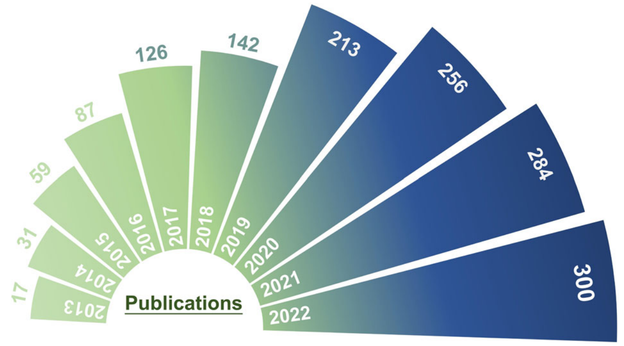

Fig. 1 Annual output of LCZs research.

Nonetheless, several noticeable gaps exist: 1) Few researchers have systematically conducted critical reviews and comprehensive summaries of LCZs research, especially concerning its recent notable advancements. 2) A thorough investigation into its development, research methodologies, and broader applications, particularly in sustainable urban development contexts, is warranted. This paper's innovations and contributions primarily involve:

1) Given recent advancements, this study comprehensively examines and categorizes research methods and application areas within the LCZs framework. This analysis provides a thorough understanding of theoretical foundations and practical applications, contributing to a more holistic comprehension of LCZs studies.

2) The paper critically evaluates the effectiveness of the LCZs classification system in supporting climate-responsive urban planning and design. This assessment is crucial in understanding the practical utility of the LCZs framework for sustainable urban development and its potential to mitigate UHI challenges.

The primary sections of this paper are structured as follows: The literature survey and corresponding quantitative analysis are presented in Literature Survey. Advancements in local climate zones framework introduces the LCZs framework and delves into the measurement of UCPs. Recent advancements in manual sampling and mapping methods of LCZs reviews the progress of LCZs research methods applied in UHI research. Application of LCZs framework in various scenarios explores the various application areas of LCZs, with a particular focus on its utility in UHI research and climate-sensitive urban design. Limitations, challenges, and future prospects engages in a discussion regarding research limitations and potential future applications of the LCZs framework. Conclusions presents the key findings and conclusions drawn from the study. This structured approach allows for a systematic and in-depth exploration of the LCZs classification system's development and its multifaceted applications in the context of research related to sustainable urban development.

Literature survey

This study conducted a comprehensive screening of all peer-reviewed journal and conference papers that cited the original LCZs framework articles based on the Web of Science dataset. As of February 2023, a total of 1534 papers were identified. Based on this, we performed literature statistics and bibliometric analysis to quantitatively assess the current state of development of LCZs research.

Literature statistics. The literature statistics were conducted from three aspects: annual output, country distribution, and research fields. Figures 1 and 2 provide visual representations of the annual output and the country distribution of LCZs research for the period spanning from 2013 to 2022. Since the introduction of the LCZs framework in 2012, there has been a notable surge in publications related to LCZs research. Specifically, the number of publications has seen a substantial increase, starting at 17 in 2013 and reaching 300 in 2022. This upward trend underscores the escalating interest and engagement in LCZs research within the academic community and beyond. Furthermore, the distribution of countries reveals five nations that have made substantial contributions to LCZs research. China stands out with the highest number of papers, accounting for 668 publications, which amounts to approximately 43.55% of the total papers. Following China, the United States, Germany, the United Kingdom, and Australia have also made significant contributions to LCZs research, with 333, 225, 176, and 104 publications, respectively. These statistics highlight the global reach and significance of LCZs research, with diverse countries actively participating in advancing this research field.

Table 2 provides an overview of the distribution of research fields related to LCZs. LCZs research is characterized by its interdisciplinary nature, encompassing a wide spectrum of academic disciplines. The research content of LCZs studies spans several fields: (1) Meteorology and atmospheric sciences: The LCZs framework is employed to investigate urban meteorology, evaluate the impact of urbanization on weather patterns, and develop models for urban climate simulations; (2) Environmental sciences and ecology: The LCZs classification system helps identify and quantify the effect of urbanization on ecosystems, biodiversity, and the overall environment; (3) Physical sciences: The LCZs classification takes into account physical parameters such as surface materials, building density, and thermal admittance. This classification helps physical scientists study the thermal characteristics of urban surfaces, develop models for energy balance calculations, and explore the impact of different materials on the UHI effect; (4) Geography: Geographers use LCZs framework to investigate urban morphology, land use dynamics, urban-rural interactions, and the relationship between urban form and climate; (5) Energy and fuels: The LCZs classification system helps identify areas with high energy demand or heat stress, guiding the development of energy-efficient buildings, urban cooling techniques, and renewable energy integration; (6) RS: RS is a prominent and integral research direction within LCZs. It involves the use of satellite and aerial imagery to map and monitor large-scale urban climates, often supported by GIS technologies. The multidisciplinary nature of LCZs research enables cross-disciplinary collaboration and knowledge integration, making it a versatile framework for understanding and addressing urban climate challenges.

Bibliometric analysis. The study employs the concept of "co-occurrence clustering" and utilizes the CiteSpace visualization software to conduct a bibliometric analysis of the screening results. In this analysis, the fundamental unit of information extraction and structural construction is the "keywords". The research utilizes a "keyword co-occurrence" network to depict the knowledge structure, research evolution, and current research focal points within the LCZs application field. In this network, each node corresponds to a keyword found in the literature, and the links represent the connections between these keywords. The objective is to visually and analytically explore the nodes, links, and overall network structure, shedding light on the present state of development in the LCZs application field. This approach allows for a systematic and data-driven examination of the relationships between keywords and their significance within the context of LCZs research. It facilitates the identification of trends, patterns, and emerging areas of

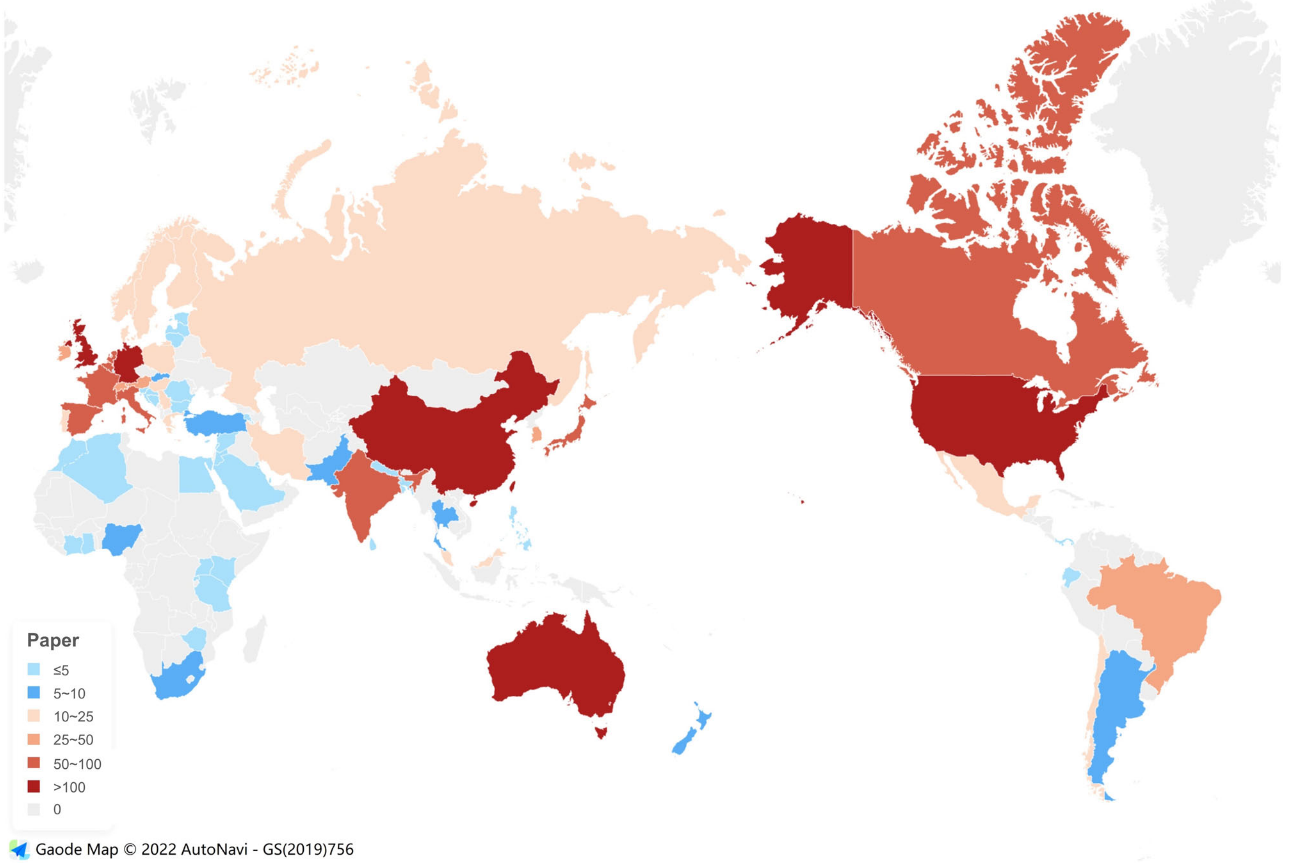

Fig. 2 Country distribution of LCZs research.

Table 2 Distribution of research fields for LCZs research.

	Research field	Number of studies	Proportion/%
1	Meteorology Atmospheric Sciences	948	61.80
2	Environmental Sciences Ecology	944	61.54
3	Physical Sciences Other Topics	615	40.09
4	Geography	500	32.60
5	Engineering	410	26.73
6	Geochemistry Geophysics	365	23.79
7	Science Technology Other Topics	333	21.71
8	Energy Fuels	310	20.21
9	Construction Building Technology	275	17.93
10	Remote Sensing	247	16.10

interest within this field, providing valuable insights for researchers and practitioners alike.

In the analyzed literature employing the LCZs framework, several recurring nodes stand out, shedding light on the primary objectives and emphases of LCZs research. The top five frequently occurring nodes include “urban heat island,” “temperature,” “climate,” “impact,” and “city,” as illustrated in Fig. 3. These nodes collectively indicate that LCZs research primarily seeks to understand the factors influencing urban climates (“climate” and “city”), particularly the impact on temperature parameters (“temperature”). There is a notable focus on examining how the factors affect UHI (“urban heat island”), which aligns with the LCZs framework’s original purpose. The high frequency of “urban heat island” (697 times, with 144 mentions in 2021) underscores its central role in LCZs research. This centrality stems from the LCZs framework’s inception, which aimed to address the limitations of the “urban-rural dichotomy” in UHI studies, enabling a more nuanced understanding of UHI impacts and the development of effective mitigation strategies.

Advancements in local climate zones framework

Local climate zone classification system. LCZs are defined as areas with uniform surface cover, structure, material, and human activity, with a minimum radius of 200–500 m, which exhibit local-scale, climatic nature, and zonal representation as depicted in Fig. 4. The LCZs classification system is based on 10 UCPs with recommended ranges, allowing for classification into 17 standard LCZ patterns, comprising 10 built types and 7 land cover types. The various LCZ types represent the diverse compositions of buildings, roads, plants, soils, rocks, and water. The names of standard built types primarily reflect three building structure characteristics (Density: compact/open; Height: high/mid/low; Material: heavy/lightweight) and building type (general/

industrial). Conversely, the counterparts of standard land cover types mainly reflected the vegetation and land cover characteristics.

The process of LCZs classification usually involves four steps: data acquisition, UCPs calculation, LCZs classification, and accuracy evaluation. The first step is to collect the required information for the study area (e.g., field measurements and satellite images). The second step involves calculating UCPs using the data gathered in the previous step. A detailed description of the calculation methods for UCPs is provided in Measurement of urban canopy parameters. For LCZs classification, the results from UCPs calculation can assist in identifying the best match between field sites and LCZ classes. Additionally, LCZs subclasses can be customized when UCPs deviate from the recommended ranges of the standard set of classes. For instance, a combination of LCZ 4 (Open high-rise) and 3 (Compact low-rise) can provide LCZ 3_4 (Compact low-rise with open high-rise).

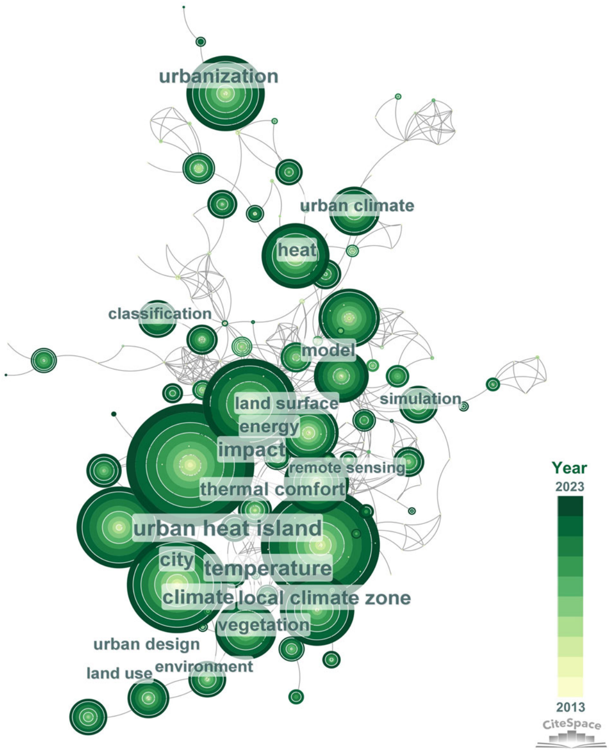

Fig. 3 Keyword co-present of the analyzed LCZs literature.

Measurement of urban canopy parameters. For achieving precise LCZs classification, obtaining accurate values for UCPs is of paramount importance. These UCPs are primarily related to surface structure parameters, including sky view factor (SVF) (Steyn 1980, Matzarakis et al. 2007, Liang et al. 2017), aspect ratio (AR) (Masson 2000), and height of roughness elements (HRE) (Yan and Huang 2022, Wu et al. 2023). They also encompass surface cover parameters such as building surface fraction (BSF) (Yu et al. 2010, Guo et al. 2022, Jifroudi et al. 2022, Wei et al. 2023), impervious surface fractions (ISF), and pervious surface fractions (PSF) (Deng and Wu 2013, Sytsma et al. 2020). Surface fabric parameters (surface admittance and surface albedo (Bartmiński and Siłuch 2022, Tahooni et al. 2023)) and human activity parameters (anthropogenic heat flux (Yu et al. 2021, Wang et al. 2022b, Liu and Li 2023)) are equally included.

In the absence of specific heat-related indicators, most current studies rely on the geometric and ground cover values to define LCZs. Table 3 highlights the various methods employed in previous studies to measure parameters related to ground cover and geometry. Measurement methods for SVF are typically categorized as fisheye photographs, satellite images, street view images, and numerical simulations. Parameters such as AR, BSF,

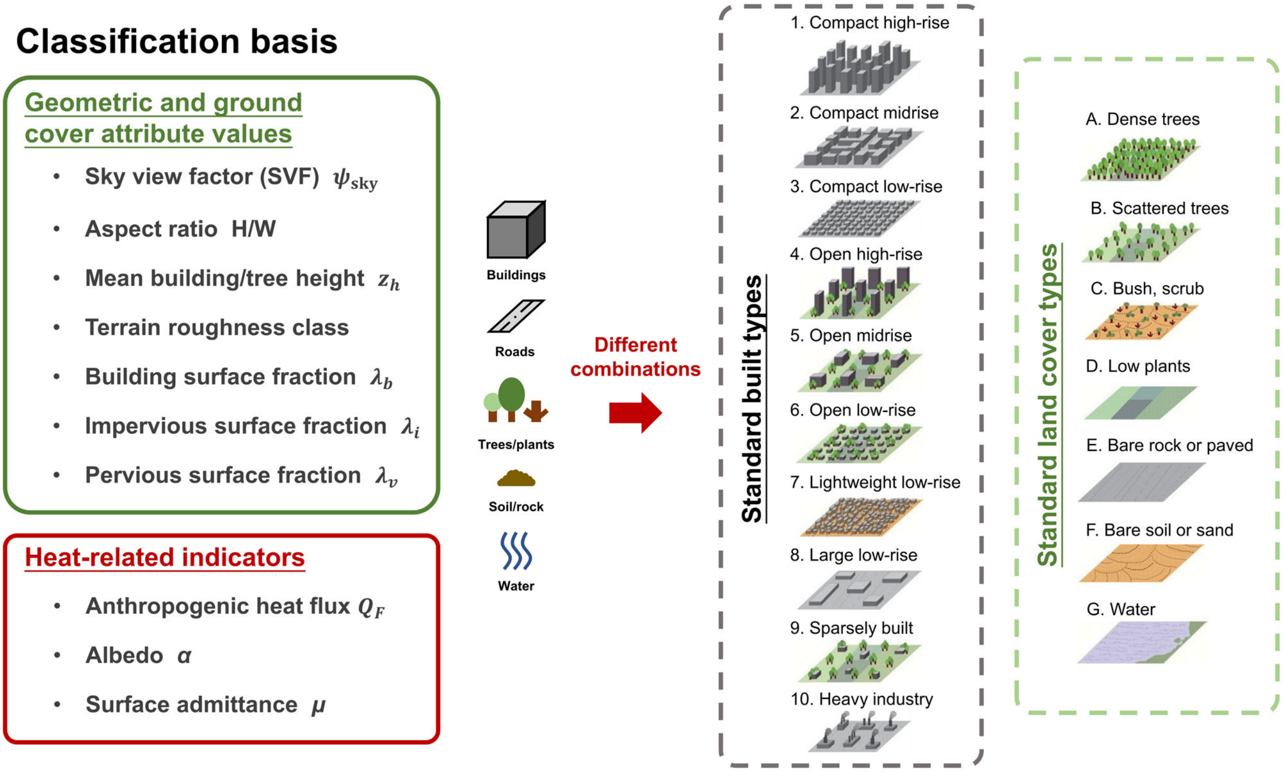

Fig. 4 Schematic diagram of standard LCZs.

Table 3 Measurement methods for measuring ground cover and geometry attribute parameters.

Reference	SVF	AR	BSF	ISF	PSF	HRE	TRC
(Leconte et al. 2015)	SAGA GIS, DSM	—	Calculation based on urban GIS database	Manually calculated (using visible satellite imagery data)	Manually calculated (using visible satellite imagery data)	Urban GIS database	Davenport classification
(Leconte et al. 2017)	SAGA GIS (DEM data)	—	Calculations based on a national database for building footprints	Manually calculated (using visible satellite imagery data)	Manually calculated (using visible satellite imagery data)	National database for building footprints	Davenport classification
(Skarbit et al. 2017)	The vector-based method from the building database	—	Calculation based on 3D building database	Calculations based on Satellite images and other databases	Calculations based on satellite images and other databases	Calculation based on 3D building database	—
(Yang et al. 2017)	ENVI-met	Manually calculated (using visible satellite imagery data)	Manually calculated (using visible satellite imagery data)	Manually calculated (using visible satellite imagery data)	Manually calculated (using visible satellite imagery data)	Building shading calculation (Google Earth)	Davenport classification
(Yang et al. 2018)	ENVI-met	Field measurements	Manually calculated (using visible satellite imagery data)	Manually calculated (using visible satellite imagery data)	Manually calculated (using visible satellite imagery data)	Building shading calculation (Google Earth)	Davenport classification
(Perera and Emmanuel 2018)	Fish-eye photographs and field surveys	Satellite imagery and field surveys	Satellite imagery and field surveys	Satellite imagery and field surveys	Satellite imagery and field surveys	Satellite imagery and field surveys	Davenport classification
(Wang et al. 2018)	Satellite image analysis	—	Satellite image analysis	Satellite image analysis	Satellite image analysis	—	—
(Demuzere et al. 2019)	SVF calculation based on google street view	—	Calculations based on the global human settlement layer and the global urban footprint	Calculations based on high-resolution impervious density datasets	—	Calculation based on city building height data	—
(Chen et al. 2020b)	Fish-eye photographs	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	—
(Liu et al. 2022)	Fish-eye photographs	Building model analysis and field survey	Manually calculated (using visible satellite imagery data)	Manually calculated (using visible satellite imagery data)	Manually calculated (using visible satellite imagery data)	Building model analysis and field survey	Davenport classification

“Unspecified”: indicates that the study calculated the parameter but did not specify the specific calculation method.
“-“: indicates that the parameter was not calculated for the study.
SVF: Fraction of sky hemisphere visible from ground level.
AR: Mean height-to-width ratio of street canyons (LCZ 1–7), building spacing (LCZ 8–10), and tree spacing (LCZ A–F).
BSF: Proportion of ground surface with building cover. ISF: Proportion of ground surface with impervious cover (paved, rock).
PSF: Proportion of ground surface with pervious cover (bare soil, vegetation, water).
HRE: Geometric average of building heights (LCZ 1–10) and tree/plant heights (LCZ A–F). TRC: Davenport classification.

ISF, PSF, HRE, and TRC are primarily grouped into three categories: field measurement, satellite image calculation, and building data acquisition.

In summary, methods for measuring UCPs mainly consist of manual measurement and satellite image calculation. Manual measurement involves collecting data from a few sampling points in a region and then averaging them to determine UCP values. However, this approach is time-consuming, labor-intensive, and prone to inaccuracies, rendering it unsuitable for large-scale urban climate studies based on the LCZs framework. In contrast, alternative methods such as RS and simulation modeling can be more effectively employed for UCPs measurements. These methods offer a more efficient and accurate means of collecting UCPs, enabling a comprehensive and reliable analysis of urban climate patterns and their impact on human well-being and the environment. Furthermore, there is a pressing need to establish standardized procedures for measuring UCPs. Future research within the LCZs framework could emphasize the standardization of UCP calculation using RS and GIS data to ensure precise results.

Calculating urban heat island intensity using the LCZs framework. The LCZs framework method focuses on defining the UHI magnitude using the temperature difference between LCZs, represented by $\Delta T_{LCZ\ X\text{-}LCZ\ D}$, rather than the traditional "urban-rural" temperature difference ($\Delta Tu\text{-}r$) (Stewart and Oke 2012). Here, *LCZ X* denotes any class within the LCZs classification system, while the temperature of *LCZ D* (low plants) serves as the baseline. This calculation method not only offers a more physically grounded understanding of UHII but also enhances its analysis and comparability. Numerous studies have affirmed the efficacy of the LCZs-based UHII calculation method. For example, Shi et al. (2021) computed surface urban heat island (SUHI) intensity by analyzing the difference in land surface temperature (LST) between LCZs and compared it with the conventional "urban-rural dichotomy" method. The results revealed that the LCZs-based UHII calculation method yielded a more precise measure of SUHI intensity. Similarly, Budhiraja et al. (2019) examined the seasonal SUHI intensity of Delhi using both LCZs-based and "urban-rural dichotomy" methods, concluding that the former provided a more detailed understanding of the relationship between urban structure and SUHI.

Two primary UHI types were assessed using the LCZs-based UHII calculation method: atmospheric urban heat island (AUHI) and SUHI. Concerning AUHI, Chen et al. (2021) explored the connection between the diurnal temperature range and AUHI intensity using the LCZs-based UHII calculation method under varying meteorological conditions categorized by precipitation. Yang et al. (2017) investigated the characteristics of local AUHI at selected LCZ sites, employing the LCZs-based UHII calculation method. Regarding SUHI, Wang et al. (2021) calculated surface urban heat island intensity (SUHII) using this method and proposed a sustainable urban green infrastructure planning strategy based on the analysis results. O'Malley and Kikumoto (2022) delved into heat storage in Tokyo Prefecture, utilizing the LCZs-based UHII calculation method to compute nocturnal-diurnal SUHI differences. Finally, Zheng et al. (2022) scrutinized the changes of LCZs and surface SUHII within Chang-Zhu-Tan's primary urban area, employing the LCZs-based UHII calculation method.

In conclusion, the LCZs-based UHII calculation method represents a significant advancement in UHI research. Its ability to capture localized UHI variations, enhance comparability across regions, and guide targeted mitigation strategies makes it a valuable tool for urban planning and climate adaptation. However, addressing data challenges and standardization issues will be crucial to fully realize its potential for widespread application. Further research should focus on refining data acquisition and measurement techniques within the LCZs framework to ensure the accuracy and reliability of UHII assessments.

Recent advancements in manual sampling and mapping methods of LCZs research

This section explores the research methods employed within the LCZs framework for UHI research, specifically focusing on the manual sampling method for limited LCZs and LCZs mapping methods for large-scale applications.

Manual sampling method for limited LCZs. In the early stages of UHI research based on the LCZs framework, the primary emphasis was on LCZs classification through a manual sampling approach. This method involved the identification of LCZ types for a limited number of land parcels using manual techniques, such as scrutinizing satellite images, live photos, and conducting field surveys, for urban climate investigations. For instance, Yang et al. (2017) conducted a study examining the local UHI characteristics across 12 LCZs. These LCZs were selected based on a thorough review of satellite images, street-level views, and on-site fieldwork. In another research endeavor, Yang et al. (2018) investigated 14 distinct LCZs using field data and high-resolution satellite images to analyze the thermal characteristics of each location.

However, it is important to note that the manual sampling method has limitations, particularly when applied to large-scale urban climate investigations. It necessitates a substantial number of researchers to manually identify the LCZ type of each plot, which is resource-intensive and time-consuming. Moreover, there is a risk of human error during the identification process, potentially compromising the accuracy and reliability of the results. Consequently, while the manual sampling method has proven valuable for in-depth studies focusing on limited LCZs, it may not be suitable for broader urban climate investigations within expansive urban areas. In such cases, alternative LCZs mapping methods are typically preferred to ensure efficiency and accuracy.

LCZs mapping methods. The evolution of the LCZs framework has given rise to LCZs mapping methods tailored for large-scale urban climate studies. These methods simplify the representation of urban climate within the LCZs framework, enabling comparative analyses across different cities and enhancing the universality and applicability of findings. Moreover, LCZs framework facilitates the transformation of "climate language," supporting the development of climate-sensitive urban design. LCZs mapping methods can be categorized into two types based on their data sources and classification algorithms: GIS-based and RS-based mapping methods (Tamás et al. 2015).

GIS-based LCZs mapping method. The GIS-based LCZs mapping method comprises six main steps, as depicted in Fig. 5 (Quan and Bansal 2021). Initially, it involves collecting GIS data and defining BSUs to segment the urban environment into smaller blocks for LCZs classification. Subsequently, the UCPs values for each BSU are calculated using GIS data, and the LCZ type for each BSU is determined based on the LCZs framework. Finally, post-processing is carried out to merge adjacent units for simplification and size adjustment, ultimately leading to the generation and evaluation of the LCZs map. BSUs refer to the spatial scale of LCZ classification, and the size of a BSU must meet the size

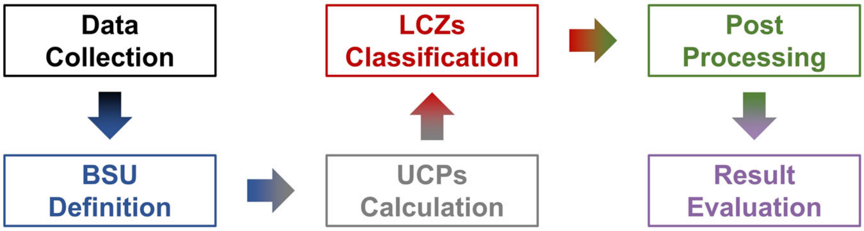

Fig. 5 General steps of GIS-based LCZs mapping method (Quan and Bansal 2021).

requirement of the LCZs framework. The definition of BSUs is typically divided into lot area polygons (Lelovics et al. 2014, Unger et al. 2014), urban blocks (Wu et al. 2018, Quan 2019), and regular grids (Chen et al. 2020a). Additionally, pre-processing of the GIS data is often necessary before calculating the UCPs. Common pre-processing includes: (1) Data cleaning: GIS datasets may contain errors or inconsistencies, such as missing values, outliers, or topological errors. It's important to clean the data to avoid inaccuracies. (2) Spatial resolution matching: GIS datasets may have different spatial resolutions, which can affect the accuracy of UCPs calculations. Pre-processing is necessary to resample or aggregate datasets to a common spatial resolution to ensure compatibility for analysis. (3) Others: Steps such as data normalization and data integration are performed as needed. Overall, pre-processing of GIS data is essential before calculating UCPs to ensure data cleanliness, compatibility, and suitability for analysis, leading to more accurate and reliable results.

The use of GIS-based LCZs mapping has gained traction in urban climate studies since the pioneering study by Lelovics et al. (2014) in Hungary. For example, Quan et al. (2017) developed and tested a bottom-up, fine-grained 3D LCZs mapping method utilizing GIS and land cover data, with urban block units serving as BSUs. Geletič et al. (2019) employed the GIS-based LCZs mapping method to explore the inter-zone and intra-zone seasonal variations of SUHI in three central European cities.

Despite its precision, the GIS-based LCZs mapping method has limitations. Firstly, obtaining accurate and consistent ground truth data for calculating UCPs poses a significant challenge, leading to limited availability of urban data. The inability to acquire comprehensive and detailed datasets for estimating UCPs, particularly those related to thermal aspects, can significantly impact the accuracy of LCZs mapping. Secondly, the merging of BSUs exists in post-processing, making it challenging to find optimal solutions, particularly in intricate urban environments. This process may not fully capture the complexity of LCZs mapping.

RS-based LCZs mapping method. RS is a technology that leverages remote sensors to collect data from target objects and analyze it to extract valuable information. Advances in RS information acquisition, transmission, and storage technologies have diminished the limitations of RS applications due to improved data quality and the increased availability of multiple RS data sources (Liu et al. 2006). RS satellites streamline fieldwork complexity and time intervals while delivering quantifiable and qualitative data (Dhingra and Kumar 2019). Optical RS imagery is gradually favored for identifying and categorizing land types and has become a pivotal research area.

RS-based LCZs mapping methods also have several limitations. One key limitation is the spatial and temporal resolution of the RS data. RS data may not always provide complete coverage or may be affected by cloud cover, which means that RS images need to be processed for stitching. However, since the spatial and temporal resolution of different remotely sensed images may vary, the stitching process may impact the accuracy and completeness of the LCZs mapping. Additionally, RS-based LCZs mapping requires specialized knowledge in remote sensing and image processing, which can be a barrier for non-remote sensing professionals. This limitation restricts the widespread application of RS-based LCZs mapping in urban planning and climate studies.

However, compared to GIS-based approaches, RS-based LCZs mapping methods offer several advantages, including higher resolution, finer spatial and temporal data, and the ability to quickly cover large areas. As a result, RS-based LCZs mapping has become the preferred approach for LCZs classification.

To enhance the accuracy of LCZs map classification, RS researchers have employed various benchmark datasets and classifiers. Regarding the benchmark dataset, Hu et al. (2018) utilized Sentinel-1 Dual-Pol data in LCZs mapping. Yang et al. (2020b) employed multi-source datasets, including Luojia1-01 nighttime light imagery, Landsat-8, Sentinel-2, and building vector data, to generate LCZs maps. They found that a combination of object-based and pixel-based data with multi-source data improved LCZs mapping workflow. Machine learning classifiers, such as random forests and support vector machines (Xu et al. 2017, Hu et al. 2018, Hay Chung et al. 2021), are widely used for LCZs classification based on free multi-temporal RS data. In recent years, deep learning techniques have also been employed in RS-based LCZs mapping, as artificial intelligence has advanced. For example, Liu et al. (2019) combined object-based image analysis with convolutional neural networks (CNN) for LCZs mapping. Huang et al. (2021) introduced a CNN-based LCZ classification model for LCZs mapping in 32 Chinese cities. Their model achieved high overall accuracy in more than 50% of the cities.

Urban climate studies based on the LCZs framework face notable challenges due to the demand for expertise in meteorological science, RS, and machine learning, as well as data availability issues and non-standardized urban description methods. To address these challenges, Bechtel et al. (2015) proposed the world urban database and access portal tool (WUDAPT) protocol for LCZs mapping, which was developed ultimately into the LCZs generator (Demuzere et al. 2021), an online platform that generates LCZs mapping solely needing a training area file as input and also provides automated accuracy assessment. This approach aims to collect, store, and disseminate climate-related data on urban physical geography globally. The WUDAPT approach merges local expert knowledge with the LCZs framework to categorize the urban landscape into LCZs, generating LCZs maps for urban regions. The WUDAPT, outlined in Fig. 6, has been widely adopted for urban climate studies in numerous regions. For example, Demuzere et al. (2022) generated a 100 m-resolution global LCZs map, accessible for download at https://doi.org/10.5281/zenodo.6364594. Cai et al. (2018) created an LCZs map for the Yangtze River Delta megaregion in China. Ren et al. (2019) generated LCZs maps for over 20 cities and three major economic regions in China, offering recommendations for enhancement. Demuzere et al. (2019) constructed LCZs maps for Europe. Beyond urban climate

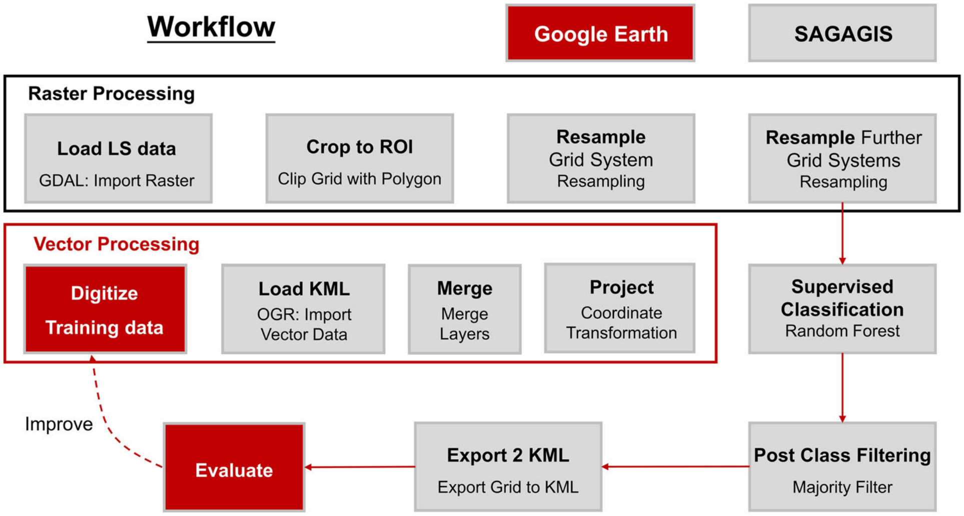

Fig. 6 WUDAPT workflow (Bechtel et al. 2015).

studies, WUDAPT finds applications in various domains, including urban pollution (Shi et al. 2019) and multi-scale urban atmospheric modeling (Ching et al. 2019).

LCZs mapping methods represent a pivotal advancement within the LCZs framework, enabling more extensive and systematic urban climate studies. These methods are indispensable for gaining insights into urban climatology, which is crucial for informed urban planning and climate-responsive urban design. While both GIS-based and RS-based LCZs mapping methods offer advantages, it's essential to consider their respective strengths and limitations. GIS-based approaches provide high precision but may suffer from data availability issues and the complexity of post-processing. In contrast, RS-based methods offer freely available multi-temporal data and can quickly capture large-scale urban environments but may require extensive computational resources and expertise. The integration of machine learning and deep learning techniques into RS-based LCZs mapping has significantly improved classification accuracy and efficiency. However, these methods often demand large training datasets and computational resources. Further research should focus on optimizing these techniques for resource-constrained environments. The WUDAPT protocol stands out as a promising approach for LCZs mapping, offering generality, simplicity, and objectivity. Its reliance on local expert knowledge enhances accuracy, especially in areas with limited data availability. However, challenges persist in implementing this protocol universally, particularly in regions lacking local expertise.

In summary, LCZs mapping methods represent a pivotal milestone in urban climate research. They offer versatile tools for understanding and addressing the UHI effect and other climate-related urban challenges. As technology and data availability continue to advance, these methods are poised to play an increasingly prominent role in shaping sustainable and climate-resilient cities.

Application of LCZs framework in various scenarios

The application domains of the LCZs framework can be categorized and analyzed based on the keywords found in the screened literature. This analysis spans three principal areas: (1) LCZs framework in UHI studies: The primary application of the LCZs framework remains in the domain of UHI research. It provides a valuable tool for investigating the causes and consequences of UHIs, helping researchers better comprehend their impacts on urban climates and devising strategies to mitigate them. Given the growing significance of UHI effects in urban areas, continued research in this area is essential. (2) LCZs research contributions to urban design and climate change mitigation: LCZs research also makes substantial contributions to urban design and climate change mitigation efforts. The framework enables a more refined understanding of how urban structures and land use impact local climates. Consequently, it aids urban planners and policymakers in developing climate-sensitive urban designs and strategies to reduce the UHI effect and its associated challenges. (3) LCZs framework in diverse fields: LCZs research has found applications in various other domains, such as urban ventilation, precipitation, thermal comfort, carbon emissions, and building energy consumption. This indicates the versatility of the LCZs framework and its potential to inform a broad spectrum of urban-related research.

In summary, the LCZs framework has evolved to become a valuable tool in various research scenarios. While its origins lie in addressing UHI research limitations, it now extends its influence to inform urban design, climate change mitigation, and a range of interdisciplinary studies. Its adaptability and versatility underscore the continued relevance of LCZs research in addressing contemporary urban challenges.

LCZs framework in urban heat island studies. UHI research is crucial for understanding the impact of urban environments and devising strategies to mitigate UHI effects. Traditional studies have focused on 2D built environment parameters, such as building density, road density, and green space area, extracted from available data sources like weather data or satellite imagery for 2D planar UHI studies. Recent investigations have revealed that 3D built environment factors, including building height and SVF, have a more substantial influence on UHI than the 2D parameters (Luo et al. 2023). Consequently, there is a growing need for research that assesses and characterizes UHI through 3D spatial analysis, rather than the planar UHI estimation (Kim and Brown 2021). The LCZs system, which integrates both 2D and 3D UCPs, is well-suited for 3D UHI studies and can contribute to advancing the understanding of UHI and its influencing factors.

Table 4 provides examples of UHI research conducted using the LCZs framework, covering various climate types and research contents. These studies span different climate types, including tropical, subtropical, temperate, and more. UHI research typically falls into two categories: SUHI, which concerns the temperature

Table 4 Case studies of UHI based on the LCZs framework.

Reference	Year	Location	Climate	UHI type	Research parameters		Research content
					Parameters	Parameter measurement method	
(Alexander and Mills 2014)	2014	Dublin, Ireland	Temperate maritime climate	AUHI	Air temperature	Fixed measurement, mobile measurement	Impact of urban indicators
(Leconte et al. 2015)	2015	Nancy, France	Temperate maritime climate	AUHI	Air temperature	Mobile measurement	Impact of urban indicators
(Emmanuel and Loconsole 2015)	2015	Glasgow, UK	Temperate maritime climate	AUHI	Air temperature, Surface temperature	Numerical simulation	Green infrastructure as UHI adaptation approach
(Geletič et al. 2016)	2016	Prague and Brno, Czech	Mid-continental climate	SUHI	LST	Ground measurement (LST retrieval)	The relationship between LST and LCZs
(Skarbit et al. 2017)	2017	Szeged, Hungary	Continental temperate climate	AUHI	Air temperature	Fixed measurement	Assess local climate and UHI conditions
(Leconte et al. 2017)	2017	Nancy, France	Temperate maritime climate	AUHI	Air temperature	Mobile measurement	Nocturnal cooling
(Kotharkar and Bagade, 2018)	2018	Nagpur, Indian	Tropical monsoon climate	AUHI	Air temperature	Fixed measurement, mobile measurement	UHI evaluation
(Nurwanda, 2018)	2018	Bogor, Indonesia	The temperate continental semi-arid climate	SUHI	LST	Ground measurement (LST retrieval)	Impact of urban expansion
(Cai et al. 2018)	2018	Yangtze River Delta, China	Subtropical monsoon climate	SUHI	LST	Ground measurement (LST retrieval)	The relationship between LST and LCZs
(Wang et al. 2018)	2018	Phoenix and Las Vegas, US	Temperate desert type climate	SUHI	LST	Ground measurement (LST retrieval)	UHI evaluation
(Yang et al. 2019a)	2019	Shanghai, China	Subtropical monsoon climate	SUHI	LST, frontal area density	Ground measurement (LST retrieval)	The performance-based and wind-sensitive planning proposal
(Yang et al. 2020d)	2020	Nanjing, China	Subtropical monsoon climate	AUHI	Air temperature	Fixed measurement	Impact of UHI on building energy demand
(Chen et al. 2020b)	2020	Changsha, China	Subtropical monsoon climate	AUHI	Air temperature	Fixed measurement, numerical simulation	Modification of trees, Albedo, and green roof as UHI mitigation strategy
(Yang et al. 2020b)	2020	Dalian, China	Temperate monsoon climate	SUHI	LST	Ground measurement (LST retrieval)	UHI mitigation strategy
(Wang et al. 2021)	2021	Guangzhou, China	Subtropical monsoon climate	SUHI	LST	Ground measurement, numerical simulation	Urban green infrastructure as UHI mitigation strategy

Table 4 (continued)

Reference	Year	Location	Climate	UHI type	Research parameters		Research content
					Parameters	Parameter measurement method	
(Yuan et al. 2022)	2022	Xi'an, China	Temperate monsoon climate	SUHI	LST	Ground measurement (LST retrieval)	Diurnal dynamics of heat exposure
(Jiang et al. 2022)	2022	9 cities, China	Mesothermal, warm, and subtropical temperate zones	AUHI	Surface air temperature	Meteorological dataset	UHI evaluation
(Li et al. 2022a)	2022	5 cities, China	Arid climate, tropical climate, subtropical climate, temperate climate, alpine climate	SUHI	LST	Ground measurement (LST retrieval)	Thermal contributions and spatial effects in different macroclimate cities
(O'Malley and Kikumoto 2022)	2022	Tokyo, Japan	Subtropical maritime monsoon climate	SUHI	LST	Ground measurement (LST retrieval)	Investigation of heat storage
(Mushore et al. 2022)	2022	Bulawayo, Zimbabwe	Tropical grassland climate	AUHI, SUHI	Air Temperature, LST	Ground measurement (LST retrieval)	The effect of urban growth on the three-dimensional thermal environment
(Dong et al. 2022)	2022	Nanjing, China	Subtropical monsoon climate	SUHI	LST	Ground measurement (LST retrieval)	Diurnally continuous dynamics of SUHI
(Xia et al. 2022)	2022	Beijing, China	Warm temperate semi-humid semi-arid monsoon climate	SUHI	LST	Ground measurement (LST retrieval)	SUHI analysis
(Zheng et al. 2022)	2022	3 cities, China	Subtropical monsoon climate	SUHI	LST	Ground measurement (LST retrieval)	SUHI analysis
(Liu et al. 2022)	2022	Guangzhou, China	Subtropical monsoon climate	AUHI	Air temperature	Mobile measurement	Association analysis on spatiotemporal characteristics of block-scale urban thermal environments
(Wang et al. 2022a)	2022	Wuhan, China	Subtropical monsoon climate	SUHI	LST	Ground measurement (LST retrieval)	Impact of urban indicators
(Zhou et al. 2022)	2022	Xi'an, China	Temperate monsoon climate	SUHI	LST	Ground measurement (LST retrieval)	Effects of 2D/3D urban morphology on LST
(Emery et al. 2021)	2022	Dijon, France	Subtropical Mediterranean climate	AUHI	Air temperature	Mobile measurement	UHI analysis

difference between urban and rural areas at the surface level, and AUHI, which examines corresponding air temperature differences. Temperature variables in UHI studies can further be categorized into LST and air temperature, depending on the type of UHI under investigation. Research objectives encompass the identification, influencing factors, and mitigation strategies associated with UHI. UHI studies employ four primary measurement methods, including fixed measurement (utilizing fixed meteorological stations or establishing stationary observation points for thermal environment measurements), mobile measurement (employing mobile vehicles equipped with climate observation instruments to collect and record climate data along predefined routes), ground measurement (retrieving LST using thermal infrared data), and numerical simulation.

Given the dispersed nature of measurement points and the limited equipment available for LCZs investigations, many UHI studies opt for mobile measurement or LST retrieval methods to gather temperature data across extensive areas. Furthermore, contemporary LCZs framework research has shifted its focus from single-city examinations to comparative analyses between cities. This shift highlights the generalizability of the LCZs framework and its contributions to the growing trend of multi-regional urban climate research.

LCZs research contributions to urban design and climate change mitigation. Well-planned cities are essential for achieving sustainable urban development (Bai 2018). Climate-sensitive urban design plays a pivotal role in addressing the challenges posed by rising temperatures, which threaten residents' thermal comfort (Kim and Brown 2021). However, existing urban planning systems struggle to cope with the complexities of local, regional, and global warming. Integrating climate considerations into data requirements and analysis methods is crucial for practical urban design applications (Perera and Emmanuel 2018).

The development of urban climate mapping systems has emerged as a responsive tool for climate-conscious urban planning. LCZs offer a structured classification system for land surface characteristics, forming the basis for surface parameterization methods (Ren et al. 2011, Jin et al. 2020). LCZs facilitate the examination of the relationship between urban morphology and climate, providing meteorological data that informs building and urban design decisions. This framework has yielded significant insights into climate-responsive urban design, as exemplified by recent research endeavors.

For instance, Perera and Emmanuel (2018) utilized the LCZs framework to guide urban planning in Colombo, establishing it as a valuable theoretical foundation for crafting climate-sensitive cities. Likewise, Maharoof et al. (2020) applied the LCZs framework to investigate the implementation of climate-sensitive urban planning in densely populated urban areas, as illustrated by their case study of Glasgow city center. Another study by Pradhesta et al. (2019) dissected the critical components of thermal comfort within the LCZs framework, emphasizing factors such as roughness feature height, packing density, surface cover, and thermal admittance of materials. These components prove pivotal in the design of urban spaces that prioritize residents' thermal comfort.

In essence, the LCZs framework offers a powerful tool for formulating climate-sensitive urban design strategies that enhance the quality of life and the sustainability of our cities. Climate-conscious urban design based on LCZs revolves around several key facets:

i) Green infrastructure: Integrating green infrastructure into urban planning stands as a critical measure for mitigating the effects of climate change on cities and their inhabitants. A comprehensive evaluation by Emmanuel and Loconsole (2015) underscores the effectiveness of green infrastructure options in combatting urban overheating, particularly within the context of a warming climate. Notably, increasing green coverage by approximately 20% over current levels could potentially eliminate up to half of the projected extra UHI effect by 2050 (Emmanuel and Loconsole 2015). Further insights from Kotharkar et al. (2020) reveal that greening initiatives not only serve as cooling strategies but also enhance pedestrian-level comfort. Intriguingly, their research highlights the superior results achieved by planting vegetation along streets, as opposed to concentrating greenery in designated areas. Li et al. (2022b) further advocate for the moderation of SUHI through the strategic implementation of urban blue-green infrastructure. Stepani and Emmanuel (2022) advocate optimizing green spaces within public realms rather than merely increasing their quantity, emphasizing that climate-responsive design necessitates a diverse array of solutions, extending beyond green infrastructure.

ii) Blue infrastructure: The concept of blue infrastructure encompasses a network of natural and artificial water systems, including rivers, lakes, canals, and drainage systems, which serve as vital resources for human communities. Li et al. (2022b) recommended harnessing the seasonal variations and spatial distribution of water bodies to enhance the cooling performance of LCZ G (Water). Factors such as distance and flow rates within rivers significantly influence the cooling effects, making them key considerations for urban planners and policymakers. Furthermore, they stress the importance of accounting for the growing risks of floods and droughts in East African cities, necessitating the design of blue infrastructure capable of adapting to seasonal variations and changing climates.

iii) Building design: Building resilience to climate change-induced extreme weather events is a crucial consideration in urban design. Passive cooling strategies, including cool roofs, emerge as effective means to reduce energy consumption and mitigate the UHI effect. Kotharkar et al. (2020) highlight the efficacy of cool roofs, specially designed to reflect more sunlight and absorb less heat than traditional roofing materials, particularly in densely populated urban areas.

iv) Street design: Urban streets represent a significant component of contemporary urban planning, encompassing approximately one-quarter of urban areas. They wield considerable influence in shaping comfortable urban environments. However, the climate-sensitive street design goes beyond rigid one-size-fits-all approaches. Maharoof et al. (2020) advocate for the integration of LCZ parameters with form-based considerations such as orientation and façade geometry. This nuanced approach recognizes that different street typologies may demand distinct design strategies, underscoring the importance of tailoring designs to specific urban contexts.

v) Other considerations: Research by O'Malley and Kikumoto (2022) suggests that mitigating UHI effects can be achieved through constructing lower-rise and open LCZs. They note that high-rise buildings possess larger heat storage capacities relative to lower-rise structures. Additionally, Zheng et al. (2022) proposed the full utilization of the cooling potential inherent in *LCZ A-D* and *LCZ G* and emphasized the need for judicious regulation of construction land areas (built LCZs) in future urban development plans.

Leveraging insights from LCZs-based research, climate-sensitive urban design should center around the integration of green and blue infrastructure, innovative building design, and flexible street design elements to counter the adverse impacts of climate change and foster the creation of sustainable, climate-responsive urban environments.

i) Green-blue infrastructure: Urban areas can benefit significantly from nature-based solutions, such as green roofs, gardens, and urban forests. These solutions serve dual purposes, including mitigating the negative impacts of climate change and promoting biodiversity. Furthermore, green corridors, such as tree-lined streets and bike paths, serve as multifunctional assets. They not only improve air quality but also offer enhanced mobility options for residents and reduce noise pollution. Water features, such as fountains and ponds, not only enhance the aesthetic appeal of public spaces but also provide cooling through evaporation.

ii) Building design: To mitigate UHI effects, building design should incorporate various strategies, including green roofs, cool roofs, shade provision, and sustainable materials. Green roofs are particularly advantageous because they contribute to cooling both buildings and their surroundings by absorbing and subsequently releasing moisture through transpiration. Additionally, cool roofs reflect sunlight and possess lower heat absorption than traditional roofing materials. The reduction in heat transfer into buildings beneath the roof not only lowers cooling costs but also enhances indoor comfort during hot weather. Moreover, building design can introduce shading solutions in outdoor areas, thereby reducing the amount of sunlight absorbed by buildings and their surroundings, thus contributing to cooler environments. Sustainable building materials, such as recycled steel, bamboo, and reclaimed wood, can play a pivotal role in reducing the environmental footprint of construction, ensuring that buildings are more sustainable, efficient, and comfortable.

iii) Street design: The design of urban streets plays a crucial role in mitigating UHI effects. Incorporating vegetation, green roofs, and other green elements into street design can effectively provide shade and evaporative cooling. Furthermore, using permeable pavement materials allows rainwater to penetrate the surface, promoting evaporation and reducing the amount of heat absorbed and re-emitted by the pavement. This is particularly important as impervious surfaces, like concrete and asphalt, tend to absorb and re-emit substantial amounts of heat, exacerbating UHI effects. By reducing the prevalence of impervious surfaces in street design, the adverse impacts of UHI can be mitigated. Additionally, thoughtful street furniture design, including streetlights and bus shelters, can be employed to provide shade and further reduce UHI effects.

In summary, urban design strategies that incorporate green-blue infrastructure, utilize innovative building design techniques, and employ street design elements prioritizing vegetation and sustainability offer comprehensive solutions to mitigate the adverse effects of UHI. These strategies enhance the overall resilience and comfort of urban areas, preparing them for the challenges posed by climate change.

Applications of the LCZs framework in other domains

Urban climate studies. Beyond its primary application in UHI studies, the LCZs framework offers substantial utility across various domains of urban climate research. This adaptable framework enables researchers to explore both spatial and temporal dynamics of ventilation and precipitation patterns at a local scale, providing crucial insights for developing effective strategies to mitigate the environmental and health impacts of urbanization. For instance, Zhao et al. (2020) effectively employed the LCZs framework to analyze local-scale urban ventilation performance in Shenyang. In another study, Yang et al. (2019a) evaluated the ventilation efficiency of different LCZs in Shanghai by assessing the frontal area index across various LCZ types. Chen et al. (2021) conducted a quantitative assessment of the relationship between daily temperature variations and UHII under varying meteorological conditions, classifying data using precipitation as a criterion. Additionally, Shi et al. (2022) assessed the influence of urban ventilation corridors on UHII using the LCZs framework. Yang et al. (2020c) explored the spatial and temporal variations in humidity within the urban canopy across eight LCZ plots in Nanjing, analyzing the interplay between humidity differences, condensation precipitation events, meteorological parameters, and UHI. In a related study, Savić et al. (2020) scrutinized precipitation patterns in different urbanization settings by segregating areas into “urbanized” and “non-urbanized” based on LCZs classifications.

In summation, the utilization of the LCZs framework within urban climate research enhances our comprehension of the intricate connections between urban design and the multifaceted facets of urban climate. This broader perspective empowers researchers to devise effective strategies aimed at mitigating the repercussions of urbanization on the environment and human well-being, ultimately contributing to the enhancement of urban living conditions.

Enhancing outdoor thermal comfort. The quality of outdoor thermal comfort significantly influences the livability of urban areas. Changes in urban surfaces can substantially affect LST, consequently leading to elevated air temperatures and increased heat stress on urban residents (Lau et al. 2019). The LCZs framework proves to be a valuable tool in advancing research on outdoor thermal comfort by capturing the nuances of urban surface characteristics. For instance, Lau et al. (2019) employed a combination of questionnaires and field measurements to gauge subjective thermal sensations within eight distinct LCZs in Hong Kong. Unger et al. (2018) examined daily and seasonal fluctuations of outdoor human thermal perceptions, scrutinizing diverse LCZ types based on meteorological data. On a quantitative note, Liu et al. (2018) analytically assessed the levels of outdoor thermal comfort within nine LCZs in Shenzhen, dissecting the impact of various urban spatial characteristics. Schibuola and Tambani (2022) engaged in an evaluation of outdoor thermal comfort using the LCZs framework, offering a basis for comparative analysis of mitigation strategies. Meanwhile, Unal Cilek and Uslu (2022) analyzed the thermal conditions in urban green spaces across three distinct canopy cover scenarios using LCZs framework. Lastly, Wu et al. (2022) assessed the thermal comfort levels in Shenzhen throughout the year 2020 based on the LCZs framework.

These studies demonstrate that the LCZs framework enables a more profound comprehension of how urban surface characteristics affect outdoor thermal comfort. This understanding is crucial for developing and optimizing mitigation strategies in urban planning and design to enhance the quality of life and comfort for urban residents.

Tackling carbon emissions and building energy consumption. Cities play a significant role in global energy consumption and carbon dioxide emissions (Zhou 2022b), making the development of sustainable urban areas pivotal for achieving climate stability objectives (Zhou 2023, Zhou et al. 2023). The form and function of the built environment closely intertwine with its carbon emission patterns. Hence, the LCZs framework emerges as a valuable tool for research focused on mitigating carbon emissions and optimizing building energy efficiency. Through the creation of a regional carbon map grounded in the LCZs framework, researchers can furnish urban planners and decision-makers with crucial insights into urban carbon emissions, thereby bolstering strategic initiatives for carbon reduction and management.

Recent studies have harnessed the potential of the LCZs framework to scrutinize and chart building carbon emissions and energy utilization within urban landscapes. Notably, Wu et al.

(2018) established correlations between building carbon emissions and LCZs classifications, culminating in a detailed mapping of LCZs-based building carbon emissions in Shanghai. This research enables a granular understanding of urban-scale carbon dynamics, essential for localized mitigation efforts. Additionally, Sharifi et al. (2018) introduced a novel LCZs-based urban carbon mapping method, offering a standardized approach to urban carbon assessment. This method found application in major global cities like Bangkok, Shanghai, and Tokyo, facilitating comprehensive carbon analysis. Moreover, the adaptability of the LCZs framework extends to energy consumption assessments for city-level energy management and planning. For instance, Yang et al. (2019b) devised a diagnostic equation for daily maximum UHI indices grounded in the LCZs framework, effectively applying it to simulate building energy consumption. In a similar vein, Kotharkar et al. (2022) explored cooling loads and energy requisites for two distinct building typologies, leveraging the LCZs framework for insights into energy planning.

Collectively, these studies underscore the versatility and promise of the LCZs framework in guiding urban sustainability endeavors and informed energy planning, ultimately steering cities toward a greener, more energy-efficient future.

Limitations, challenges, and future prospects

Limitations and challenges. While the LCZs framework presents a promising avenue for standardizing the exchange of global urban temperature data, its widespread adoption faces challenges due to the lack of a unified approach to data sourcing and LCZs classification, leading to inconsistencies in LCZs framework research. To ensure methodological consistency, it is essential to establish a standardized LCZs framework research protocol. The WUDAPT method, designed for data sharing and user-friendliness, shows promise for future urban climate studies based on LCZs mapping. However, a critical challenge remains in improving this method's accuracy. Consequently, a key concern in LCZs research is developing a large-scale, effective, and precise LCZs mapping approach by leveraging various benchmark datasets and classifiers. This paper highlights current issues in the LCZs mapping process and suggests potential enhancements.

i) Data availability: Data availability poses significant challenges for LCZs mapping, stemming from several factors. These include limitations in the spatial and temporal resolution of RS data, difficulties in obtaining accurate and consistent ground truth data for calculating UCPs, the high cost associated with accessing high-quality RS data, etc. These challenges emphasize the need for a generalizable framework that addresses data availability issues. The WUDAPT team is actively working towards this goal and has curated a list of datasets for UCPs calculation, including building data, tree data, and urban population data, which can be accessed on the official website (https://www.wudapt.org/third-party-data/).

ii) RS-based mapping: RS-based mapping predominantly relies on freely available Landsat satellite image data. However, the limited image resolution of Landsat data can compromise LCZs mapping accuracy. To mitigate this limitation, the use of low-cost and user-friendly unmanned aerial vehicles (UAVs) devices for high-resolution RS image capture is worth considering. This approach can mitigate the impact of weather conditions and cloud cover on images, ultimately enhancing the precision of training sample identification and LCZs classification.

iii) Training samples: The overall accuracy of the WUDAPT method depends on the precise identification of LCZ types within the training samples. However, challenges may arise during data collection and UCPs calculation due to limited professional knowledge among researchers, potentially leading to inaccurate LCZs identification. To mitigate these challenges, the accuracy of training sample recognition can be improved through the standardization of data collection and UCPs calculation processes. This will help reduce subjective errors and address expertise-related constraints that can hinder manual recognition.

iv) Classifier: Apart from training samples, the classifier's ability to achieve high-precision LCZ type recognition is pivotal in LCZs mapping research. Recent advancements in artificial intelligence, particularly deep learning, have revolutionized image recognition and found widespread application in image classification tasks. Consequently, the emerging trend is to leverage neural network algorithms to achieve large-scale, efficient, and precise LCZs mapping.

By addressing these challenges and limitations, the LCZs framework can evolve into a more robust tool for urban climate research and planning, ensuring improved accuracy and consistency across studies.

Future prospects. The LCZs framework's generality, simplicity, and objectivity make it remarkably versatile, positioning it for extensive application across various future research domains. Beyond its current role in UHI effect research, the framework exhibits potential for a plethora of other areas, such as urban design, outdoor thermal comfort, carbon emissions, building energy consumption. The trajectory of LCZs framework research can be delineated into the following directions:

i) Enhancing understanding of UHI: Previous studies evaluating UHI effects have predominantly relied on 2D planar analysis, which does not account for the 3D physical form of cities. The LCZs framework provides an avenue for 3D spatial analysis, facilitating a more comprehensive evaluation of UHII. This advancement can significantly enhance our understanding of UHI effects and foster the development of innovative UHI mitigation strategies.

ii) Urban design: The LCZs framework serves as a valuable tool for identifying climate risks within urban areas. Urban planners, government decision-makers, and stakeholders can leverage this framework to formulate plans for climate-sensitive urban development, thereby promoting the creation of sustainable and resilient cities. Through the utilization of the LCZs framework, these stakeholders can gain valuable insights into potential climate risks, enabling them to proactively implement measures that enhance the effectiveness and efficiency of urban planning and development.

iii) Exploring complex urban climates: While recent urban climate studies have started to consider the influence of complex geographical factors such as topography and water bodies, there remains a research gap concerning mountainous cities. These cities, characterized by unique topographical elements and complex urban climates, have received comparatively less research attention. Therefore, future urban climate research can delve into the analysis of urban climates in mountainous cities using the LCZs framework. By leveraging this framework, researchers can gain a deeper understanding of the intricate interactions between topographical features and urban climates in these unique settings.

iv) LCZs-based economic-environmental analysis: Economic-environmental analysis aids policymakers and businesses in harmonizing economic growth with environmental sustainability by quantifying the environmental impacts of economic activities (Zhou 2022a). Future LCZs research can evolve towards economic-environmental analysis. The LCZs framework provides a foundational understanding of urban physical characteristics and functions, which can be correlated with economic activities and environmental impacts. Integrating economic analysis into

LCZ studies, such as integrating lifecycle assessment methods to quantify the environmental impacts of various urban development scenarios, enables researchers to investigate the cost-effectiveness of diverse urban development strategies, evaluate the economic implications of carbon emission reduction, and assess the financial advantages of sustainable building practices.

These future research directions promise to further amplify the applicability and impact of the LCZs framework in urban climate studies, urban planning, economic activities, and climate-conscious urban development.

Conclusions

This study provides a systematic and critical overview of LCZs framework research, exploring its evolution, current status, and future prospects based on recent advancements. It underscores the LCZs classification system's effectiveness in guiding climate-responsive planning and design. The study's key contributions are summarized as follows:

1) The proliferation of publications on the LCZs framework has been remarkable, escalating from 17 in 2013 to 300 in 2022. This surge in research reflects a prominent trend towards interdisciplinary collaboration, with LCZs research encompassing ten primary categories, including meteorology atmospheric sciences, environmental sciences ecology, and physical sciences among others.

2) The ongoing challenge of achieving large-scale, efficient, and accurate LCZs mapping remains a central concern in LCZs research. Efforts to address this challenge have been underway, with researchers integrating diverse benchmark datasets, employing UAVs, and utilizing deep learning classifiers.

3) In the realm of UHI studies, the LCZs framework has demonstrated its suitability for 3D UHI analysis, enriching the comprehension of UHI dynamics and their repercussions on urban environments. Recent LCZs framework investigations have evolved from single-city analyses to comparative studies encompassing multiple cities. Moving forward, the LCZs framework holds promise for deciphering the complexities of urban climates influenced by intricate geographical factors.

4) For climate-responsive urban design, the LCZs framework serves as an invaluable instrument for devising strategies that prioritize climate sensitivity in urban planning and development. The integration of green and blue infrastructure, building design principles, and innovative street design emerges as fundamental elements in fostering climate-conscious cities through the LCZs framework.

5) The LCZs framework exhibits versatility across various research domains, including outdoor thermal comfort, carbon emissions analysis, and building energy consumption assessments. Its application contributes significantly to advancing ecological urban construction and promoting sustainable urban development.

In summation, the LCZs framework stands out as a powerful instrument with broad implications for urban climate research, urban planning, and the advancement of climate-resilient and sustainable cities. Its ongoing evolution and refinement are poised to catalyze innovation and advancements in these crucial domains.

Data availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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Ethical approval was not required as the study did not involve human participants

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Competing interests

The authors declare no competing interests.

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