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Evaluation of Thermal Environments in Central Urban Areas (CUAs): Analysis of Existing Focuses and Directions for Future Investigation

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ABSTRACT

Central urban areas (CUAs) are particularly vulnerable to rapid environmental changes and contemporary emerging climatic threats, given their complexity of spatial patterns and intensity of human activities. Typically, CUAs exhibit high-density and heterogeneous morphological characteristics through the combination and interaction of various building blocks constructed across multiple ages, showcasing socio-cultural inheritance and ecological-environmental diversity. The scarcity of open spaces and the dense clustering of buildings in these CUAs impede outdoor thermal comfort and ventilation, reducing residents' opportunities to conduct outdoor activities during extreme weather conditions. Given these circumstances, it is crucial to conduct systematic evaluations of thermal environmental performance in CUAs. Despite widespread global discussion on this topic, conflicting investigation results persist due to the variations in the observation spatial scales, research techniques, analytical approaches, evaluation indices, and socio-geographical contexts. Focusing on the relationships between urban morphological characteristics and outdoor thermal environmental performance, this paper provides an overview of existing related studies across multiple spatial scales and analyses the advantages and shortcomings of prevalent research techniques. The paper aims to outline a systematic framework for investigating the thermal environments in CUAs facing complex social situations and climatic challenges. The paper suggests that integrating both *top-down* and *bottom-up* perspectives is important for evaluating thermal environments in CUAs, while a multi-scale investigation should be conducted to identify the essential issues and the underlying mechanisms across various spatial scales. By adding insights from CUAs, the paper seeks to propose suggestions for future improvements in the domain of urban environmental evaluation.

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1. Introduction

1.1. Radical Urban Transformation and Climate Change

In the contemporary era, rapid urban transformation along with global climate change pose significant challenges for humans' health and social well-being. urban neighbourhoods have been confronting the growing issues of intensified urban heat islands, more frequent heat waves, high energy consumption and carbon emissions. These issues have garnered considerable attention and been thoroughly discussed over the past few decades, with particular focus during the recent COP29. As economic growth and technological advancements drive rural-to-urban migration, accelerating urban transformation necessitates sustainable renewal [1, 2]. Since the past century, compact and mixed-functional urban forms have emerged as a prevalent development strategy, featuring the urban landscape of *Generic City* [3, 4]. Compact urban form offers several benefits: maximizing land use, enhancing efficiency of infrastructure and amenities, shortening commutes, improving public transportation, and reducing car trips, while providing convenience for social interactions [5-7]. However, high-density urban neighbourhoods also present environmental and social problems, including inadequate daylighting, ventilation obstruction, pollutant accumulation, heightened pandemic virus transmission risks, as well as social segregation, etc. These problems impair city operations, residents' outdoor activity willingness, social well-being, and health, particularly in high-density central urban areas of Asian metropolises [8-10]. Hence, creating high-density urban blocks with efficient, resilient, and healthy living patterns has become a public priority, especially in the post-pandemic era.

1.2. Urgency of Rehabilitating Central Urban Areas

Central urban area (CUA) refers to clusters of highly developed building blocks situated within metropolitan districts in cities [11]. These clusters are comprised of buildings and spaces spanning various eras and encompass diverse socio-economic elements and formations [8, 9, 12]. The CUA represents a complex yet self-organizing urban subsystem, and is distinct from the notion of a modern central business district (CBD), examples like *Chiyoda* in Tokyo, *Central* in Hong Kong, *Futian* in Shenzhen, and *Hanzhengjie* in Wuhan. The high-density built environments in cities are increasingly vulnerable to climatic hazards, particularly urban heat waves and floodings [13, 14]. The thermal environment is especially important to cities' resilience and adaptability [15]. Typically, CUAs exhibit high-density and heterogeneous morphological characteristics through the combination and interaction of various types of building blocks constructed across different ages, showcasing socio-cultural inheritance and environmental diversity (Fig. **1**).

Figure 1: The *Generic City* in Asian metropolises - Image showing high-density heterogenous central urban areas in Wuhan City, China (VCG.COM, with permission for academic publication).

With escalating building density and height, outdoor public spaces in CUAs are dwindling, creating narrow street canyons with environmental and health risks for both outdoor and indoor spaces. The high-density CUAs enhance surface roughness of the urban landscape, reducing wind speed near the ground and impeding evaporation, which in turn increase humidity and foster bacterial growth [16-18]. The scarcity of public open spaces and the dense clustering of buildings in these CUAs impede outdoor thermal comfort and ventilation, influencing residents' ability to participate in outdoor activities during extreme weather conditions, such as heat waves. In the context of global climate change, urban architectural developments should prioritize human well-being, enhancing residents' living conditions, quality of life, and sense of happiness and security. Thus, systematic investigation and evaluation of CUAs' morphologies and thermal environmental performances provide scientific support and practical guidance for rehabilitating CUAs towards more resilient and sustainable development directions.

1.3. Purpose of the Paper

The topic of impacts of urban morphological characteristics on outdoor thermal environmental performance has been a widespread concern in the global [19]. Thousands of investigations have provided insights into sustainable urban practices and governance. Nevertheless, conflicting investigation results persist due to their variations in observation spatial scales, investigating techniques, analytical approaches, evaluation indices, and socio-geographical contexts. For instance, some of the existing studies that focused on micro-scale situations and conducted field measurement or computational simulations revealed that high-density traditional and old neighbourhoods in cities usually exhibited better outdoor thermal comfort conditions due to cooling effect of the shading, such as [9, 20, 21]. By contrast, many investigations on regional and city scale situations usually adopted remote sensing technique, and their findings illustrated high-density areas, in particular, those informally developed traditional and old neighbourhoods (e.g., Wuhan's *lifen*, Tianjin's *lao-cheng-xiang*, China's *urban village*, Turkey's *gecekondu*, and Southeast Asia's *desakota*) always presented very poor thermal environment and stronger urban heat island effects, such as [22-24]. On the other hand, urban and rural areas in many regions and countries, especially China, are increasingly interconnected in recent decades, with a clear trend towards urban-rural integration. As cities have grown in population and scale, local governments have shifted from quantity-based growth to quality-oriented and connotative redevelopment [25]. In this context, regenerating urban neighbourhoods in city centres towards healthier and more sustainable directions is a pressing priority. Notably, these neighbourhoods embody cities' history and culture and are central to residents' memories. Balancing these elements in urban renewal is crucial for the city's coordinated social, economic, and cultural sustainability.

Therefore, this paper concentrates on the object of those high-density heterogeneously developed central urban areas (CUAs) and advocates for establishing a multi-scale evaluation framework. While a reliable evaluation requires integration of contents, knowledges and methods in multiple domains (Fig. **2**). The paper primarily discusses the outdoor situations in CUAs, excluding the indoor conditions and indoor-outdoor interactions. The paper firstly highlights the emerging environmental issues in CUAs and followed by a comprehensive overview of the existing studies on their thermal environmental performances. It aims to identify current research foci and methodological constraints, subsequently outlining an evaluation framework based on the elucidation of the interconnectedness of thermal environmental performance across various spatial scales within the CUAs. By adding the insights from the diversity and complexity of CUAs, the paper seeks to propose suggestions for future improvements in the domain of urban environmental evaluation.

2. Energy Exchange and Urban Heat Island

2.1. Energy and Heat Exchange in Cities

Urban heat island (UHI) is a typical climatic phenomenon when the temperature of an urban zone is significantly higher than its surrounding suburbs and natural areas [26] (Fig. **3**). Radical urbanization and continued large-scale anthropogenic heat emissions are two of the main reasons for strengthening UHI effect. The UHI effect mainly resulted from buildings and built elements which absorb heat and energy during the day and

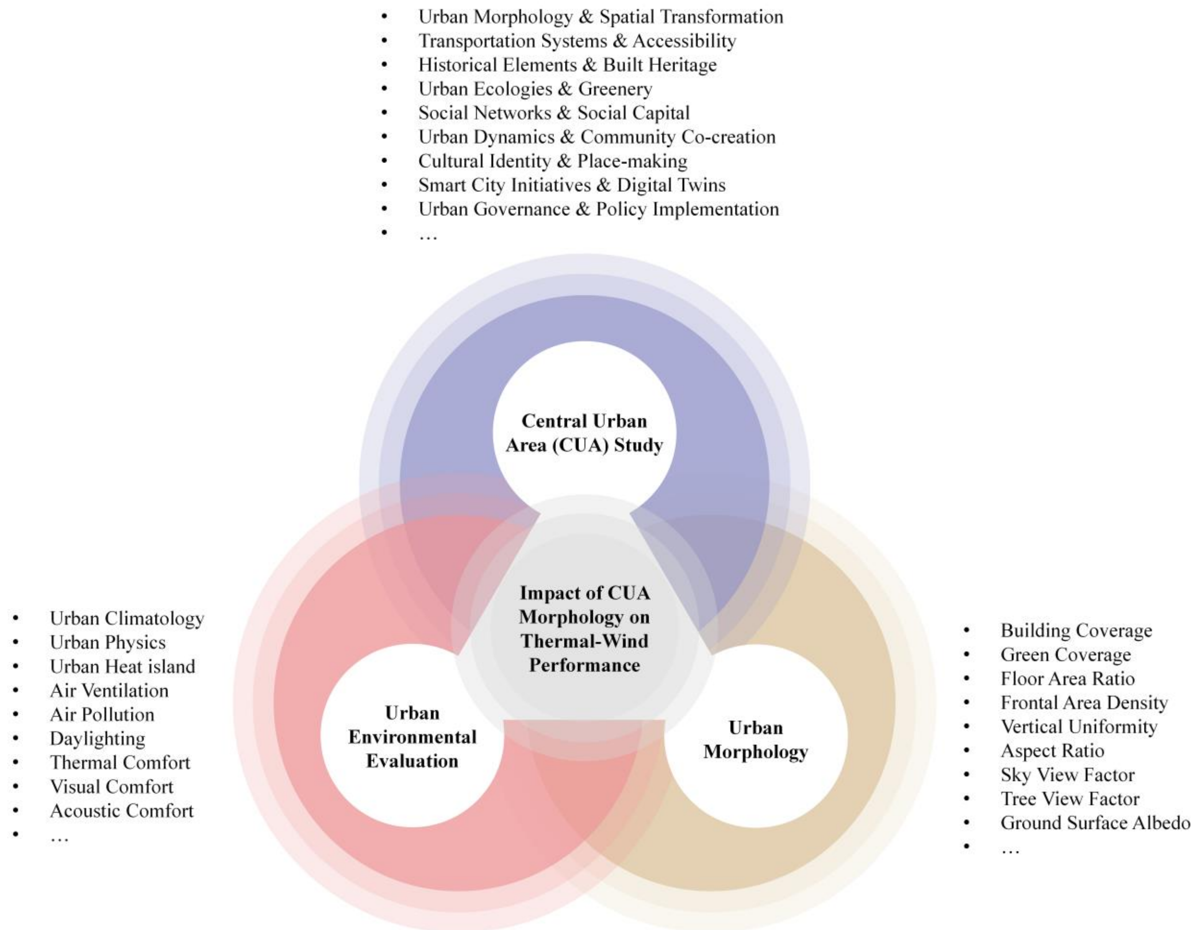

Figure 2: Related areas and research domains in this paper.

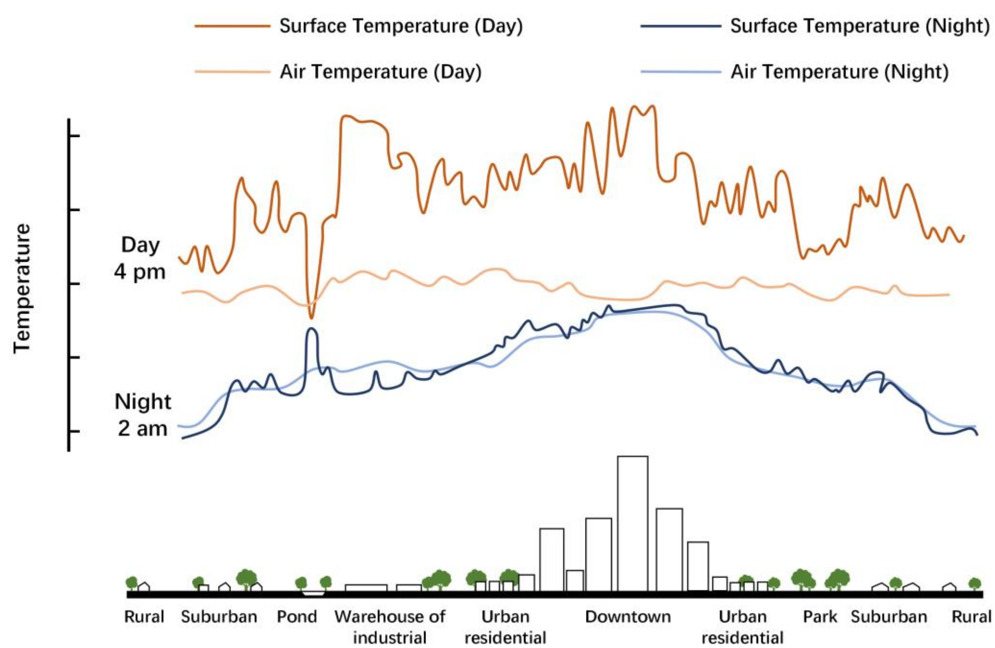

Figure 3: Profile of urban heat island over different types of land use land cover (adapted from EPA available from https://www.epa.gov/heatislands/what-are-heat-islands).

release them into the atmosphere at night, raising temperatures in city areas [27]. Moreover, UHI formation and changes are affected by multi-dimensional elements and factors, including changes in the physical properties of the underlying surface, large-scale release of anthropogenic heat by humans' daily activities, water vapor effects, weak wind environmental field, accumulation of air pollution, insufficient of green-blue infrastructures, and urban population concentration [28-30]. Continued intensification of the UHI effect, on the one hand, both intensifies air pollution and increases the number of days of heat waves, and on the other hand, poses a threat to the health of urban residents, particularly through causing heat stroke. Investigations of UHIs and its hidden mechanism and influencing factors have been an important task to be conducted since the 1800s [26, 31]. The exact formation and development of UHIs is complicated and varies across different regions and countries globally. Looking at the climatic and environmental challenges in contemporary cities, it is of great importance to explore the UHI formation mechanism and the thermal environmental performances in high-density heterogeneous CUAs in order to identify key influencing factors for urban practice and governance.

Eq. 1 and Fig. (**4**) illustrate the energy fluxes in the urban environment. Specifically, Q^* stands for net all-wave radiation, which encompasses both long-wave and short-wave radiation; Q_F is anthropogenic heat, such as heat produced by urban transportation systems or building energy consumption; Q_H is the convective sensible heat flux, which is transferred to the air through convection; Q_E is the latent heat flux, which is transferred through evaporation; $\triangle Q_S$ is stored energy, heat retained in materials; $\triangle Q_A$ is the net horizontal heat advection, for the reason that there are temperature variations around the city, which will lead to air circulation [32-34].

$$Q^* + Q_F = Q_H + Q_E + \triangle Q_S + \triangle Q_A \qquad \text{(Eq. 1)}$$

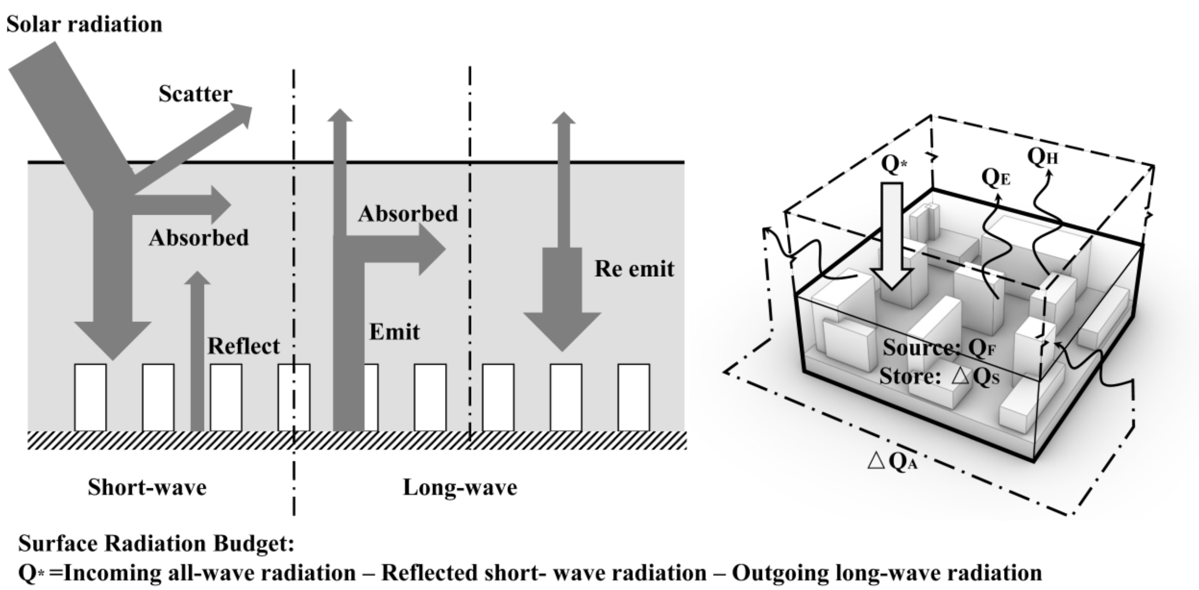

Figure 4: Schematic diagram of the energy fluxes in the urban environment (reinterpreted and redrawn from [32, 33]).

2.2. Formation and Mechanism of Urban Heat Islands

The destruction of the urban heat balance results in the formation of UHI effect. Although many environmental factors need to be considered for the formation of UHI effect and development of thermal environments in CUAs, including temperature, solar radiation, wind speed, humidity, etc. [1, 35], temperature is one of the major factors influencing thermal environmental performance in urban areas (Fig. **5**). At a global or regional scale, the temperature profile is mainly impacted by the geographical location of the area [36]. At a city or neighbourhood scale, temperature is significantly affected by the characteristics of urban pattens and spaces. Under the same solar radiation intensity, the urban underlying surface absorbs more energy and heat than the suburban underlying surface. However, the heat capacity of the urban underlying surface is relatively small, and it heats up rapidly, causing the urban near-ground air temperature to more rapidly increase and reach high values. Solar radiation is the main source of energy on the earth's surface, and the layout of high-density urban blocks, especially high-rise building clusters, affects the city's absorption of solar radiation, thereby influencing local urban climate conditions. Due to the different shading effects between buildings and trees, the performances of thermal environments and micro-climates exhibit differently [37, 38]. However, a typical characteristic of the cityscape in contemporary urban contexts is the rapidly increasing number and volume of buildings, in terms of scale and density. As these buildings increase in number in cities, it can lead to an increase in landscape surface roughness and formation of resistance to underlying winds [28, 39]. Consequently, the air velocity at a pedestrian level or close to the ground surface significantly slows down, presenting poor ventilation performance. Humidity is another key environmental indicator that affects urban thermal comfort conditions. Under weak wind and high air temperature conditions, higher humidity leads to lower rates of evaporation and stronger thermal discomfort perception, significantly impacting human quality of life [40].

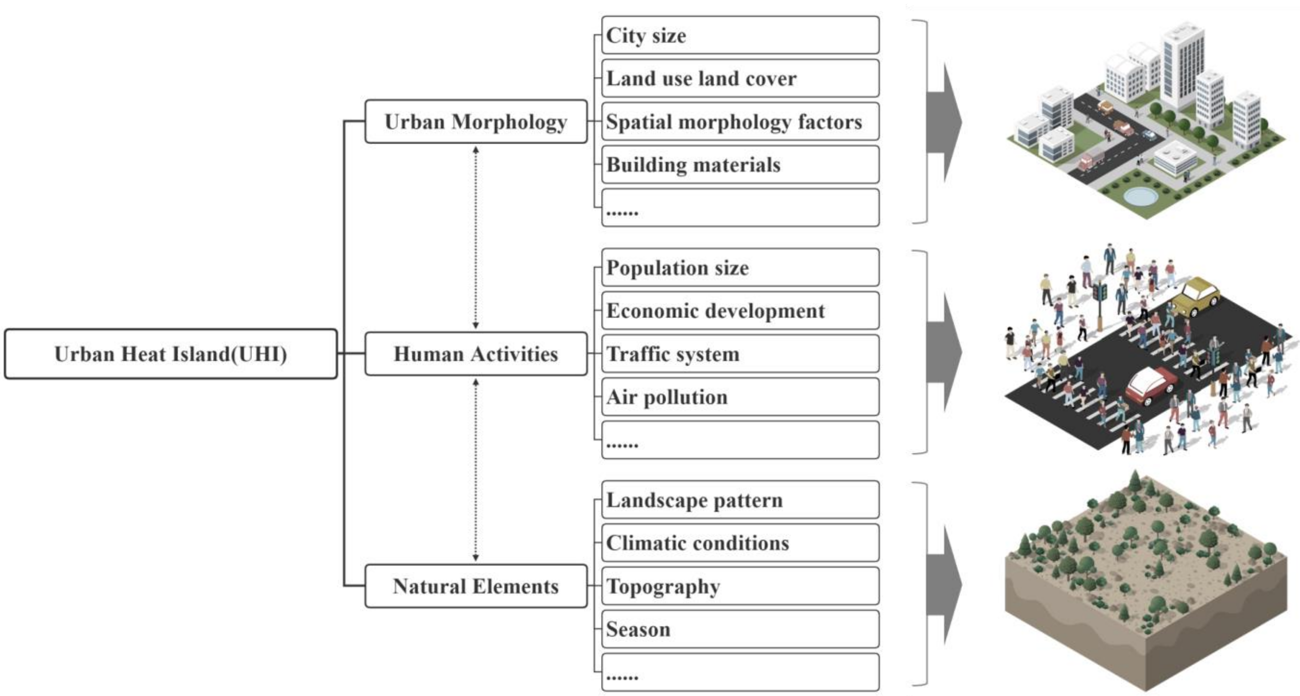

Figure 5: Formation and mechanism of Urban Heat Island effects (adapted from literature review, sketch maps available from: www.vecteezy.com).

To sum up, the climatic phenomena of increasing urban heat islands and heatwave events in recent years have been threatening human dwelling systems, particularly those highly developed built areas with extreme high population density. Central urban areas (CUAs) are particularly vulnerable to such environmental and climatic threats, given their high level of development and the complexity of spaces and human activities they exhibit. Therefore, it is crucial to conduct more systematic and effective evaluations of thermal environmental performance in high-density heterogeneous CUAs.

3. Multi-scale Quantification of CUA Morphologies

The spatial characteristics of high-density CUAs, such as building coverage, floor area ratio, building cluster layouts, building height, street canyon orientation, street aspect ratio, building façade and ground surface materials, as well as greenery coverage, have been extracted from previous studies (Table **1** and Fig. **6**). These features of urban morphologies are closely linked to urban climatic adaptation and foundational for thermal environmental evaluations [40-43].

Table 1: Definition of existing widely adopted urban morphological descriptors (source: summarized and organized by authors, based on literature review [10, 17, 18, 21, 34, 40, 43]).

Category	UMD	Abbreviation	Unit	Definition
Site-specific UMD	Building Coverage Ratio	BCR	0~100%	Ratio of building base area to total site area
	Floor Area Ratio	FAR	--	The ratio of the total construction area to the site area in the site
	Frontal area density	FAD	--	The ratio of the frontal area (AF - total area of building facets facing the wind direction) and the total surface area (A_T - lot area) at a specific height. FAD (λ_F) = $A_F \cdot MBH/A_T$
	Mean Nearest Neighbor Distance	MNND	m	The average value of the distance between the centre of mass of all buildings in the site and the centre of mass of the nearest neighbouring buildings.
	Mean Building Height	MBH	m	The total height of all buildings in the site divided by the number of buildings
	Vertical Uniformity	VU	m	The difference between the height of the highest building in the site and the average building height
	Normalized Difference Vegetation Index	NDVI	-1~1	A vegetation index that quantifies vegetation by measuring the difference between near-infrared (strong vegetation reflection) and red light (vegetation absorption). NDVI = (NIR - Red) / (NIR + Red)
	Green Coverage Ratio	GCR	0~100%	The ratio of green plant coverage area to the total area of the site
	Building Function Mixing Degree	BFMD	--	The ratio of the construction areas of different urban functions to the total construction area
Space/ Point-specific UMD	Aspect Ratio	H/W	--	The ratio of the average height of the buildings on both sides of the street to the width of the street.
	Sky View Factor	SVF	0~100%	The ratio of the visible sky area to the total sky area within a certain point of view in space, ranges from 0 to 100%
	Total Site Factor	TFS	0~100%	To quantify solar access at a measurement point in an integrative manner (integrated parameter of site geometry, sun track, solar radiation intensity, and time etc.), ranges from 0 to 100%
	Tree view Factor	TVF	0~100%	To estimate the amount of tree cover visible in the overlying hemisphere, ranges from 0 to 100%
	Ground Surface Albedo	GSA	0~1	The ratio of the reflected radiation energy projected onto the ground to the total radiation energy
	Ground Surface Heat Conductivity Coefficient	GSHCC	W/(m·℃)	Under stable heat transfer conditions, 1 m thick material, the temperature difference between the two sides of the surface is 1 degree, in 1 second, through 1 square meter area of heat transfer.
	Building Shape Coefficient	BSC	--	Building Shape Coefficient (S) refers to the ratio of the external surface area of a building in contact with the outdoor atmosphere (F_0) to the volume it surrounds (V_0) $S = F_0 / V_0$
	Canyon Axis Orientation	CAO	--	The angle between the main orientation of the block building and the prevailing wind direction

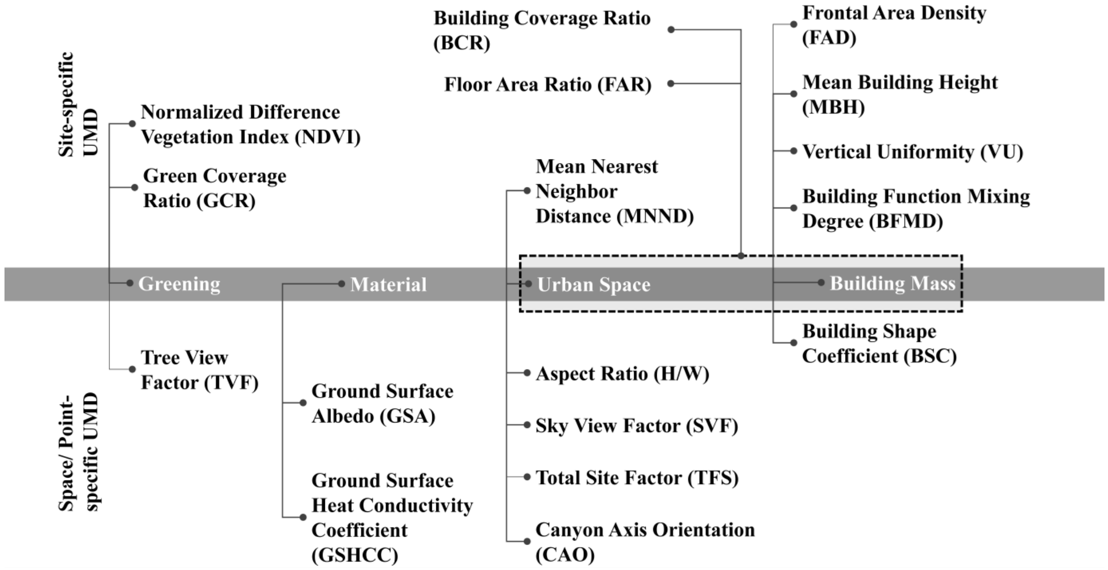

Figure 6: Relationships among different aspects of urban morphological descriptors.

In urban climatology and urban physics studies, the general classification of investigating scales ranges from global, regional-city, area-district, neighbourhood, building, to human body [44] (Fig. **7**). It is worthy noted that assessing impacts of urban morphologies on the urban climate and thermal environmental performances requires considerations of spatial *Scale* (Fig. **8**). The widely adopted local climate zone (LCZ) classification system has provided a useful and quick reference for urban design practice and climatic governance [42], while not covering the new situations and heterogenous spatial pattens in the high-density CUAs of Asian metropolises. The emerging mapping techniques have enabled finer and more accurate establishment of urban and architectural models, which can be further utilized for more detailed spatial analysis and environmental evaluations. Such as the recent prevailing unmanned aerial vehicle (UAV) oblique photography technology that allows researchers and practitioners capture high-resolution top and side-view images of urban buildings through vertical and multi-angle oblique perspectives [45]. This ensures comprehensive data collection and facilitates the digital reproduction of urban spaces with technical precision and efficiency.

Figure 7: Classification of investigation scales in studies of urban climatology and urban physics (drawn by authors based on [44]).

Currently, most evaluations of the thermal environmental performance of high-density urban built-up areas tend to yield negative conclusions, highlighting issues such as weak wind environments, uncomfortable outdoor thermal conditions, and more pronounced the urban heat island effects. A few researchers concluded that those old urban neighbourhoods characterized by high-density, multi-spatial morphologies in CUAs were one of the fundamental contributors to these environmental problems, adversely affecting overall urban ecosystem [23, 24, 47]. Nevertheless, most of these studies observe at a specific spatial scale and mostly from a *top-down* perspective, while lacking consideration of the performance from a *bottom-up* angle. They also lack sufficient consideration of the near-human spatial scale, which encompasses dynamically changing environmental factors and influencing mechanisms, such as air flow, humidity, and temperature gradients [48] (Fig. **8**). It is necessary to discuss how urban morphological characteristics affect the thermal environmental performances in CUAs based on a systematic understanding across city, district, neighbourhood, building, and even human body scales (Fig. **9**).

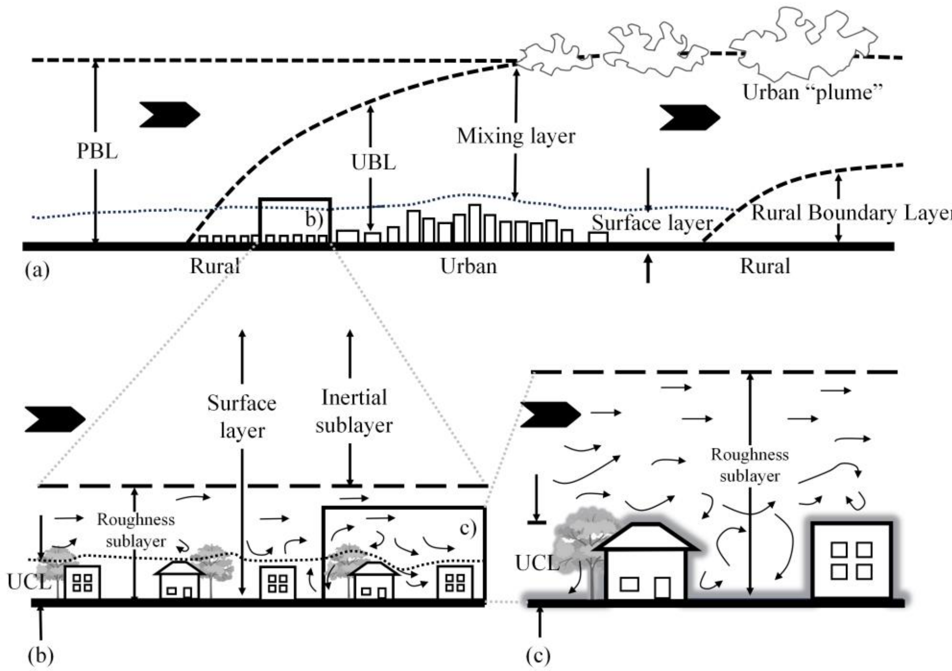

Figure 8: Vertical structure of the urban atmosphere over (**a**) a regional/urban/district area (macro-mesoscale), (**b**) a land-use zone/urban neighbourhood (local scale/mesoscale), and (**c**) a street canyon/outdoor space (microscale) (adapted from [35]).

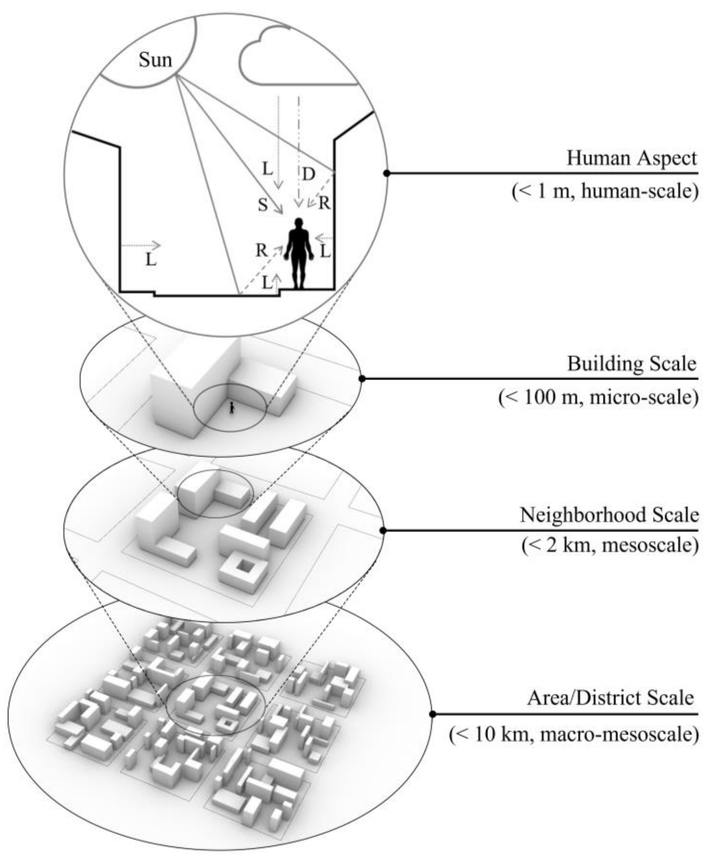

Figure 9: Inter-linked relationships between different spatial scales for urban environmental evaluations (drawn by authors, the image of human aspect adapted from [46]).

3.1. Area/District Scale

Existing studies on CUAs' thermal environments have looked at the district scale, comprising several building blocks. The primary focus of these studies is on the overall morphological features of the examined urban districts (usually covering an area of < 10 km^2), including street canyon orientation, street aspect ratio, and density of street network, and greenery coverage. From this perspective, the urban landscape can be decomposed into fundamental components, with further analysis hinging on the relative positional relationships between streets, public spaces, green areas, and building clusters at a broader scale (Fig. **10**). Several scholars have also investigated the diverse impacts of various greening configurations on urban heat islands at a district scale, as well as the cooling effects of different urban axes and greenery layouts on the urban thermal environmental performances (such as tree coverage, grassland coverage, vegetation shading ratio, greening roofs, size of green space, greening facades and so on).

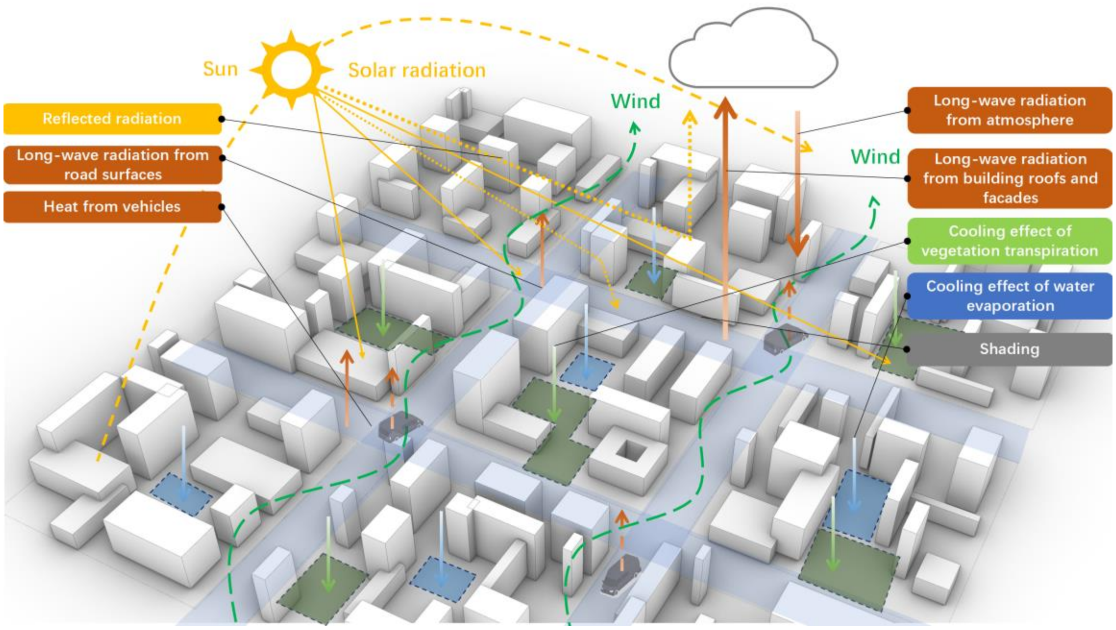

Figure 10: Schematic diagram illustrates the impacts of urban morphologies on thermal and wind environmental performances at *area/district scale* (drawn by authors).

3.2. Neighbourhood Scale

Most studies also focused on neighbourhood scale (usually covering an area of < 2 km^2) (Fig. **7**). The investigation on block or plot enables more detailed analysis of morphological characteristics of urban neighbourhoods like floor area ratio (FAR), building spacing, and arrangement of building clusters. Building cluster layout's influence on the thermal environments in urban neighbourhoods hinges on its angular relationship with urban wind direction. Alignment within a specific range boosts ventilation, heat removal, and thermal conditions for individual buildings and blocks (Fig. **11**). The evaluation should consider how building spacing and FAR impact the urban thermal environmental performance. For instance, higher FAR necessitates increased vertical architectural spaces, assuming constant site coverage and building spacing. The impact of building heights on the urban thermal environment has been extensively discussed [9, 49, 50]. Notably, it is known that different layouts of building clusters can achieve the same FAR via variations in building coverage or building spacing [51, 52]. High-density low-rises and low-density high-rises, for instance, represent distinct types of urban form achieving the same FAR. Low-density high-rises have relatively low land utilization, increasing inter-building distances and individual trips. However, wider streets do not necessarily ensure efficient traffic flow and accessibility, and growing distances between buildings tends to increase unnecessary travel by foot or bike [53]. Researchers should consider the long-term impact of FAR on the urban thermal environments, and how it aligns with future development objectives and cities' schemes of carbon reduction and energy savings potential. Examination of FAR alone can lead to diverse conclusions.

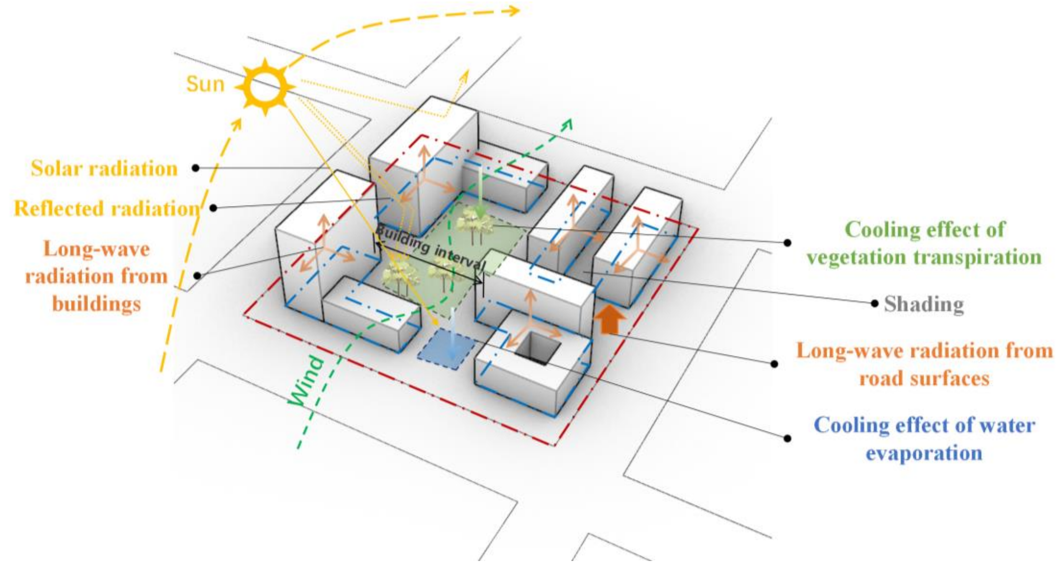

Figure 11: Schematic diagram illustrates impacts of urban morphologies on thermal and wind environmental performances at *neighborhood scale* (drawn by authors).

3.3. Building Scale

Examination at building scale allows scrutiny of morphological attributes like building height, materials, and envelopes. Materials not only define a building's facade characteristics but also play a key role in assessing its outdoor-indoor thermal insulation performances (Fig. **12**). In cities that feature hot summer and cold winter, enhancing materials' thermal resistance while mitigating outdoor temperature fluctuation can improve both outdoor and indoor thermal comfort conditions, and consequently, reducing energy consumption and lowering carbon emissions [54]. To some extents, the urban thermal environment is determined by how buildings absorb solar radiation during the day and release it at night [34, 55]. Existing studies at building scale have shown that high-thermal-resistance materials are vital for maintaining a balanced indoor thermal comfort condition, while contributing to mitigating the urban heat island intensity (UHII) and reducing energy absorption. Moreover, the pros and cons of UHI effects are context specific regarding geographical, climatical, and socio-cultural variations. In winter-prone cities, the UHI effect can raise temperatures, lower artificial heating demands, and decrease energy consumption, while might increase air pollutant accumulation. Therefore, it is necessary to understand

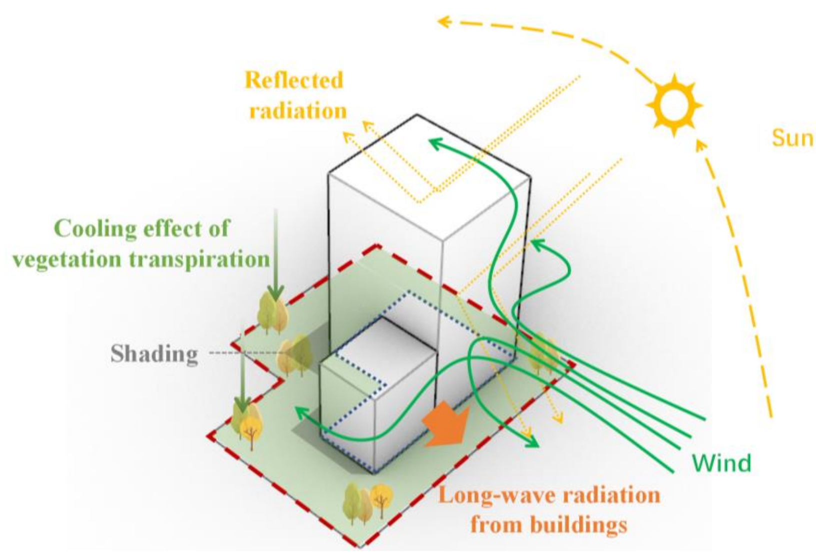

Figure 12: Schematic diagram illustrates impacts of urban morphologies on thermal and wind environmental performances at *building scale* (drawn by authors).

how building coverage and building height affect the thermal environment. Higher building clusters expand shaded areas for pedestrians during the daytime. Additionally, buildings in cities emit more anthropogenic heat and result in more carbon emissions and energy consumptions [1, 56]. However, if area is fixed, an inverse relationship exists building coverage and building height: under the same FAR condition, taller buildings reduce coverage, creating space for wind corridors and greening. Greening and cooling initiatives are also key strategies that can be applied at building scale to ameliorate urban thermal environment [57-59].

3.4. Human Aspect

A number of studies have shown that urban dwellers, as active participants in city growth and evolution, their daily routines and activities have significant impacts on urban thermal environments and vice versa (Fig. **13**) [9, 60-62]. According to Jan Gehl, there are three major types of residents' activities in urban public spaces: necessary, optional, and social [63]. Necessary activities include working, shopping, and transportation, while optional activities span amusement, casual meetings, and conversations. With the evolution of society, some optional activities have become integral to residents' daily life, increasing the overall energy consumption and carbon emissions of cities. As diverse social groups engage in varied activities influenced by age, occupation, and gender, analysing population categorization and understanding group impacts on the thermal environment is necessary as well. Communities that are younger are more vibrant, consuming more energy and generating more heat to support the social groups' daily activities. Community culture and folk activities, shaped by historical and regional contexts, also play a role in energy consumption. Religious rituals like bonfires and sacrificial practices (e.g., burning paper souvenirs) will produce flames and emit heat. These cultural events typically take place during particular festivals across the year. Notably, these activities are also ethnically and regionally specific. Some ethnic groups spend part of their life engaged in these pursuits, whereas others do not. Consequently, it is important to consider whether these anthropogenic heats affect the evaluation results when examining the thermal environments. In this regard, compared to architectural-spatial morphologies, social morphological features exert a more intricate influence on the urban thermal environment.

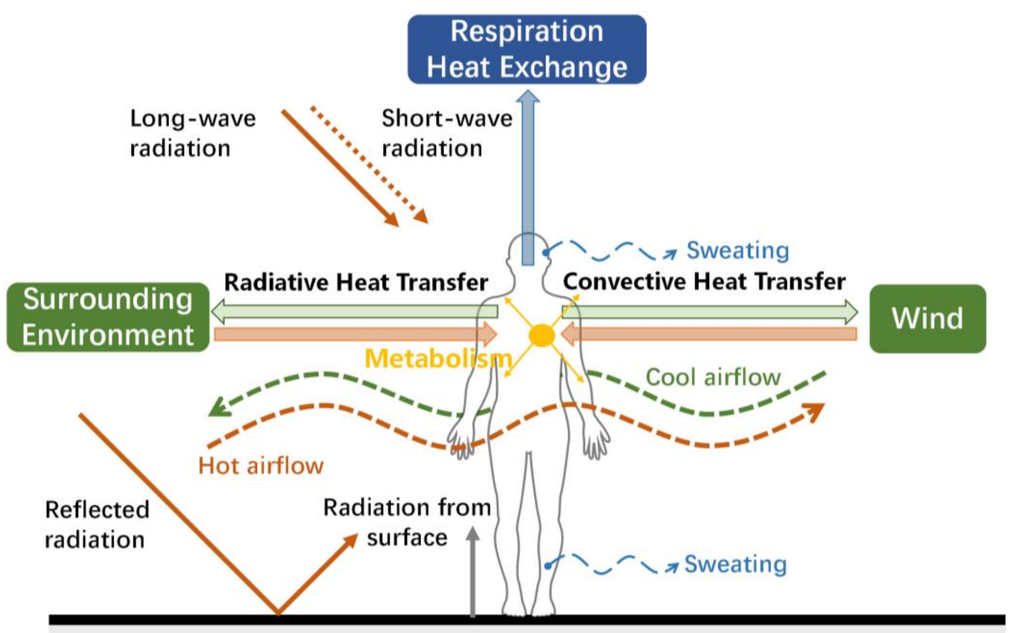

Figure 13: Schematic diagram illustrates heat transfer mechanism at *human body scale* (drawn by authors).

In the face of persistently high urban heat island (UHI) effects and average temperatures exacerbated by climate change, urban design researchers and practitioners are now directing their focus on "socio-spatial" morphological features as well, analysing their impacts on the urban thermal environmental performance. These analyses prioritize socio-morphological features to enhance urban spatial morphology, mitigate UHI effects, and alleviate frequent high temperatures. However, different urban spatial characteristics exert varying degrees of influence on the thermal environmental performance, necessitating thorough analysis to pinpoint their specific effects. Considering only one trait risks producing biased results. Instead, by identifying an urban morphological node and comprehensively analysing the superposition of all benefit curves, researchers and urban managers can ensure integrity, balance, and long-term sustainability, leading to the development of more energy-efficient urban forms [64, 65]. Enhancing the thermal environment through improvements in urban spatial morphology necessitates a more systematic and incremental approach than merely addressing the heat source. While modern architectural designs may not directly influence sociological behaviours and urban thermal environments, architects still bear the responsibility to conduct investigations and strive for maximum efficiency. Consequently, researchers are exploring how socio-morphological features affect the urban thermal environment, meticulously examining and organizing the diverse needs of inhabitants. This enhances accessibility among spaces, reducing functional granularity [66, 67]. Building spaces are being designed to possess predictability for future events or changes and accommodate complex and varied needs. By improving functional connectivity, it is possible to minimize unnecessary travel distances, thereby potentially reducing heat production. Scholars have also concerned the psychological effects of UHI on urban residents in recent years, such as [68-70]. This has enlarged the scope of mechanism detection while providing human-centred yet system-oriented insights into urban thermal environmental evaluation [14].

4. Existing Techniques for Urban Thermal Environmental Evaluation

Globally, research on urban form based on thermal environments primarily use one-site measurement approach, satellite remote sensing inversion, computational simulations, and machine learning powered techniques. The choice of method depends on the specific circumstances and should balance their advantages and limitations. Typically, many studies integrate on-site measurement and numerical modelling for the evaluations. As the most common and direct approach, on-site measurement offers real time, more accurate and reliable data representing real-world conditions, serving as a benchmark for verifying, comparing, and correcting other evaluation methods. Less common but often used in the initial stages of large-scale, long-term studies, computers can be used to construct mathematical or physical models replicating actual urban block environments. Moreover, the application of machine learning technique allows manipulation of microclimate parameters via statistical settings, enabling extensive research, exploration, and insights into guiding urban design.

4.1. Remote Sensing

Remote sensing observation, leveraging satellite sensors, can be used to collect comprehensive thermal environment data for metropolitan areas. The temperature derived from the remote sensing images of land surface temperature retrieval can be meticulously calculated, offering consistent data for the establishment of urban climatic map in the domain of urban climatology [71, 72]. This method offers manpower economic and convenient advantages to some extents, specifically for a regional or city district scale investigation. Here are some example studies that adopted this technique.

In their study on urban thermal environments based on local climate zoning in Beijing, Ren *et al*. [17] used Landsat 8 data to compare morphological criteria, including sky openness of spaces, mean building height, permeable and impervious surface ratios, as well as building footprint ratio. They found that forests and water bodies could significantly mitigate UHI intensity, while increased building density (building coverage ratio) exacerbates the heat island effect; taller buildings reduce the receiving of ground solar radiation. Gao and Zhao [50] similarly used Landsat 5 and Landsat 8 data to investigate block morphology's influence on surface temperature in Xi'an City over a five-year period. Categorizing the underlying layer, they analysed floor area ratio, building coverage ratio, mean building height, sky openness of spaces, urban porosity, and building height variability. They discovered that urban parks, green spaces, and water bodies presented lower temperatures than the commercial and industrial areas, with building density and construction land percentage having the most beneficial effects, and green space percentage the most detrimental. Leng and Diao [73] used Landsat OLI/TIRS imagery to study how building layout indicators affect block thermal environments, comparing building density, road aspect ratio, and volume ratio. They found no significant impact from building orientation but a strong correlation between building density and block temperature. Additionally, building height's effect varied seasonally, with a negative correlation in summer and positive in winter. Road density and floor area ratio had insignificant impacts. Bahi *et al*. [74] employed remote sensing to examine the surface urban heat island (SUHI) in Casablanca from 1987 to 2015, finding that the SUHI effects were more prominent in high-density urban areas compared to other types of urban neighbours. Notably, some studies also exhibit that the density issue of urban areas might not be so crucial for the contribution of UHI effects under some conditions. Sobstyl *et al*. [75] discovered that the uniformity and homogeneousness of urban textures contributed more to the increase of UHII. In addition, an investigation from Wu *et al*. [76] illustrated that those high-density traditional urban neighbourhoods embedded in city centres of Pearl River Delta region actually presented a lower UHII or even could generate urban cool island (UCI) effect sometimes during hot summer days.

4.2. One-site Measurement (Fixed-point and Mobile Modes)

To evaluate urban thermal environments with the field observation, climatic parameters, including air temperature (Ta), wind speed (*v*) and direction, relative humidity (RH), and mean radiation temperature (MRT), is directly collected at measurement sites. This approach, incorporating both fixed-point measurement and mobile measurement modes, has been widely adopted in examining CUAs' thermal environmental performance. Jin and Cui [77] applied this method to Harbin Central Street, arranging 27 grid-based measurement points and examining the correlation between morphological elements and temperature in summer and winter. Their study also considered anthropogenic heat sources such as vehicles and building air conditioning. Their test results highlighted sky openness of space (SVF - sky view factor) as the primary factor influencing average temperature: higher openness of space led to cooler nights and warmer days due to less retained heat at night and increased solar radiation in the day. Green spaces, however, by blocking sunlight absorption to some extents, maintained lower temperatures than adjacent areas. Similarly, Jin & Meng [78] conducted field measurement recordings of the real time temperatures of various paving materials and the outdoors using index of wet bulb globe temperature (WBGT) in cloudy and rainy days to assess the impact of ground surface permeability on urban thermal environmental performances. Their findings recommended permeable materials for outdoor paving in urban practice due to the lower temperatures experienced compared to impermeable alternatives. The study also evaluated the cooling effect of shading, revealing significantly cooler shaded areas with permeable materials. They noted that cement floors' reflectivity caused a hot and dry sensation, detracting from outdoor thermal comfort. Wang & Li [79] used microclimate dynamic measuring technology to analyse the summer and winter environmental features of Baocheng Road's urban blocks in Wuhan City. Their results showed enclosed layouts were more effective in expanding shadow areas than arrayed ones, and blocks angled 30 degrees north blocked summer solar radiation, enhancing shadow coverage. Yamaoka *et al*. [80] also conducted field measurements on an Osaka roadway to analyse the effects of urban canyon features on its thermal environment. By measuring the temperature, air humidity, and surface temperature of building walls and streets, they found that increasing vegetation and altering building heights and ground materials could improve the thermal environment by up to 2.0°C. In a hot summer period, Siret *et al*. [81] investigated spatial structure's impact on thermal comfort conditions in the city centre of Nantes, France. In order to collect details of the small scale urban spatial features and climatic data, they conducted mobile mode measurement by employing traffic lanes. The concept of the Day PET Signature (DPS) was adopted, and a Radiative Portrait was introduced for analysis. The results illustrated that the variations of thermal environments between clusters resulted from the radiative conditions in different spaces tested, while thermal diversity could only be achieved through the effects of shading by buildings, vegetation, and other built elements. Interestingly, Yang *et al*. [82] conducted an experiment to examine the thermal environmental performance of high-density CUAs of Hong Kong by simplifying the complex urban geometry as a lumped system and adopting the idealized city-scale energy balance model. Their test results illustrates that the high-density CUAs presented a significant urban cool island (UCI) effect in summer when neglecting the impacts of humans' daily activities.

4.3. Computational Fluid Dynamics (CFD) Simulations

To determine the relevant dynamic and thermodynamic properties of the model, numerical simulation involves creating a computational representation of the study subject and applying theoretical and computational analysis (computational fluid dynamics, CFD) [44]. This approach has gained significant attention in recent decades and shows potential for complementing or replacing on-site observations for further explorations (Table **2**).

Table 2: **Some of the prevailing computational simulation platforms in urban thermal environmental evaluations (summarized and organized by authors).**

Platform/ Software	Logo	Year of Release	Developer	Application	Examples of Studies
ENVI-MET	ENVI _MET	1998	Michael Bruse & Heribert Fleer	ENVI-met is a 3D modelling platform with advanced numerical algorithms for urban microclimate simulations and analysis. It has been widely employed for both research and practice in architectural design, urban planning, as well as green infrastructure development.	[39,83,84]
PHOENICS		1981	D.B. Spalding	Phoenics is a versatile CFD software for simulating fluid flow and heat transfer processes, which has been extensively utilized in analysing and forecasting fluid dynamics across diverse engineering scenarios.	[87-89]
LADYBUG		~ 2013	Mostapha Roudsari	Grasshopper-Ladybug is a useful environmental analysis plug-in, which provides great convenience for diverse environmental parameter analysis and visual interactive design simulations.	[90-92]
HONEYBEE		~ 2015	Mostapha Roudsari	Grasshopper-Honeybee plug-in enables simulations on building energy consumption, thermal comfort conditions, daylighting, and indoor lighting environmental performances.	[93-95]
FLUENT	ANSYS FLUENT®	1983	Hasan Ferit Boysan, Bill Ayers, & Bart Patel	ANSYS Fluent, beyond calculating mechanical and thermal stresses in solids submerged in fluids, excels in simulating and computing complex flow and heat transfer problems, providing comprehensive solutions.	[96-98]
OPENFOAM	OpenFOAM The Open Source CFD Toolbox	2004	Henry Weller, Chris Creenshields, & Mattijs Janssens	OpenFOAM is an open-source CFD software characterized by its modular design and extensive physical models. It has been widely applied in the investigations and simulations of fluid dynamics and heat transfers in many contexts.	[99-101]
ECOTECT	Autodesk Ecotect	1997	Andrew Marshall	Ecotect offers a wide range of environmental performance simulations and analysis, including solar radiation, visibility, daylighting, acoustic, and thermal environments.	[102-104]

A number of studies have adopted the CFD techniques to evaluate the thermal environmental performances of spaces in urban centres. Wang *et al*. [83], for their study on optimizing the planning and design of a central business district based on thermal environment, used the ENVI-met simulation software to assess the impact of various factors, including axis count and direction, neighbourhood layouts with different floor area ratios, and green space configurations, on the urban thermal environmental performance. Their findings showed that the arrangement of green spaces, diversity in floor area ratios, and number and orientation of axes significantly affected the UHI intensity. Similarly, they found that these factors also affect outdoor thermal comfort to varying degrees, and positioning green spaces along the central axis in a north-south orientation enhances thermal comfort conditions most effectively. Yang *et al*. [84] employed a combination of field measurements and numerical simulations using ENVI-met to investigate the impacts of various planning and design strategies for high-rise residential areas on the outdoor thermal environment of two communities. Their results indicated that building layout, greening, and street orientation impact the communities' thermal environment. Their study also explored various coping mechanisms in heat environments, finding that increasing tree canopy density and green space coverage, alongside the use of reflective paving materials, can enhance thermal comfort and mitigate the urban heat island effect. Wang & Meng [85] utilized DUTE data to simulate and analyse eleven cases across four climate zones, focusing on the effects of greening on the thermal environment of commercial areas. By incorporating relevant parameters into the simulation software, they compared the impacts of tree area ratio, roof greening ratio, and green space ratio. Their results show that, roof greening does not significantly reduce urban heat stress. However, increasing the tree area ratio can enhance outdoor thermal comfort conditions. Takahashi *et al*. [86] measured and carried out CFD simulation to predict Tokyo's urban thermal environment at three locations. Their CFD modelling forecasted air temperature, relative humidity, wind speed, and boundary layer heat flux in urban settings, examining boundary layer heat flux and surface temperatures of building walls and roadways. Their findings demonstrated that computational simulations could predict actual urban thermal environments and provided insights into strategies to mitigate urban heat island effects and enhance the urban thermal environment at the street level.

4.4. Machine-learning and Artificial Intelligence

Machine learning (ML) is a crucial subset of artificial intelligence (AI) and enables computers to detect patterns and rules in data. Existing studies have demonstrated its promising applications in managing the thermal environment of compact urban areas. A few scholars have also put forward the working flow to be referenced by both environmental researchers and urban design practitioners (Fig. **14**). With the aim to efficiently address increasing heat stress in cities, Shahrestani *et al*. [105] developed a ML-based framework for assessing outdoor thermal comfort conditions. Mohamed & Zahidi [106] have also discussed the possible combination of AI techniques to the study of urban heat island effect. To explore further, Ji *et al*. [90] explored to optimizing environmental performance using intelligent generation and design with ML technique for residential areas. Using Shenzhen Qianhai New District as a case study, they simulated wind and thermal performance with Ladybug, Honeybee, Butterfly, and other models on Rhino/Grasshopper. Implementing a ML agent with TensorFlow and Python, they optimized volume ratio, solar radiation, universal thermal climate index (UTCI), and landscape view. Their findings underscored ML's ability to integrate performance into design, balance practicality and aesthetics, and enhance performance evaluation efficiency. Similarly, Yao *et al*. [107] analysed the morphological design of complex buildings using a multi-agent system approach, leveraging Python and the Rhino-Grasshopper platforms. Their model, aimed at optimizing external wind and sunlight, iteratively deduced an optimal two-dimensional building arrangement. To optimise renewal of urban living environments, Zhou *et al*. [108] also examined intelligent detection and modelled the urban micro-meteorology conditions, taking a university campus located in Shanghai as the case study site. Deploying sensors for long-term monitoring, they established a real-time meteorological model through introducing the technique of cloud-based internet of things (IoTs). Their results have highlighted ML's potential to aid in refining building environment adjustments, reducing energy consumption and carbon emissions, mitigating heat island effects, and thus enhancing quality of urban thermal environments.

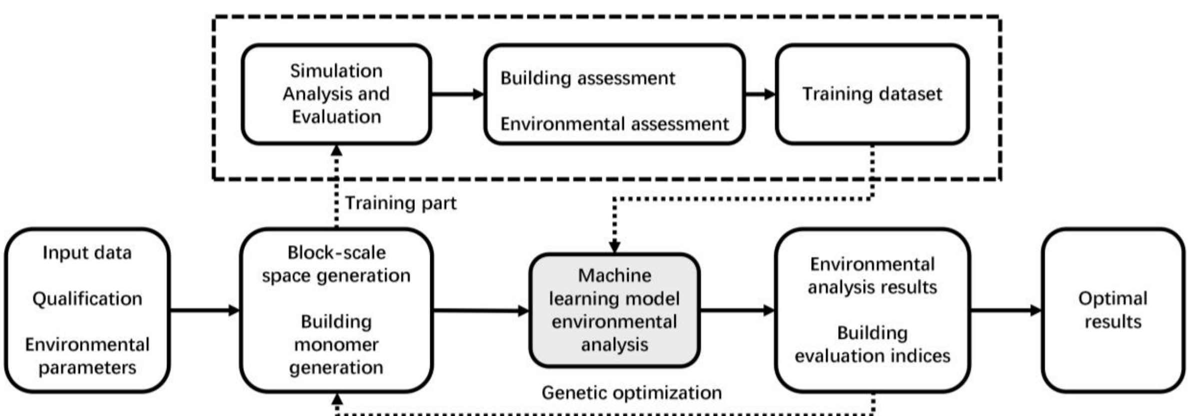

Figure 14: A suggested framework of machine learning to be applied in investigation on urban thermal environmental performances (adapted and translated from [90]).

5. Discussion

The existing studies highlights three prevalent methods to investigate the impacts of urban forms on thermal environmental performances: on-site measurements, computational simulations, and their combination. On-site measurements offer objective, direct, and authentic data but have limitations. Although on-site measurements are critical, they are limited in data scale due to resource constraints. Further, data is typically collected at block intersections or in grids, hindering accurate reconstruction of urban plane temperatures from point data. The temporal scope is also limited by measurement capabilities, often simplifying the urban thermal environment with non-granular hourly data curves. This makes it difficult for researchers to account for the impact of anthropogenic heat sources, though it can be very accurate. Mobile observation offers larger-scale data collection but may lack temporal alignment and authenticity. Moreover, avoiding variations in the measurement conditions for solar radiation across blocks is challenging. Remote sensing data, reflecting the city's thermal environment, is accessible for long-term trend analysis but has limited resolution and needs accuracy enhancements. Computational simulations are convenient and offer significant research potential for investigating urban heat island mitigation tactics or testing improvement strategies. However, mirroring real-world conditions is crucial for reliable feasibility indicators. Emerging artificial intelligence (AI) technologies provide some efficient solutions to current research methodology limitations. For instance, using a real-world building block data from on-site data measurement, AI can be employed to refine computational simulations and parameters to closely mimic reality. Moreover, by modelling the impacts of morphological elements on urban thermal environments, it is possible to determine their proportional significance using AI technologies. It can therefore identify measures to enhance the thermal environment without altering existing urban designs or identify unhealthy structures for rehabilitation or reconstruction.

To achieve a more systematic and holistic environmental evaluation on central urban areas (CUAs), an integrated working framework is put forward here (Fig. **15**).

1. Firstly, a comprehensive examination of the principles should be conducted by considering both the emerging new ecological-environmental phenomena and the changing of the existing identified situations, in particular, the energy exchange and urban heat island mechanisms in the transforming CUAs.
2. Secondly, a more detailed and systematic quantification of the morphological characteristics of the CUAs is necessary to scientifically exhibit the real-world conditions as much as possible, which covers diverse aspects and spatial scales, including building masses, spatial geometries, vegetation and natural elements, as well as ground surface materials, etc.
3. Thirdly, multi-domain along with multifactorial assessments need to be carried out and compared, as some of the environmental aspects or factors are intercorrelated while with contradictory effects on CUAs under different temporal-spatial contexts.

For example, a compact neighbourhood pattern is good for achieving thermally comfortable outdoor environment during hot summer days while not always beneficial for sufficient daylighting and ventilation to some extents. Thus, rather than looking at the optimization of single environmental aspect in such type of neighbourhoods, exploration of a take-off condition among multiple environmental factors is of great importance for establishing good quality urban environments for residents. Moreover, the advancement of sophisticated simulation and predictive tools, such as computational simulation platforms and machine learning techniques, presents great opportunities to detect deeper underlying mechanisms of the dwelling ecologies in CUAs. This, in turn, aids in achieving the objectives of urban resilience and sustainable governance.

6. Conclusion

Nowadays, advancements in measurement techniques have broadened the scope of evaluating urban climate and thermal environmental performances. These evaluations have expanded from a macro- to mesoscale approach (encompassing regional, city, and district scales) that previously focused on examining a single key environmental indicator, to a microscale analysis (neighbourhood, block, and building levels) that now tests multiple variables across various environmental aspects. It has shifted from traditional fixed-point or mobile on-site measurements, which are time-consuming and influenced by real-time dynamic meteorological conditions, to the utilization of CFD simulation tools and machine learning technologies. Moreover, the investigation focus has

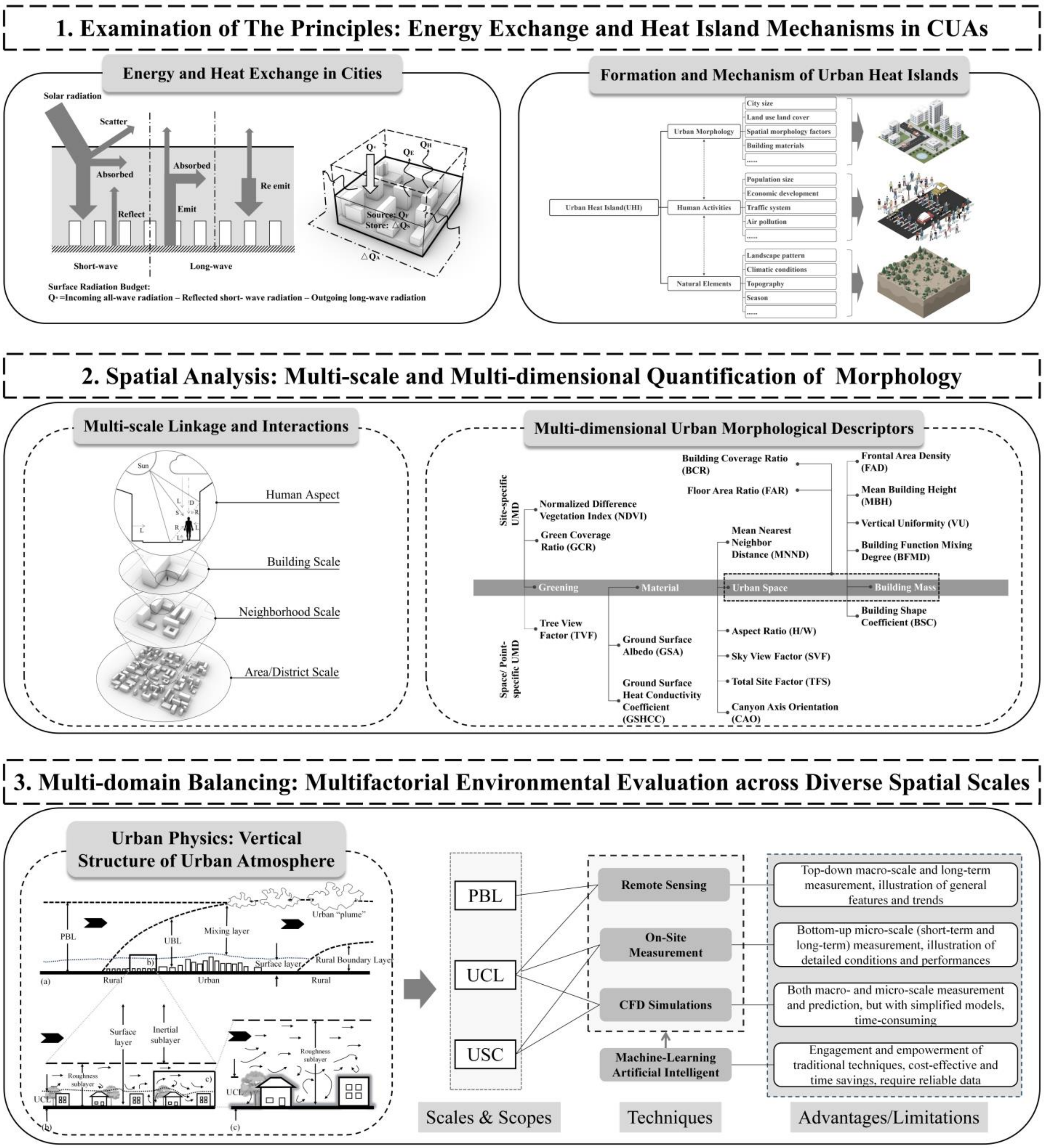

Figure 15: A framework for CUA environmental investigations and evaluations (some of the conceptual diagrams were reinterpreted based on [32, 33, 35, 46]).

evolved from solely considering physical factors to holistically incorporating the combined effects of both physical and socio-cultural factors. Specially, further investigating and integrating people's adaptive thermal comfort mechanisms along with their psychological impacts into the examination of central urban areas' thermal environments. This comprehensive approach aims to explore the interconnections among various environmental parameters, urban density and morphological characteristics, as well as residents' behaviours and responses. In response to climate change and urban intensification, this paper provides a few insights and reflections pertinent to both the research domain and urban policymaking. Looking at the relationships between urban morphological characteristics and outdoor thermal environmental performance, the paper has overviewed the existing studies at different investigating spatial scales and analysed the strengths and limitations of prevalent evaluation techniques. From the presented analysis, it can be concluded that integrating both *top-down* and *bottom-up* perspectives is essential for evaluating thermal environmental quality in central urban areas, which enables a comprehensive understanding of the underlying mechanisms and identification of core issues. Therefore, a systematic and holistic evaluation framework is necessary to clarify the interconnections of thermal environmental performances across multiple spatial scales within urban built-up areas.

Conflicts of Interest

The authors declare no known conflicts of interest.

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Author's Contribution

All authors contributed equally to this work.

Abbreviations

AI	=	Artificial intelligence
BCR	=	Building coverage ratio
BFMD	=	Building function mixing degree
BSC	=	Building shape coefficient
CAO	=	Canyon axis orientation
CBD	=	Central business district
CFD	=	Computational fluid dynamics
CUA	=	Central urban area
FAD	=	Frontal area density
FAR	=	Floor area ratio
GCR	=	Green coverage ratio
GSA	=	Ground surface albedo
GSHCC	=	Ground surface heat conductivity coefficient
H/W	=	Aspect ratio

IoTs = Internet of things

LCZ = Local climate zone

LULC = Land use/land cover

MBH = Mean building height

ML = Machine learning

MNND = Mean nearest neighbor distance

MRT = Mean radiant temperature

NDVI = Normalized difference vegetation index

PBL = Planetary boundary layer

RH = Relative humidity

SUHI = Surface urban heat island

SVF = Sky view factor

Ta = Air temperature

TSF = Total site factor

TVF = Tree view factor

UCI = Urban cool island

UCL = Urban canopy layer

UHI = Urban heat island

UHII = Urban heat island intensity

UMD = Urban morphological descriptor

USC = Urban street canyon

UTCI = Universal thermal climate index

v = Air velocity or wind speed

VU = Vertical uniformity

WBGT = Wet Bulb Globe Temperature

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