



Human Interaction with Urban Morphology under the Influence of Urban Heat Island: A Systematic Review

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ABSTRACT

Outdoor urban spaces are essential to residents' well-being, yet their thermal comfort is increasingly compromised by urbanization and climate change. Although urban morphology has been widely studied, its effects on human thermal comfort within microclimates remain inadequately understood. This study addresses this gap by examining the interactions between urban morphology, microclimate, and pedestrian thermal comfort. We employed a systematic literature review guided by the PRISMA framework, alongside parametric thinking using General Morphological Analysis (GMA) to systematically explore how variations in urban form parameters influence microclimatic conditions and pedestrian thermal comfort. The study's objectives were threefold: (1) to systematically analyze the existing literature, identify key trends, and uncover knowledge gaps; (2) to explore the psychological, physical, and social factors influencing thermal perception; and (3) to assess how urban morphological features affect microclimate and pedestrian thermal comfort. To address these challenges, we developed a novel framework, Design Tools, which quantitatively links urban morphology parameters, outdoor thermal indices, and pedestrian comfort. By prioritizing outdoor thermal comfort in urban design, this approach offers valuable insights to enhance climate-responsive design strategies and improve pedestrian well-being amid the growing challenges of urban heat islands.

Keywords: general morphological analysis, outdoor thermal comfort, parametric thinking, urban morphology

1. INTRODUCTION

The global urban population is projected to grow from 56% in 2020 to 68% by 2050, while climate models indicate a potential rise of 1.5°C in global temperatures over the next two to three decades, accompanied by elevated risks of severe climate impacts [1,2]. Increasing energy demands across buildings, transportation, and industry are the primary drivers of this trend. Urban areas, as centers of human activity, currently consume approximately 66%

of the world's primary energy and contribute over 71% of energy-related greenhouse gas emissions [3-6]. Continued urbanization and economic growth are expected to increase energy consumption by 70% and carbon emissions by 50% by 2050 relative to 2013 levels [2]. Rapid urban expansion necessitates high-density development, profoundly shaping urban morphology, influencing energy dynamics, and intensifying the urban heat island (UHI) effect [7,8]. These challenges underscore the critical need for integrated mitigation strategies and adaptive measures, including nature-based solutions, to support sustainable and climate-resilient urban futures [3,9]. Urban morphology, particularly the spatial organization of buildings and open spaces, strongly influences outdoor thermal comfort, affecting pedestrian

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NOMENCLATURE

<i>AT</i>	<i>Apparent Temperature</i>	<i>UM</i>	<i>Urban Morphology</i>
<i>DI</i>	<i>Discomfort Index</i>	<i>UF</i>	<i>Urban Form</i>
<i>ESI</i>	<i>Environmental Stress Index</i>	<i>UHI</i>	<i>Urban Heat Island</i>
<i>ET</i>	<i>Effective Temperature</i>	<i>UG</i>	<i>Urban Green</i>
<i>H</i>	<i>Humidex</i>	<i>UGS</i>	<i>Urban Green Spaces</i>
<i>HI</i>	<i>Heat Index</i>	<i>LAI</i>	<i>Leaf Area Index</i>
<i>RSI</i>	<i>Relative Strain Index</i>	<i>UGI</i>	<i>Urban Green Infrastructure</i>
<i>WGBT</i>	<i>Wet-Bulb Globe Temperature Index</i>	<i>GI</i>	<i>Green Infrastructure</i>
<i>WCI</i>	<i>Wind Chill Index</i>	<i>UWB</i>	<i>Urban Water Body</i>
<i>WCT</i>	<i>Wind Chill Temperature</i>	<i>GHG</i>	<i>Greenhouse Gas</i>
<i>COMFA</i>	<i>COMfort Formula</i>	<i>CO2</i>	<i>Carbon Dioxide</i>
<i>ETU</i>	<i>Universal Effective Temperature</i>	<i>LST</i>	<i>Land Surface Temperature</i>
<i>HL</i>	<i>Heat Load Index</i>	<i>2D</i>	<i>Two-dimensional</i>
<i>HTCI</i>	<i>Outdoor Human Thermal Comfort Index</i>	<i>3D</i>	<i>Three-dimensional</i>
<i>ITS</i>	<i>Index of Thermal Stress</i>	<i>FAR</i>	<i>Floor Area Ratio</i>
<i>PHS</i>	<i>Predicted Heat Strain</i>	<i>SVF</i>	<i>Sky View Factor</i>
<i>mPET</i>	<i>Modified Physiological Equivalent Temp</i>	<i>H/W</i>	<i>Height-to-Width Ratio</i>
<i>OUT_SET*</i>	<i>Standard Effective Temperature (Outdoor)</i>	<i>WWR</i>	<i>Window-to-Wall Ratio</i>
<i>PMV</i>	<i>Predicted Mean Vote</i>	<i>SRI</i>	<i>Solar Reflectance Index</i>
<i>PET</i>	<i>Physiological Equivalent Temperature</i>	<i>NW</i>	<i>Northwest</i>
<i>PT</i>	<i>Perceived Temperature</i>	<i>NE</i>	<i>Northeast</i>
<i>SET*</i>	<i>Standard Effective Temperature</i>	<i>SE</i>	<i>Southeast</i>
<i>STI</i>	<i>Subjective Temperature Index</i>	<i>SW</i>	<i>Southwest</i>
<i>UTCI</i>	<i>Universal Thermal Climate Index</i>	<i>V</i>	<i>Air Velocity</i>
<i>IREQ</i>	<i>Required Clothing Insulation</i>	<i>WD</i>	<i>Wind Direction</i>
<i>TSV</i>	<i>Thermal Sensation Vote</i>	<i>WS</i>	<i>Wind Speed</i>
<i>ASV</i>	<i>Actual Sensation Vote</i>	<i>W</i>	<i>Wind</i>
<i>TSI</i>	<i>Tropical Summer Index</i>	<i>Ta</i>	<i>Air Temperature</i>
<i>PRISMA</i>	<i>Preferred Reporting Items for Systematic Reviews and Meta-Analyses</i>	<i>RH</i>	<i>Relative Humidity</i>
<i>GMA</i>	<i>General Morphological Analysis</i>	<i>Met</i>	<i>Metabolic Rate</i>
<i>SLR</i>	<i>Systematic Literature Review</i>	<i>Iclo</i>	<i>Clothing Insulation</i>
<i>ASHRAE</i>	<i>American Society of Heating, Refrigerating and Air-Conditioning Engineers</i>	<i>PTC</i>	<i>Pedestrian Thermal Comfort</i>
<i>ISO</i>	<i>International Organization for Standardization</i>	<i>OT</i>	<i>Outdoor Thermal</i>
<i>SDGs</i>	<i>United Nations' Sustainable Development Goals</i>	<i>EN</i>	<i>European Standards</i>

well-being and satisfaction [10,11]. Thermal comfort, as defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), refers to the state of mental satisfaction with the thermal environment. Ensuring outdoor thermal comfort has become essential for public health amid accelerating urbanization and increasing extreme heat events [12,13]. Although traditional research has primarily addressed indoor thermal comfort, understanding outdoor conditions requires a paradigm shift embracing the complex interactions among environmental variables, urban form, and human perception [14]. Assessing outdoor conditions requires consideration of complex interactions among environmental variables, urban form, and human perception [15,16]. Urban morphology encompasses both the physical characteristics of buildings and their spatial arrangement within urban areas [17,18]. Features such as urban canyons, building form and orientation, construction materials, vegetation, and water bodies significantly impact the urban microclimate [19-21]. Microclimatic conditions

including air and surface temperature, humidity, wind speed, and wind direction are shaped by building attributes such as height, façade design, orientation, and incorporation of green materials [22-25]. Given the substantial effects of microclimates on outdoor thermal comfort, integration of human factors such as activity level, age, gender, clothing, cultural practices, and social norms is essential for accurate evaluation [26-29]. Recognizing the dynamic interplay between environmental and human factors supports the development of sustainable urban environments and enhances adaptive capacity in response to climate change [18,30].

This research investigates the influence of urban morphology on microclimates and pedestrian thermal comfort. It evaluates a range of thermal comfort indicators applicable to outdoor environments, assessing implications for human health and alignment with urban design objectives. By applying established benchmarks and thermal comfort thresholds, adaptive strategies can be developed to mitigate UHI effects and respond to local environmental conditions. The study aligns with the United Nations Sustainable

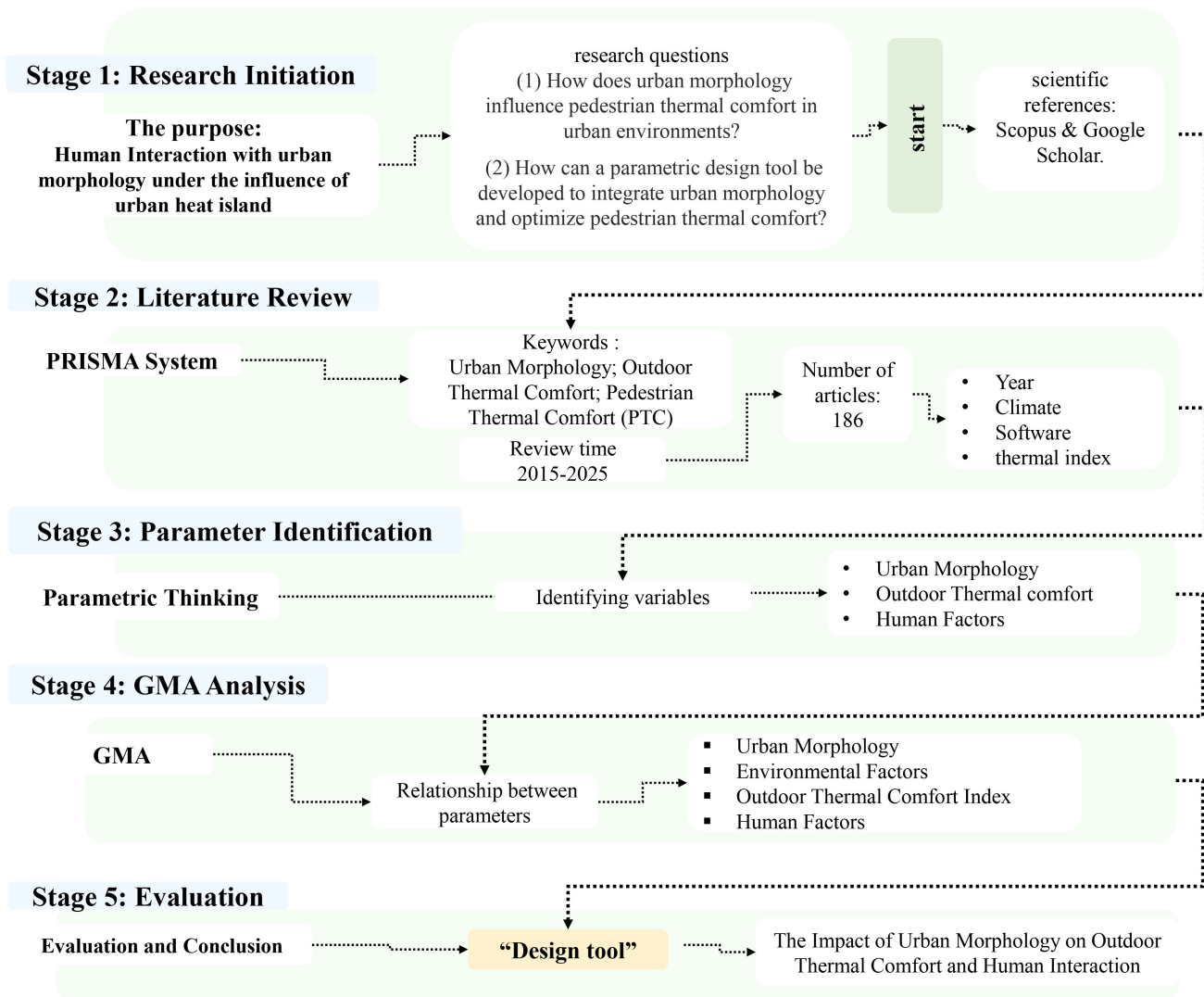


Fig. 1. Five-stage framework: (1) Research Initiation, (2) Systematic Review (PRISMA), (3) Parameter Identification, (4) Morphological Analysis (GMA + CCA), and (5) Design Tool Development—linking urban morphology, thermal comfort, and human-responsive design.

Development Goals, particularly Target 13 on Climate Action [31], emphasizing the role of urban resilience in addressing increasing urban heat challenges [32]. Cities are conceptualized as dynamic systems, where environmental and human factors are intricately interconnected, facilitating a comprehensive understanding of complex urban interactions. The research addresses two primary questions:

1. How does urban morphology influence pedestrian thermal comfort in urban environments?
2. How can a parametric design tool be developed to integrate urban morphology and optimize pedestrian thermal comfort?

The study is structured into methodology, thematic literature review, presentation of the design tool, and key findings, providing insights to inform adaptive strategies for mitigating the effects of urban heat islands.

2. METHODOLOGY: SYSTEMATIC REVIEW AND PARAMETRIC THINKING

A structured five-stage research framework was applied (Fig. 1): (1) Research Initiation, (2) Systematic Literature Review, (3) Parameter Identification, (4) General Morphological Analysis (GMA), and (5) Evaluation and Design Tool Development. This framework systematically explores the relationship between urban morphology and outdoor thermal comfort, emphasizing the role of the urban heat island (UHI) and integrating environmental, morphological, and human factors for climate-responsive urban design.

2.1. Systematic literature review

A systematic literature review was conducted following the PRISMA protocol (Fig. 2), to ensure transparent and rigorous selection of relevant studies. Peer-reviewed publications from

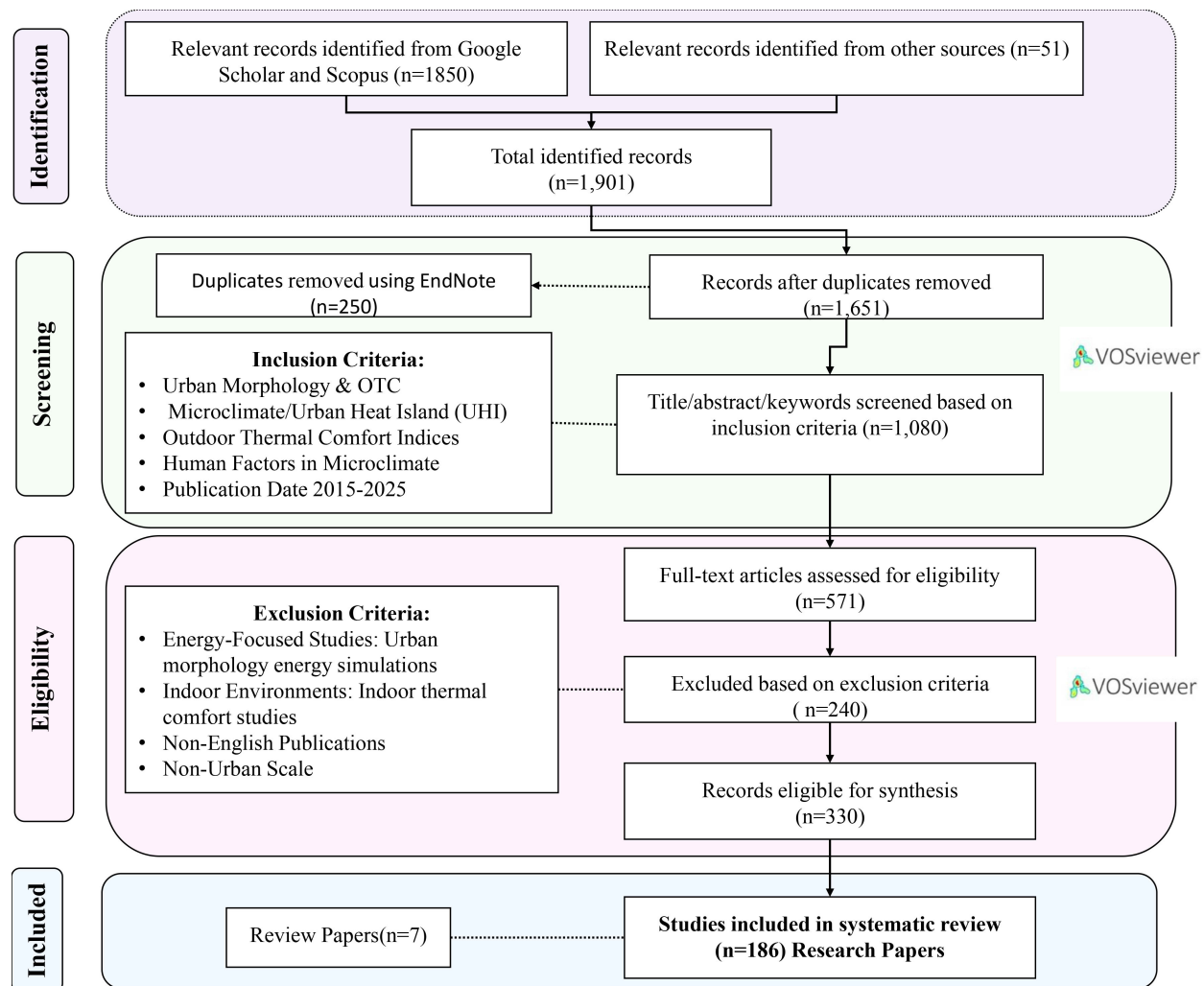


Fig. 2. PRISMA flow diagram illustrating the systematic literature review process, including identification, screening, eligibility, and inclusion of studies.

2015 to 2025 were searched in Scopus and Google Scholar, covering research on urban morphology, outdoor thermal comfort (OTC), and microclimate. The period was selected to capture recent developments and trends in the field. The initial search yielded 1,901 records. After removing 250 duplicates, 1,651 records were screened based on titles, abstracts, and keywords. Inclusion criteria encompassed relevance to urban morphology, outdoor thermal comfort indices, microclimate, UHI, and human factors. Exclusion criteria included indoor thermal comfort studies, energy simulations, non-English publications, and non-urban scale studies. Following screening, 1,080 records remained, and 571 full-text articles were assessed for eligibility. After applying exclusion criteria at the full-text stage, 330 studies were considered eligible. Ultimately, 186 studies were included in the synthesis, representing the most relevant and high-quality research for this study.

2.2. Parametric framework for urban morphology and outdoor thermal comfort using generalized morphological analysis (GMA)

To examine human interaction with urban morphology under UHI conditions, a structured three-stage parameter specification process was conducted. The process aimed to extract and organize key variables influencing human interaction across environmental, spatial, and behavioral dimensions.

In the first stage, comprehensive parametric identification was conducted through an extensive literature review. Key variables were identified across multiple scales of the built environment, including urban density and form, canyon geometry and orientation, surface materials (e.g., greenery, water features), building characteristics, thermal comfort indices, and pedestrian-level behavioral factors. In the second stage, Generalized Morphological Analysis (GMA) was applied to explore potential interactions among variables and develop new system

Table 1. Parameter analysis of urban morphology and human comfort using the Generalized Morphological Analysis (GMA) method. The table illustrates the relationships between urban morphological parameters, thermal comfort indices, and human factors. Checkmarks indicate significant interactions, highlighting the multidimensional effects of urban form on outdoor thermal comfort under UHI conditions.

		Human							
		Direct influences			Indirect influences				
		Physical factors	Physiological factors	Psychological factor	Behavioral factors: Clothing and Activities	Personal factors	Social & Cultural factors	Site	Alliesthesia
Parametric Urban Morphology	Urban Density and Form	✓	✓	✓	✓		✓	✓	✓
	Urban Canyons and Orientation	✓	✓					✓	
	Urban Material (Green, Water)	✓	✓	✓	✓	✓	✓	✓	✓
	Building Characteristics	✓	✓		✓			✓	
Thermal Out-door Comfort- Index	PMV	✓	✓	✓	✓		✓		✓
	PET	✓	✓	✓					✓
	WBGT	✓	✓		✓		✓		
	UTCI	✓	✓	✓				✓	✓
	TSV	✓	✓	✓		✓	✓	✓	✓

configurations [33]. Constraint Cross-Analysis (CCA) was integrated to ensure internal consistency within the GMA framework. Incompatible parameter combinations were systematically eliminated through pairwise comparisons, refining the morphological matrix into a coherent and viable design space (Table 1). In the final stage, insights from the GMA-CCA process informed the development of a climate-responsive design tool. This tool provides evidence-based morphological configurations to enhance outdoor thermal comfort and support positive human interaction in urban spaces affected by UHI. Minor design adjustments were shown to significantly influence environmental performance and pedestrian experience. The framework contributes to human-centered, climate-adaptive urban design, offering a practical foundation for shaping thermally comfortable and resilient public spaces under urban heat and microclimatic variability.

2.3. Bibliometric analysis

A bibliometric analysis was conducted using data extracted from Scopus and Google Scholar and visualized with VOSviewer to identify key research trends at the intersection of urban morphology, outdoor thermal comfort, and the UHI phenomenon. Keyword co-occurrence analysis, based on titles, abstracts, and author keywords, revealed four primary thematic clusters (Fig. 3). The first cluster (red) centers on thermal and morphological terms such as urban heat island and urban form. The second cluster (blue) highlights spatial and structural aspects, including urban morphology, urban canyon, and land use. The third cluster (green) reflects the increasing role of nature-based solutions, represented by terms such as green infrastructure, vegetation, and urban water. The fourth cluster (yellow) emphasizes human-related dimensions, including thermal perception, human behavior, and

psychological factors. Overall, the analysis demonstrates a multidisciplinary trend toward integrating urban form, climate responsiveness, and human experience. Computational modeling tools such as ENVI-met, CFD, and GIS are increasingly applied to assess urban microclimates. Nevertheless, significant gaps remain in addressing thermal perception and behavioral aspects within these models, underscoring the need for their stronger integration into urban morphological and energy resilience frameworks.

2.4. Global and temporal research trends

A global overview of the geographical distribution of studies on the urban morphology and UHI phenomenon is shown Fig. 4(a). Red circles indicate locations where research has focused on the intersection of urban morphology and UHI. The size of each circle corresponds to the number of publications, with larger circles representing higher research output. The figure clearly shows that the most studies are concentrated in developed countries. In contrast, many rapidly urbanizing developing nations despite being highly vulnerable to climate-related challenges have produced fewer than 15 relevant publications. Temporal trends in research output between 2015 and 2025 are illustrated Fig. 4(b), showing a notable increase in publications from 2018 to 2022, reflecting growing interest in the relationships among urban morphology, outdoor thermal comfort, and UHI. However, research growth remains uneven across regions. The top publishing journals in this field are highlighted Fig. 4(c). The majority of relevant studies appear in Building and Environment, Sustainable Cities and Society, and Energy and Buildings, identifying these outlets as leading contributors to interdisciplinary research on urban form and climate responsiveness. Overall, the analysis underscores both the

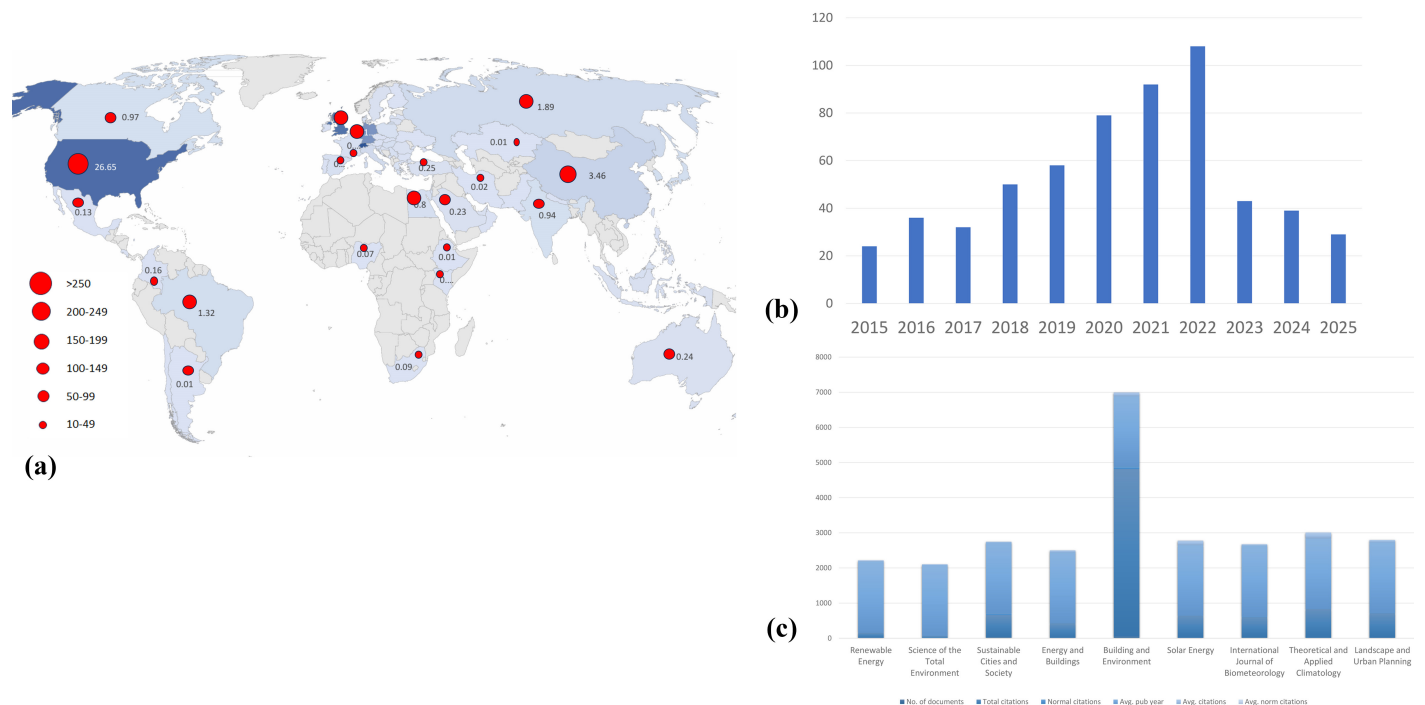


Fig. 4. (a) Global distribution of studies; circle size shows publication count. (b) Publication trends from 2015 to 2025. (c) Leading journals publishing research on urban morphology, outdoor thermal comfort, and UHI.

Empirical indices, derived from field surveys, relate subjective thermal sensation to microclimatic measurements, providing local insights but often constrained by cultural, regional, and acclimatization biases [18,44–46]. Each category has limitations: linear models neglect human adaptability, mechanistic models lack socio-cultural sensitivity, and empirical models face scalability challenges [47,48]. Future directions suggest hybrid models combining mechanistic precision with empirical contextualization, supported by cross-climate validation and advances in biometric sensing and machine learning [49–52].

3.1.2. Frequency of outdoor thermal comfort indicators

The most frequently used OTC indices are PET, UTCI, PMV, and SET (Fig. 5). Other commonly applied indices include Apparent Temperature (AT), Discomfort Index (DI), Perceived Temperature (PT), and Wet Bulb Globe Temperature (WBGT). Indices cited only once were excluded from the analysis.

OTC is often assessed using PET and UTCI, valued for applicability across diverse climates. PET, derived from the Munich Energy Balance Model for Individuals (MEMI), integrates environmental and physiological variables and often outperforms SET, PMV, and UTCI in dynamic outdoor conditions [15,16,30,53]. UTCI, based on the multi-node UTCI-Fiala model, offers high accuracy but is limited by reliance on European–Russian datasets and fixed clothing assumptions [54]. PMV, developed for stable indoor settings, shows lower accuracy outdoors due to insensitivity to solar radiation and variable wind [16,55]. Its adaptation, OUT-SET, improves radiation modeling

but may overestimate physiological responses despite strong correlations with thermal sensation votes [30,56]. WBGT, widely applied for heat stress assessment, demonstrates reduced accuracy in humid climates and often produces results comparable to UTCI [35].

3.1.3. Research methodologies in OTC studies

OTC studies employ empirical methods, based on field measurements, and numerical approaches using simulation models. Choice depends on objectives, resources, and data availability. Increasingly, integrated approaches combine real-world accuracy with analytical depth, as illustrated in (Fig. 6), enhancing the robustness and comprehensiveness of OTC assessments.

3.1.3.1. Numerical and simulation-based approaches

Numerical methods in OTC research employ tools such as computational fluid dynamics (CFD), ENVI-met, RayMan, and Rhino, along with parametric platforms like Ladybug and Dragonfly, integrated with EnergyPlus and OpenFOAM [57–61]. Geographic Information Systems (GIS) and sensing technologies further enable localized, real-time assessments [62–65]. Advanced predictive tools, including machine learning algorithms such as support vector machines, random forests, and neural networks and agent-based modeling are increasingly applied to forecast thermal comfort in complex outdoor environments. These methods bridge computational rigor with empirical validation, supporting robust urban microclimate analysis and sustainable urban design [66–68].

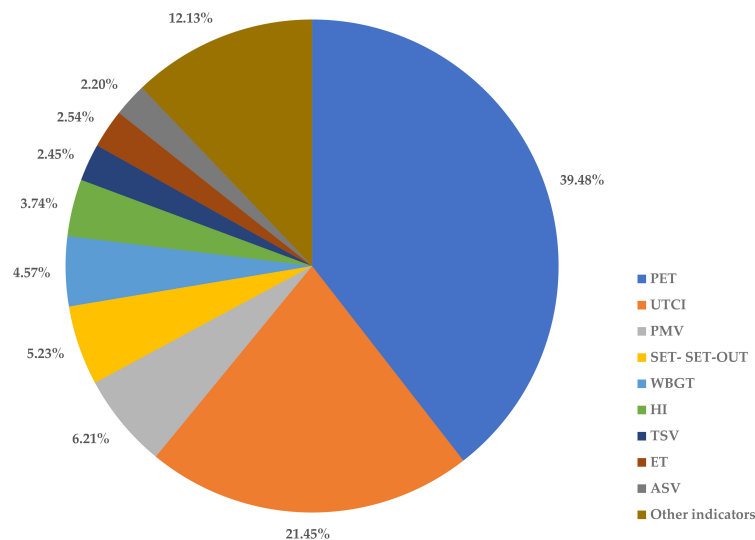


Fig. 5. Frequency of outdoor thermal comfort indicators.

3.1.3.2. Empirical methodologies

Empirical methodologies in OTC research integrate conventional and advanced techniques to evaluate both environmental conditions and human thermal responses. Environmental data are obtained using weather stations, data loggers, and microclimate sensors, measuring parameters such as air temperature, humidity, wind speed, and solar radiation [17]. Urban morphology is analyzed through fisheye lens photography, video documentation, and geospatial tools, with hemispherical imagery frequently employed to calculate the SVF and solar exposure patterns [69]. Subjective data are collected via spot measurements and thermal satisfaction surveys based on ASHRAE Standard 55, complemented by structured interviews and observational approaches such as activity logs and posture tracking. For instance, Peng (2019) applied path analysis to examine how age, BMI, health status, and outdoor activity frequency influence thermal perception, emphasizing individual variability [70]. Qualitative methods, including photographic comparisons, enrich OTC assessments by linking visual preferences to perceived comfort [71]. Since the late 20th century, technological progress has advanced Objective Physical Environment Measurement (OPEM), replacing manual techniques with automated systems such as Data Acquisition Systems (DAS) and GIS for high-resolution spatial analysis [72,73]. Recent innovations, including Building Information Modeling (BIM), the Internet of Things (IoT), and Virtual Reality (VR), enable real-time data integration and immersive visualization. For example, Shahin Moghadam et al. (2021) developed an IoT-based BIM platform employing edge computing to estimate MRT in alignment with PMV and PPD indices [74]. Non-contact technologies, such as smartphone thermal cameras and video-based motion detection, also support mobile, behavior-sensitive OTC monitoring, though challenges remain regarding outdoor measurement accuracy [64,75].

3.2. The impact of urban morphology and microclimate interactions on outdoor human thermal comfort

Urban morphology (UM) the spatial arrangement of buildings and open spaces significantly affects local microclimates and outdoor thermal comfort (Fig. 2). Early research focused on two-dimensional aspects like green cover and impervious surfaces related to land surface temperature (LST), while recent studies highlight three-dimensional factors such as building height, density, and volume [23]. This section reviews macro- and micro-scale literature to inform thermally responsive urban design.

3.2.1. Interaction between urban density, form

Global urbanization is projected to reach 68–70% by 2050, driving denser city structures typically measured by Building Coverage Ratio (BCR) and Floor Area Ratio (FAR) [23]. While density improves infrastructure efficiency and reduces per capita energy use, it also intensifies microclimatic extremes. Urban canyons and impermeable surfaces amplify the UHI effect, elevating nighttime temperatures by 2–5°C and diminishing OTC [9,28,76]. Tall building clusters, as observed in cities such as Beijing and Toronto, reduce daytime solar exposure but trap heat after sunset; in contrast, low-density sprawl facilitates ventilation yet increases daytime heat stress [23,77]. Field investigations and CFD simulations reveal density-related temperature increases of up to 1°C and 2.5°C, respectively [78]. Vertical configurations aggravate surface temperature gradients, while horizontal sprawl restricts airflow. A large-scale study in southern China identified urban density as the dominant predictor of thermal discomfort, surpassing vegetation cover and surface reflectivity [79].

Urban form also plays a decisive role in shaping thermal conditions. Low SVF designs, such as mid-rise buildings with narrow streets, enhance summer shading but obstruct winter sunlight, whereas high SVF grids promote solar gain yet disrupt

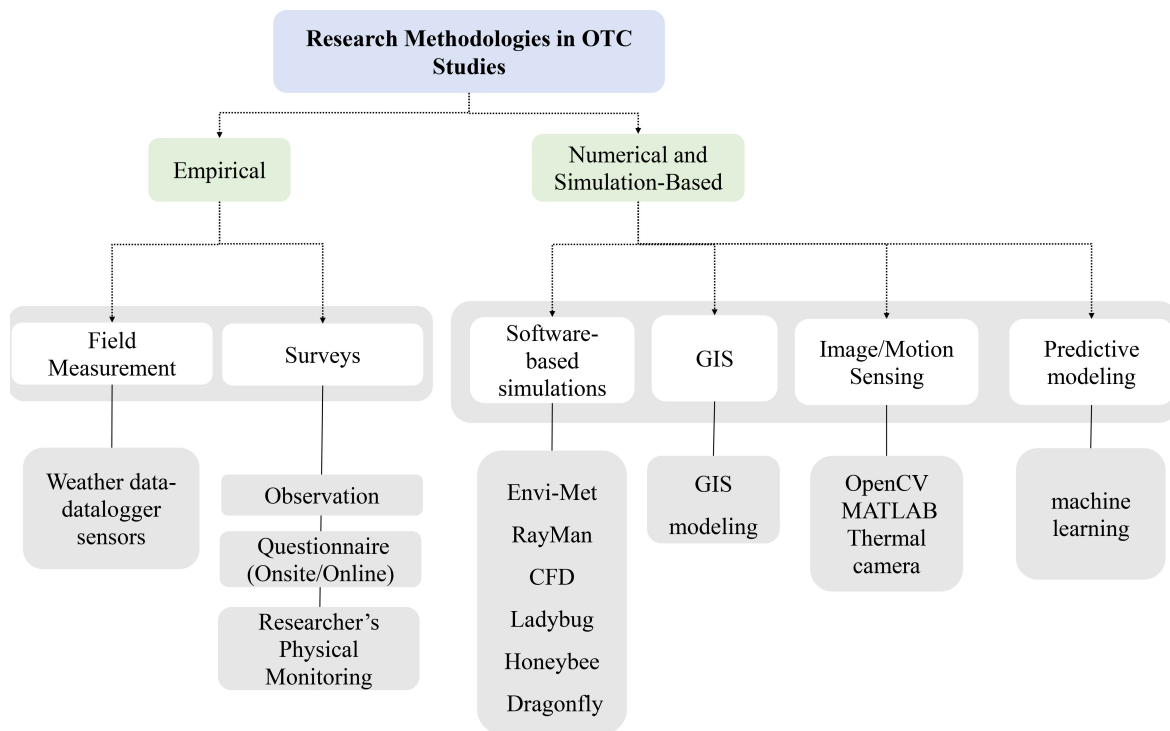


Fig. 6. Research methodologies in OTC studies.

airflow, intensifying heat stress [78]. Seasonal trade-offs persist: compact forms reduce summer PET but limit winter warmth, while open forms yield opposite outcomes [80,81]. Beyond physical form, human adaptation reflects both environmental and sociocultural contexts. High density and steep thermal gradients elevate psychological stress, requiring hybrid solutions such as shaded courtyards and comfort-oriented urban design [82]. Cultural background and behavioral adaptability also shape thermal perception. Populations in warmer climates, such as Greece, often report lower heat sensitivity, whereas residents of colder regions, such as Harbin, display higher TSV under similar PET levels [83,84]. Temporary populations during heatwaves exhibit elevated TSV, reflecting differences in thermal expectations [85]. Evidence from Shanghai and Cairo further demonstrates how migration and gender influence thermal behavior, underscoring the need for culturally responsive design. Achieving urban thermal resilience requires the integration of ecological infrastructure, density-sensitive planning, and sociocultural understanding [86,87].

3.2.2. Interaction between urban canyons, orientation

The geometry and orientation of urban canyons strongly shape microclimates and OTC by regulating solar access, ventilation, and UHI intensity. Core parameters H/W, SVF, and L/W control solar penetration and heat retention within canyon spaces [10,88]. Among these, the interaction between H/W and orientation is particularly critical. East–west canyons often record higher PET due to prolonged solar exposure, while diagonal orientations (e.g., NW–SE, NE–SW) provide more balanced conditions through

improved shading and solar modulation [89,90]. In hot climates, high H/W ratios (> 2.0) lower SVF and PET, enhancing summer comfort, as reported in Agadir and Fez [81]. However, excessive shading combined with limited ventilation may reduce comfort in colder or humid climates. Cultural and climatic contexts further influence perception; for example, residents in Phoenix and Marrakech display distinct responses to heat stress [91].

3.2.3. Interactions between urban materials and urban heat islands

UHI intensity is influenced by land use, vegetation cover, and material properties, such as albedo, emissivity, and thermal conductivity, which affect OTC and urban energy demand at multiple scales [32,92]. Surface albedo and the SRI are critical for UHI mitigation. High-SRI, light-colored materials reduce surface temperatures, improve pedestrian comfort, and lower building energy consumption [93]. Their effectiveness depends on urban form; wide street canyons typically show air temperature reductions, whereas narrow canyons may experience increased T_{mrt} from reflected radiation [94]. Combining reflective surfaces with shading elements, such as street trees, optimizes air and radiant temperatures, enhancing UTCI [95]. Thermal emissivity mitigates UHI by allowing surfaces to radiate stored heat [96]. Cooling strategies prioritize surface reflectivity, urban geometry, and materials with appropriate thermal properties. Pavement color and texture influence surface temperatures, with light, smooth surfaces lowering ST by up to 5°C [97,98]. Thermal conductivity and heat capacity govern heat transfer; high heat capacity suits

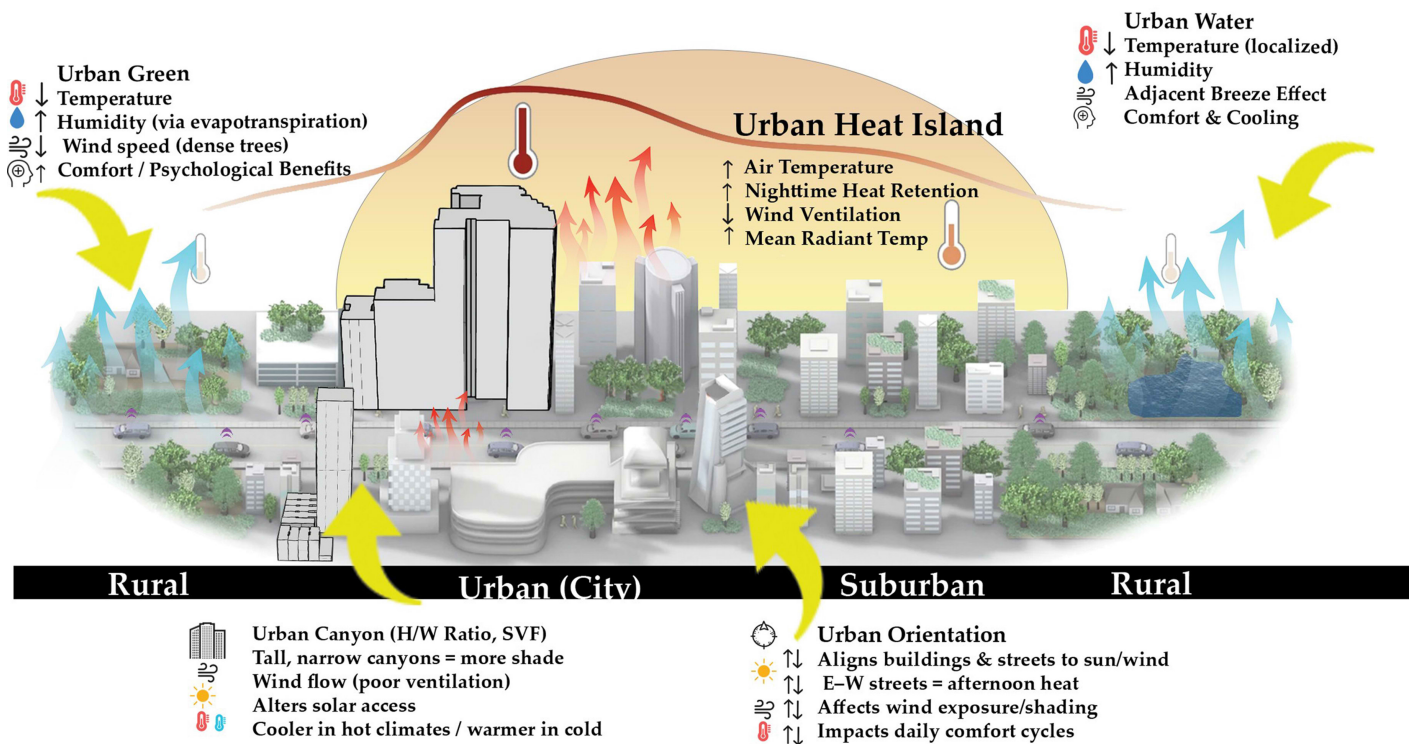


Fig. 7. Influence of urban morphology on environmental factors and urban heat island effect.

ventilated canyons, while low conductivity benefits dense urban areas [20].

3.2.4. Interactions between urban green and outdoor thermal comfort

Urban green infrastructure including forests, street trees, gardens, wetlands, green roofs, and green walls significantly mitigates UHI effects and enhances OTC [99]. Vegetation improves microclimates by providing shade, promoting evapotranspiration, and facilitating airflow. In the U.S., shade trees reduce surface temperatures by approximately 3.1 °C, while dense tree planting in Riyadh lowers PET by up to 16.9 °C, outperforming green walls [100–103]. Seasonal and contextual factors strongly influence effectiveness. In Changchun, summer LST decreased by 1.27 °C, with vegetation density (NDVI) affecting thermal conditions more than patch size or fragmentation [104]. In Chengdu, tree cover enhanced summer comfort, whereas open lawns were preferred in winter [22]. In Xi'an, winter thermal sensation was driven primarily by solar radiation, followed by air temperature and humidity, with residents favoring sunlit areas, emphasizing the need for seasonally adaptive, climate-sensitive urban design [105]. Time of day strongly influences the cooling effect of urban vegetation. In Cairo, increasing canopy cover to 35–50% reduced PET by over 5 °C during peak afternoon hours, while efficient irrigation decreased water use by 85% [101]. Tree placement near tall buildings, as observed in Prague, reduced cooling by 1 °C [103]. Mixed tree species, including *Acer*, *Ulmus*, and *Pinus* in Tabriz, lowered PMV to 2.39 [106]. In Xi'an, *Ginkgo biloba* significantly reduced UTCI, and aesthetic characteristics affected

perceived warmth by up to 2 °C [107]. Seasonal performance varies with species composition; mixed deciduous-evergreen canopies were most effective in tropical and temperate zones, whereas evergreens performed best in arid climates [104,108–110]. At the building scale, green roofs reduce energy loads but provide limited pedestrian benefits, whereas green walls lower Tmrt by up to 5 °C and reduce pollutants, enhancing street-level comfort [105]. Thermal comfort is both physical and perceptual: in Nuevo Bosque Park, Colombia, 90.91% of visitors reported comfort under tree cover despite a THI of 55 °C, while 69.69% experienced discomfort in open area [111]. Physiological studies confirm brief exposure to greenery lowers heart rate, increases parasympathetic activity, and enhances emotional well-being [112].

3.2.5. Interactions between urban water bodies and urban heat island mitigation

Urban water bodies (UWBs) including lakes, rivers, ponds, and wetlands significantly mitigate UHI effects and improve thermal comfort through thermal inertia and evaporative cooling (Fig. 7). By absorbing solar radiation and releasing moisture, UWBs can lower nearby air temperatures by up to 3 °C during peak heat [113,114]. Cooling effects vary by climate: tropical regions experience year-round moderation but limited evaporation due to high humidity; Mediterranean climates benefit most during hot summers; arid regions experience both daytime and nighttime cooling due to low humidity. Diurnal cooling ranges from 3–5 °C, with minor nighttime warming of 1–2 °C, while seasonal cooling

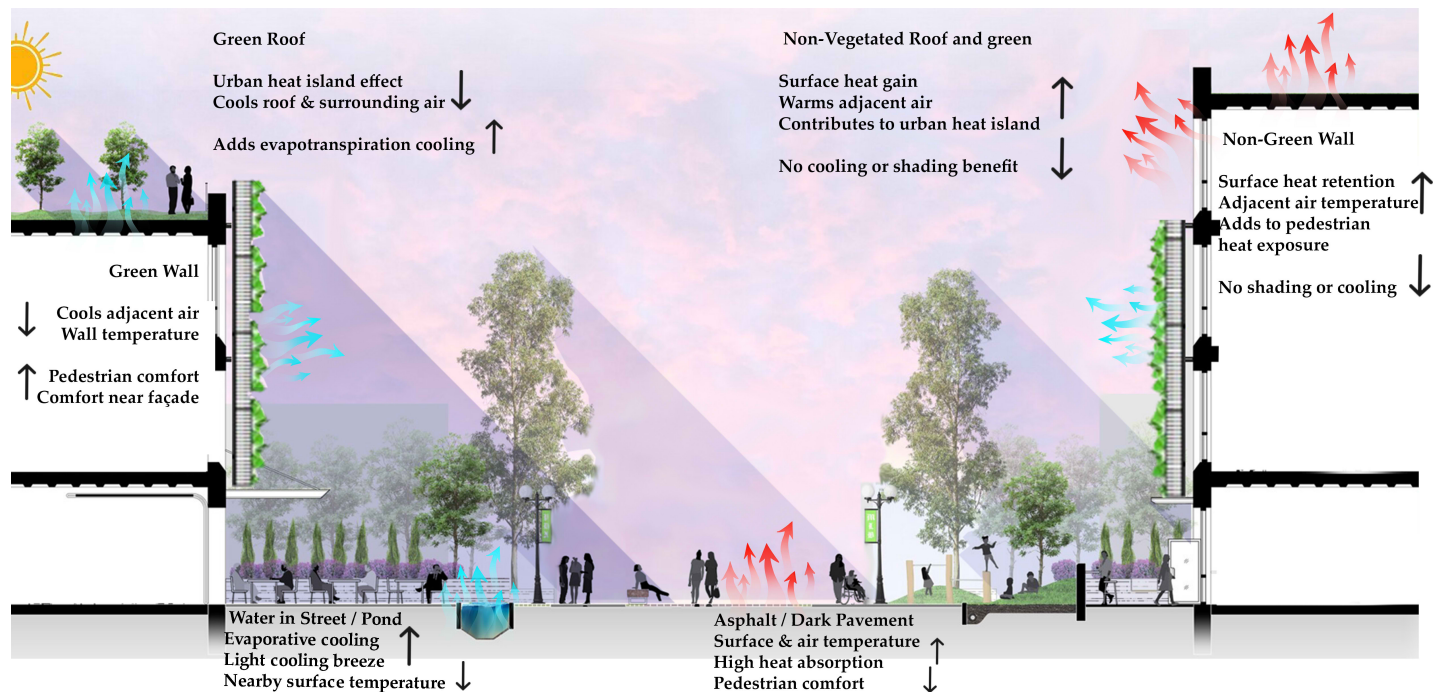


Fig. 8. Microclimate strategies for enhancing outdoor thermal comfort.

peaks in late spring and summer, dropping by 0.5–2 °C in winter [114,115]. Cooling efficiency depends on size, depth, shape, and location. Larger, deeper water bodies retain cooling longer, and alignment with prevailing winds enhances airflow. Urban density and surface roughness limit UWB influence to 100–50 [116], with optimal relief occurring 10–20 m from edges. While UWBs have limited effect on mean radiant temperature, combining them with vegetation and permeable surfaces increases effectiveness [113]. Modern mist systems reduce temperatures by 2–3 °C, improving PET during heatwaves [115–117]. Traditional designs, such as Iranian gardens, also enhance comfort. Urban blue spaces are increasingly recognized for their thermal and health benefits [81,118].

3.2.6. Building-scale morphology and façade strategies for outdoor thermal comfort

Building height, spacing, and orientation significantly influence OTC by shaping radiative and convective exchanges at street level. ENVI-met simulations in Toronto indicate that clustering high-rise towers enhances airflow and reduces air temperature, lowering MRT and mitigating UHI effects in cooler climates [119]. In Tabriz, characterized by cold winters and hot summers, combined ENVI-met and RayMan analyses show that a specific H/W ratio and street orientation optimally balance solar access and shading, improving PET throughout the year [120]. Façade geometry including canopies, podiums, and permeable floors can be designed to improve wind conditions at street level [121]. Canopies reduce wind intensity around pedestrian areas, podiums lower wind speeds near buildings, and mid-tower permeable floors contribute to airflow control. Poorly positioned ground-level

openings, however, may increase local wind exposure. Strategic façade design is critical for enhancing pedestrian comfort and creating favorable microclimates [122–127]. Large-eddy simulations demonstrate that windward-facing balconies may block canyon airflow, reduce wind speeds, increase pollutant concentrations, and raise sidewalk exposure, impairing convective cooling and worsening localized UHI [24]. ENVI-met simulations in Mediterranean climates show that green façades and roofs reduce air temperature and UTCI, particularly in courtyard designs [25]. Reflective glass and metal façades increase heat absorption and re-radiation in tropical areas, exacerbating pedestrian thermal stress [128,129]. Advanced materials, such as phase change materials, cool coatings, and glass-ceramics, further reduce UHI, highlighting the importance of climate-responsive façades [130,131]. External shading devices including overhangs, louvers, and canopies effectively reduce solar gain and lower MRT. Passive shading in Southern China decreases PET and UTCI during summer [132] (Fig. 8).

3.3. Human–environment interactions and outdoor thermal comfort

This section introduces a holistic framework for OTC using GMA. It considers OTC as a multidimensional outcome influenced by direct factors physical, physiological, and psychological and indirect factors such as behavioral, personal, social, cultural, and alliesthesia contexts (Fig. 9). The framework guides climate-sensitive urban design to enhance comfort in diverse outdoor environments.

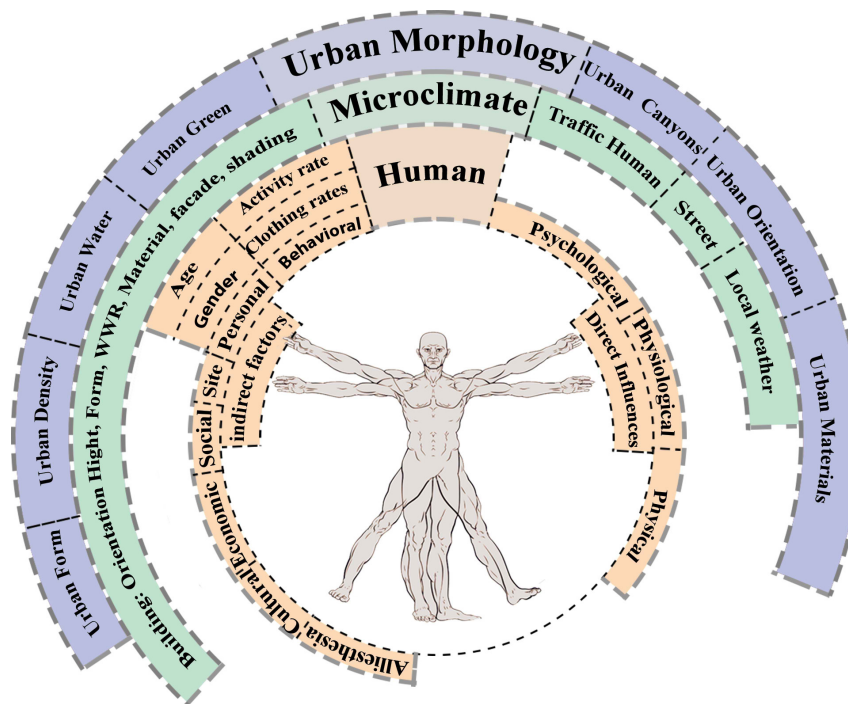


Fig. 9. Human–environment interactions and outdoor thermal comfort.

3.3.1. Direct influences

3.3.1.1. Physical factors

OTC results from the complex interaction of environmental factors air temperature, solar radiation, wind, and humidity that influence the body's heat exchange through conduction, convection, radiation, and evaporation. Air temperature is the most influential factor. A year-long study in Harbin, China, confirmed temperature as the primary driver of thermal perception, shaped by seasonal behavior and clothing adaptations [39]. Cognitive and behavioral factors also affect thermal sensation; Liu et al. reported discrepancies between expected and actual thermal experiences [70]. In Guilin's hot-summer, cold-winter climate, children exhibited heightened thermal sensitivity, with a neutral temperature near 15 °C and a comfort range of 5–26 °C, emphasizing the importance of passive strategies such as shading, high-albedo materials, and cross-ventilation [133]. Solar radiation and wind substantially modify thermal comfort: sun exposure improves comfort in cool conditions but increases MRT in hot climates, while wind enhances convective cooling, particularly in warm, breezy environments [134]. Humidity significantly affects comfort in hot-humid regions, such as Singapore [135].

3.3.1.2. Physiological factors

Physiological responses including sweating, vasodilation, and cardiovascular regulation are essential for thermal balance outdoors. Key indicators such as skin temperature, core temperature, sweat rate, and heart rate variability measure thermal strain. Skin temperature, around 32.7 °C in neutral conditions, is

highly sensitive to environmental changes. Solar radiation, wind, and clothing influence regional skin temperature variations, sometimes exceeding core temperature effects [136,137]. Transient heat transfer models estimate mean skin temperature, but local deviations can reach 15 K in extreme cold [52]. Machine learning methods, including Support Vector Machines, accurately predict thermal states from localized skin temperature and thermal load [138]. Urban morphology, via SVF, affects physiological responses. Sweat rate varies by sex, fitness, and humidity, with high humidity reducing evaporative cooling and increasing thermal strain [127,139].

3.3.1.3. Psychological factor

Psychological factors critically influence outdoor thermal comfort, encompassing subjective aspects such as prior experience, individual expectations, and perceived control, beyond physiological responses. ASHRAE (2017) defines thermal comfort as a “condition of mind expressing satisfaction with the thermal environment,” emphasizing mental and emotional dimensions amid variable outdoor conditions affected by solar radiation, wind, and humidity [12]. Adaptation and experience shape thermal neutrality and preference. In Nepal, residents tolerated higher temperatures than recent migrants, reflecting behavioral and physiological acclimatization to subtropical climates [140]. European studies indicated that neutral PET increased with annual mean temperature, demonstrating climate-responsive adaptation [141]. A large survey in Szeged, Hungary, revealed notable seasonal variations in neutral PET, highlighting

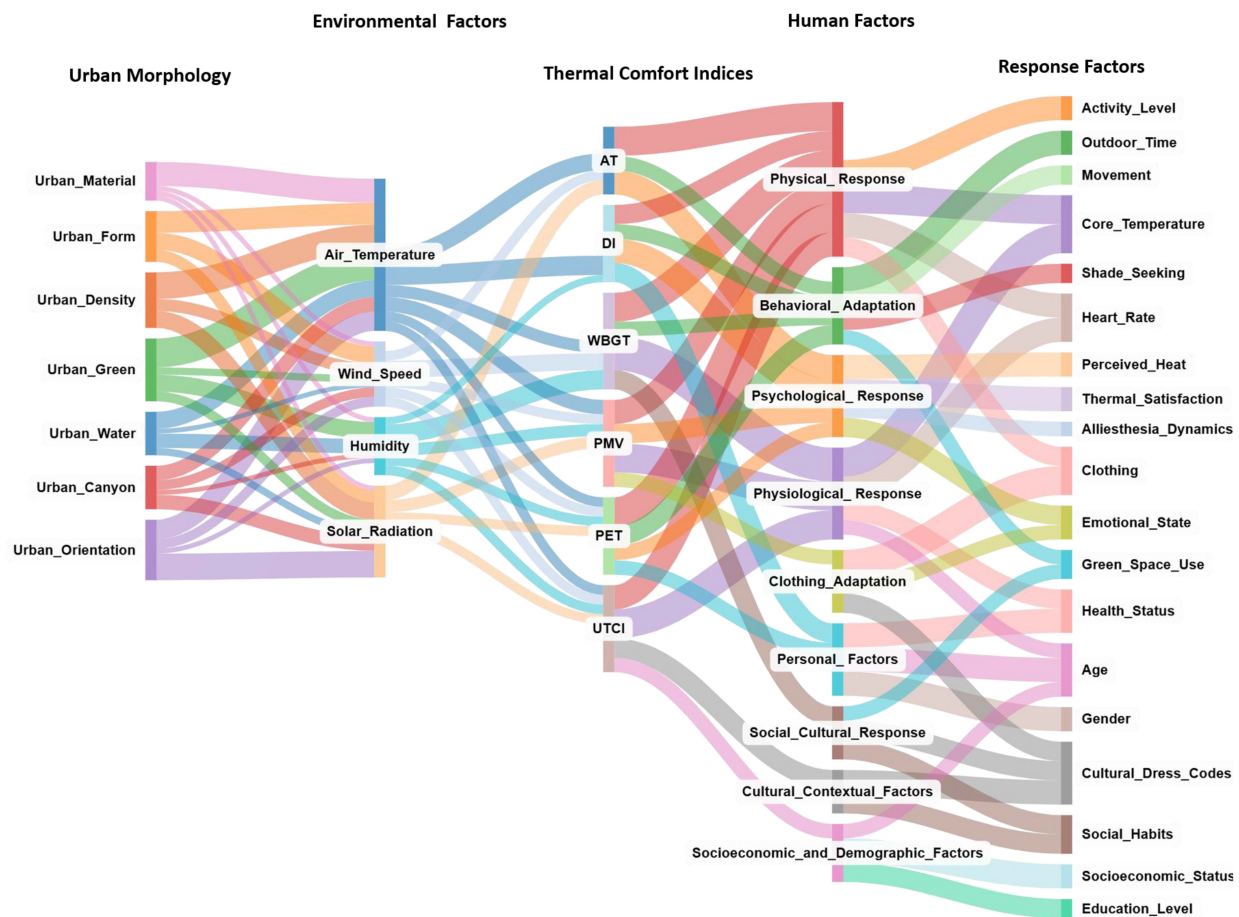


Fig. 10. Development of the design tool.

the importance of regional and seasonal factors in thermal comfort models [142]. Expectations influence perception; indoor conditions, time of day, and environmental context affect comfort independently of outdoor climate [143]. Anticipated shade, wind, or leisure settings enhance comfort, as shown in Hong Kong [144] and the Caribbean [145]. Additionally, greenery, shading, and perceived control significantly improve well-being and emotional adaptation [146,174].

3.3.2. Indirect influences

3.3.2.1. Behavioral factors: clothing and activities

Behavioral responses including clothing choices and activity patterns significantly influence outdoor thermal comfort, reflecting complex interactions between environmental conditions and socio-cultural norms. In urban environments, user attendance strongly correlates with microclimatic factors such as air temperature, solar radiation, wind, and humidity. A study in Taichung City, Taiwan, reported peak attendance at moderate PET ranges, with over 75% of users preferring shaded areas, engaging primarily in passive activities, and prolonging their stay, emphasizing psychological aversion to direct sunlight and the critical role of shade and tree canopy in warm-climate urban

design [38,148]. Clothing insulation regulates heat exchange and strongly affects thermal perception. A survey of 563 tourists in Porto showed that both clothing and activity levels significantly influenced comfort, with clothing insulation highly correlated with air temperature. Seasonal and demographic variations were observed: women wore lighter clothing in summer, while older adults preferred higher insulation in winter. In culturally conservative settings, such as Tehran, clothing flexibility is constrained. Observed behaviors including sun avoidance, activity-driven thermal tolerance, gender-based solar sensitivity, and adaptive strategies in hot-arid climates underscore the complex and adaptive nature of thermal comfort responses [39,149-152].

3.3.2.2. Personal factors

Gender significantly affects outdoor thermal perception across climates. Women often report thermal neutrality at higher PET values and demonstrate greater sensitivity to environmental fluctuations than men [151]. In Harbin, females preferred warmer conditions and recorded lower Mean Thermal Sensation Votes at equivalent UTCI levels [153]. In Al Ain, men tolerated higher heat, while women sought shade and reported greater discomfort,

emphasizing the need for gender-responsive design [152]. Generally, females exhibit lower tolerance to cold and wind, whereas males prefer stronger airflow in hot, stagnant settings, though differences diminish with increased air velocity. ASHRAE-55 has been criticized for overestimating airflow's cooling effect, especially in mixed-gender contexts [154]. Simulations indicate females experience higher PET and greater thermal sensitivity, reinforcing the importance of gender-informed urban planning [155]. In Xi'an, girls showed greater heat resistance during light activity, whereas boys tolerated intense exertion more effectively [156]. Cross-climate studies further reveal females' higher susceptibility to cold and reduced thermal neutrality, with younger individuals reporting greater discomfort than older adults [157]. Age also influences thermal comfort through physiological and behavioral mechanisms. In Prague, middle-aged adults reported the highest comfort during hot summers, whereas younger and older groups felt less comfortable; the elderly often experienced discomfort even in cooler conditions due to reduced metabolism and adaptability [158]. Older adults in northeastern China displayed narrower, lower UTCI neutrality ranges, indicating cold sensitivity but greater heat tolerance [159]. However, a year-long study in Kitakyushu found no significant age-comfort relationship [29,160]. Body characteristics such as skin color, body weight, and composition affect thermal comfort. In Mexico, brown-skinned women exhibited higher BMI and obesity rates than white-skinned women, a gender-specific association not observed in men [161]. Among young male students, fitness and body fat percentage influenced comfort under neutral-cool conditions [162]. Integrating BMI, exercise habits, tissue thickness, and skin temperature shows that greater fat or muscle mass shifts thermal preference toward cooler environments, with muscle mass enhancing cold tolerance [163].

3.3.2.3. Social & cultural factors

Social characteristics significantly influence OTC by shaping perception and adaptive behaviors. In cold-climate regions of China, occupational roles and daily routines markedly affected thermal perception, demonstrating the role of social identity in mediating environmental experience [164]. In Lebanon, social behaviors, cultural norms, and spatial usage patterns strongly impacted perceived comfort, emphasizing the importance of urban design that reflects local social dynamics [165]. In Mexico, higher obesity rates among brown-skinned women compared to white-skinned women were linked to structural inequalities, such as limited education, discrimination, and reduced access to neighborhood services, which also affect comfort and well-being [161]. Cultural background further shapes OTC by influencing thermal preferences, adaptive behaviors, clothing choices, and environmental attitudes. Traditional dress codes in Marrakech and Phoenix altered clothing insulation and behavioral adaptation [91], while tourists' cultural origins in Porto affected both comfort perception and attire selection [150]. Collectively, these findings highlight the need for socially and culturally sensitive urban climate strategies that integrate occupation, daily routines, local

practices, and cultural norms to enhance outdoor thermal comfort inclusively and effectively.

3.3.2.4. Site

Site specific factors critically shape OTC by altering local microclimates through material selection and urban form. In Hangzhou, China, high-albedo surfaces in children's play areas increased thermal discomfort during peak sunlight, highlighting the need for adequate shading [50]. In hot climates, pavement albedo affected air temperature and UTCI more than building façades [166]. In Harbin, open campus spaces with diverse landscape elements promoted winter outdoor activity, showing how thoughtful spatial design can reduce cold stress [167]. Conversely, simulations at Tehran's Mehr-Abad Airport indicated that tree cover improved summer comfort by lowering PET but also blocked beneficial solar gain in winter, reducing comfort [21]. These findings highlight the importance of seasonally adaptive, site-specific design balancing shading, material choice, and vegetation to optimize OTC year-round.

3.3.2.5. Alliesthesia

Recent research on alliesthesia has clarified how dynamic thermal environments shape OTC through interconnected temporal, seasonal, microclimatic, and neurophysiological processes. Field research in Sydney identified four categories of thermal experience strong (Hot/Cold) and moderate (Warm/Cool) and demonstrated that thermal pleasure increases as conditions approach neutrality and decreases when they deviate from it. Seasonal adaptation was evident through preferences for cooler conditions in summer and warmer conditions in winter, illustrating temporal alliesthesia [168]. Experimental studies using the humidity-inclusive Adaptive Thermal Comfort model (ATCRH) emphasized the interaction between humidity and airflow. Low humidity produced comfort across all airspeeds, whereas high humidity required higher airflow to maintain satisfaction. Perceptual differences were also influenced by culture: British participants described humid heat as sauna-like, while Indian participants perceived it as heavy and oppressive [169]. Seasonal alliesthesia also revealed that individuals preferred slightly warm conditions in cool seasons and slightly cool ones in warm seasons, reinforcing the need for seasonally adaptive outdoor design [170]. Seasonal alliesthesia indicated preferences for slightly warm conditions during cold periods and slightly cool conditions during warm ones, reinforcing the importance of seasonally adaptive design [155]. Field-based thermal walks in Phoenix revealed that microclimatic features such as shading and lower sky view factor enhanced thermal pleasure. The PET, which integrates temperature, humidity, radiation, and wind speed, effectively captured variations in perceived comfort [171]. Neurophysiological investigations confirmed the biological foundation of alliesthesia, as thermoreceptor-based models combined with machine-learning algorithms accurately identified pleasant and unpleasant states. These findings emphasize that

outdoor spaces should be designed to promote sensory delight rather than mere thermal neutrality [172].

4. DISCUSSION

This research aimed to unpack the complex relationship between urban morphology and OTC, with a particular focus on addressing the challenges posed by UHI effects in dense cityscapes. A systematic literature review, guided by the PRISMA framework, synthesized a wide array of empirical studies, modeling approaches, and theoretical insights from across climate-sensitive urban design literature. Analytical methods, including GMA and CCA were employed to translate this body of knowledge into a structured design logic. These methods facilitated the identification of key parameters, interactions, and constraints that shape OTC outcomes in complex urban environments.

4.1. Development of the design tool

The principal outcome of this study is the Design Tool. This five-layered framework helps urban designers and planners assess and optimize the thermal impacts of morphological and material decisions. It integrates urban form, environmental modifiers, thermal comfort indices, and human adaptive responses, functioning as both an analytical tool and an early-stage decision-support system. As illustrated in (Fig. 10), its hierarchical structure and feedback loops connect design, climate, and user experience. Adaptable to diverse climatic, cultural, and demographic contexts, the tool supports evidence-based, climate-responsive design by demonstrating how spatial choices shape environmental conditions and ultimately influence human thermal comfort.

4.1.1. Urban morphological parameters

The first layer comprises the fundamental spatial and material determinants of the urban microclimate, including urban form, density, canyon geometry (e.g., H/W, SVF), surface material properties (e.g., albedo, thermal mass), and green–blue infrastructure. These parameters collectively influence solar exposure, wind patterns, air temperature, humidity, and radiative exchange—ultimately shaping the pedestrian thermal experience. For example, narrow, high-density urban canyons with low SVF provide shade in hot climates but may restrict ventilation. In contrast, more open forms enhance airflow and solar access, which is beneficial in colder regions. Street orientation also plays a crucial role: east–west-oriented streets tend to accumulate heat in the afternoon, while diagonal layouts distribute solar gains more evenly throughout the day. Surface material characteristics further impact thermal conditions; high-albedo materials can reduce heat absorption but may increase MRT if not adequately shaded. Vegetation offers evaporative cooling and psychological benefits, while water features can help mitigate heat but may also increase humidity, especially in already humid climates. Therefore, these strategies must be contextually adapted and aligned with user behavior and prevailing environmental conditions to ensure their effectiveness.

4.1.2. Environmental modifiers and microclimatic strategies

The second layer focuses on refining microclimatic conditions through strategic material and landscape interventions that modulate four key environmental variables: air temperature, wind speed, humidity, and solar radiation. Air temperature is influenced by factors such as thermal mass, shading, and surface albedo; wind dynamics are shaped by building configuration, orientation, and vegetation density; humidity is moderated by vegetation, water features, and permeable surfaces; and solar radiation is governed by orientation, canyon geometry, and SVF. High-albedo surfaces reflect shortwave radiation and reduce surface heating, though they may elevate MRT if not sufficiently shaded. Vegetation contributes to microclimatic regulation through evapotranspirative cooling and also offers psychological benefits. Similarly, water features can provide localized cooling but may increase humidity levels, particularly in already humid environments. The design rationale emphasizes climate- and site-specific strategies that are responsive to temporal dynamics, including diurnal and seasonal variations as well as patterns of human activity. Accounting for these temporal factors is essential to ensure that microclimatic interventions align with actual exposure scenarios and user behavior.

4.1.3. Thermal comfort indices

The third layer functions as an interpretive bridge between environmental conditions and human thermal perception by incorporating a range of thermal comfort indices. Mechanistic indices—such as PET, UTCI, and PMV—simulate thermo-physiological responses under standardized assumptions, providing reliable benchmarks for evaluating thermal performance. However, these models may not fully capture the variability of microclimatic conditions or the dynamic nature of human responses. Empirical and hybrid indices address these limitations by integrating subjective comfort feedback, behavioral adaptations, and cultural expectations. Such approaches enhance contextual relevance and inclusivity by accounting for local climatic conditions and population-specific sensitivities. Incorporating demographic variables and aligning with established standards, such as ASHRAE 55 and ISO 7730, further improves the precision of comfort assessments. Recent advances in machine learning and real-time environmental sensing enable dynamic comfort modeling by linking sensor data with user feedback, offering predictive and adaptive insights for responsive urban design. By combining quantitative and qualitative assessments, this layer ensures that thermal comfort evaluations are both scientifically grounded and human-centered.

4.1.4. Human factors and behavioral adaptation

The fourth and fifth layers of the design tool underscore the critical role of human variability and adaptive behavior in shaping outdoor thermal comfort, moving beyond the simplified standardized occupant model assumptions commonly embedded in conventional frameworks. These layers incorporate a wide

spectrum of factors: physiological characteristics such as age, gender, metabolic rate, and body composition influence thermal tolerance and sensitivity, with vulnerable populations such as the elderly and women often exhibiting heightened susceptibility to heat and cold extremes. Behavioral adaptations including clothing insulation, activity levels, shade-seeking behavior, and timing of outdoor exposure significantly affect thermal perception and comfort outcomes. Socio-cultural dimensions, such as regional dress codes, lifestyle patterns, and cultural expectations, further mediate adaptive responses, as illustrated by diverse practices ranging from Mediterranean siestas to attire norms in desert cities. Psychological factors, including alliesthesia and thermal history, reveal that thermal comfort is not static but is dynamically shaped by prior thermal experiences and emotional states. By integrating demographic profiling, real-time environmental sensing, and behavioral mapping, the tool enables context-sensitive and inclusive design strategies. This comprehensive, human-centered framework is essential for promoting equitable thermal comfort and enhancing urban resilience in the face of escalating heat stress and increasing climatic, cultural, and demographic diversity.

5. CONCLUSION

Urban morphology plays a pivotal role in shaping pedestrian thermal comfort in urban environments by influencing microclimatic conditions such as solar exposure, ventilation, humidity, and radiant heat exchange. Key morphological parameters including urban density, canyon geometry, street orientation, surface materials, vegetation, and water features determine how pedestrians experience outdoor conditions. These features interact dynamically with environmental modifiers, human adaptive behaviors, and the localized effects of the urban heat island, producing thermal comfort outcomes that are highly context-dependent. Physiological characteristics, behavioral adaptations, and socio-cultural or psychological factors further influence individual perception of comfort. Consequently, pedestrian outdoor thermal comfort emerges as a multidimensional, context-sensitive phenomenon arising from the complex interplay between urban morphology, human interaction with urban morphology, and the influence of the urban heat island. Addressing this complexity, the study developed a five-layered parametric design tool that integrates urban morphology, microclimatic strategies, thermal comfort indices, and human adaptive behavior into a single, unified framework. Analytical methods, including General Morphological Analysis and Constraint Cross-Analysis, translate theoretical insights into practical design logic, allowing systematic exploration of urban form variations. The tool enables simulation of alternative configurations, prediction of microclimatic impacts, and evaluation of pedestrian comfort outcomes across diverse climatic and cultural contexts. By bridging urban morphology with human-centered considerations, the parametric design tool provides a decision-support system for climate-responsive, evidence-based, and inclusive urban design strategies.

This integrated approach demonstrates that optimizing pedestrian thermal comfort requires both an understanding of morphological influences and the ability to translate these insights into actionable urban design interventions. The relationship between urban form, human behavior, and environmental conditions underscores the value of parametric tools for creating adaptive, resilient, and socially inclusive urban environments that respond effectively to the challenges posed by the urban heat island.

5.1. Limitations

Several limitations should be acknowledged when interpreting the findings. The systematic review relied on selected peer-reviewed sources published in specific languages, potentially excluding regional studies or non-English research addressing local climatic and cultural conditions. The proposed Design Tools framework, though comprehensive, simplifies the multiscale and context-dependent interactions among urban morphology, microclimatic parameters, thermal indices, and human adaptive responses. Existing comfort models such as PET, PMV, and UTCI assume steady-state conditions, which may not capture transient or subjective outdoor thermal perception. Microclimatic variations from vegetation, water bodies, and materials are dynamic and may not be fully represented. Empirical validation and predictive capacity under future climatic or socio-technological changes remain uncertain, highlighting the need for longitudinal, cross-cultural, and multi-scale studies.

5.2. Future research directions

Future research should prioritize empirical testing and refinement of the parametric design tool in diverse climatic, urban, and socio-cultural contexts. Longitudinal field studies incorporating real-time microclimatic measurements and participatory pedestrian feedback will enhance predictive capacity. Expanding data sources to underrepresented regions and integrating non-traditional knowledge can further illuminate urban morphology–comfort interactions. Advances in computational modeling, GIS-based visualization, mobile platforms, and machine learning offer opportunities to improve precision, scalability, and interactivity, ultimately supporting the design of inclusive, equitable, and thermally comfortable urban environments.

APPENDIX A

Summarizes key previous studies conducted between 2015 and 2025, highlighting major findings and methodologies related to outdoor thermal comfort ([Table A1](#)).

Reference	Year	Climate-KG	Country	Data Logger	Standard	Data Collection Methodologies			
						Measurements	Questionnaires	Mathematical Modeling	Computer Simulations
[11]	[40]	[184]	[56]	[55]	[45]				
2023	2023	2024	2024	2024	2024				
Cfa	Csa	BSk-Cfb	Dwb	Cwa	Cfa				
China	Algeria	Poland and Spain,	China	China	China				
EXDG Circular Fisheye Lens- Kestrel 5400-TES 1339R - (Nikon D610)	Testo 480	UNIT-T UT333	Portable microclimate - SPN1 information meter	TR-72wf (TANDD•CEM DT- 8880 , CEMHuashengchang					
ASHRAE- 5-point			ASHRAE 2017	ASHRAE 7-point ENI5251-2007					
*	*	*	*	*		Measurements	Questionnaires	Mathematical Modeling	Computer Simulations
14	336	1205	643	178	927				
TMrt		BMR							
RayMan	ENVi-met	CAPI	RayMan						
Summer	Summer	Summer	Summer/Winter	Summer	Summer/Winter				
PET,TCV,TVF	UTCI,SET, PET,	BMR	PET,TAV,TSV	PMV,TSV	PET, AQV, BSV ,TSV				

Table A1. Previous studies from 2015–2025.

[182]	[15]	[16]	[44]	[38]	[41]	[186]	[35]	[185]
2018	2018	2019	2020	2020	2022	2022	2022	2023
Cwa	Csa	BSk	BWh	Cwa	Cfa	Cwa	Csb	Af
China	Italy	Iran	Egypt	China	chine	China	Greece	Malaysia
HOBO		mic-98620/98583		Testo-174H-Mini-JT TECHNOLOGY	meteological- crown	Kestrel 5500 (Nielsen-HOBO Pro V2 sensor Kellerman Co., Boothwyn, PA, USA	MOD11A1-MYD11A1	(Davis Instruments Corporation ,Hayward , CA ,(AWS)
ASHRAE 9-point ASHRAE 7-point ASHRAE 7-point-ASHRAE 7-point ASHRAE 7-point								
	ISO 10552	ISO 7730		ASHRAE 7-point		ASHRAE 7-point ISO 7729	Other 5-point	ASHRAE ISO 10551
		*		*	*	*	*	*
427	869	800	160	419	5715	304	266	1157
		Tn	TMrt				TMrt	
			CFD	RayMan		RayMan	RayMan	RayMan
Summer	winter and spring	Summer/Winter	Summer	Summer/Winter		Summer	Summer	Summer/Winter
UTCI, PET								
	PMV,UTCI, PET,MOCl	PMV, PET	PET, TSV	UTCI, PET,TCV, TSV	UTCI	TMRT,TSV,UTCI,TS V,OTCV	TMRT,WBGT,ASV	OTC

APPENDIX B

Classifies outdoor thermal comfort indices into three categories: Linear (environmental variables), Mechanistic (physiological and environmental factors), and Empirical (subjective or objective assessments ([Table B1](#)).

Table B1. Categorizing outdoor thermal comfort indices.

Category	Index Name	Abbreviation	Key Variables	Unit	References
Linear (Environmental-Based)	Apparent Temperature	AT	Ta, WS	°C	[39,47]
	Discomfort Index	DI	Ta, RH	°C	[47]
	Environmental Stress Index	ESI	Ta, RH, SR	°C	[173]
	Effective Temperature	ET	Ta, RH, WS	°C	[174,175]
	Humidex	H	Ta, RH	°C	[173]
	Heat Index	HI	Ta, RH	°C	[48]
	Relative Strain Index	RSI	Metabolic rate, clothing	–	[175]
	Wet-Bulb Globe Temperature Index	WBGT	Tg, Tw, Ta		[35]
	Wind Chill Index	WCI	Ta, WS	°C	[37]
	Wind Chill Temperature	WCT	Ta, WS	°C	[176]
	COMfort Formula	COMFA	Ta, RH, WS, activity level	W·m ⁻²	[77]
Mechanistic (Thermophysiological)	Universal Effective Temperature	ETU	Ta, RH, WS, M	°C	[178]
	Heat Load Index	HL	Ta, RH, WS	W·m ⁻²	[179]
	Outdoor Human Thermal Comfort Index	HTCI	Ta, RH, WS	W·m ⁻²	[26]
	Index of Thermal Stress	ITS	Ta, RH, WS	W	[43]
	Predicted Heat Strain	PHS	Ta, RH, WS	–	[180]
	Modified Physiological Equivalent Temp	mPET	Ta, RH, WS, M, Icl, Tmrt	°C	[42]
	Standard Effective Temperature (Outdoor)	OUT_SET*	Ta, RH, WS, M, Icl, Tmrt	°C	[30,43]
	Predicted Mean Vote	PMV	Ta, RH, WS, M, Icl	–	[15,36]
	Physiological Equivalent Temperature	PET	Ta, RH, WS, M, Icl, Tmrt	°C	[40]
	Perceived Temperature	PT	Ta, RH, WS, Tmrt	°C	[181]
	Standard Effective Temperature	SET*	Ta, RH, WS, M, Icl	°C	[53]
	Subjective Temperature Index	STI	Ta, RH, WS	–	[179]
	Universal Thermal Climate Index	UTCI	Ta, RH, WS, M, Icl, Tmrt	°C	[40,182]
	Required Clothing Insulation	IREQ	Ta, WS, M	m ² ·K·W ⁻¹	[183]
Empirical (Subjective/Objective)	Thermal Sensation Vote	TSV	Subjective survey responses	–	[44]
	Actual Sensation Vote	ASV	TSV + microclimate data	–	[18]
	Tropical Summer Index	TSI	Ta, RH (empirically derived)	°C	[46]

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AUTHOR CONTRIBUTIONS

F. Shoghi: Conceptualization, Methodology, Data curation, Writing-Original draft preparation, Visualization, Investigation, Validation, Writing- Reviewing and Editing; S. M. Hosseini: Conceptualization, Methodology, Investigation, Validation, Writing- Reviewing and Editing, Supervision; S. Heidari: Methodology, Writing- Reviewing and Editing, Supervision; J. Wang: Writing- Reviewing and Editing; M. Mahdavejad : Writing- Reviewing and Editing; S. Attia: Writing- Reviewing and Editing.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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