International Journal of Urban Management and Energy Sustainability (IJUMES)

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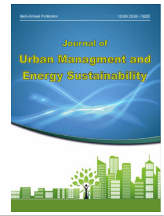

ORIGINAL RESEARCH PAPER

Mitigating Pedestrian Thermal Discomfort: A Systematic Review of Design Strategies for Urban Thermal Walkability

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ARTICLE INFO

Article History:
Received 2025-08-22
Revised 2026-02-17
Accepted 2026-08-01

Keywords:
Climate-Responsive Design; microclimate Indicators; thermal comfort; thermal walking; urban spaces

ABSTRACT

Thermal walking has gained prominence in urban design as cities face rising temperatures and expanding urban heat islands. Understanding how pedestrians experience rapidly changing thermal conditions is essential for improving walkability, health, and urban livability. This review aims to: (1) synthesize recent research on outdoor thermal comfort indicators; (2) identify microclimatic and design factors affecting thermal walking; (3) summarize climate-responsive design strategies; and (4) outline key challenges and future directions. A systematic literature review was conducted using Web of Science, Scopus, and Google Scholar, covering studies from 2010 to 2023. Peer-reviewed research on outdoor thermal comfort, pedestrian movement, and urban design was thematically coded and compared across climatic contexts, focusing on microclimatic variables, biometeorological indices (PET, UTCI, SET), subjective measures (TSV, TCV), and design interventions. Mean Radiant Temperature consistently emerges as a major determinant of pedestrian thermal sensation. Urban geometry, materials, vegetation, and water features substantially influence radiant flux, shading, and ventilation. No single index fully captures thermal walking; integrating objective and subjective indicators provides the most robust assessment. Advances in thermal imaging, mobile sensing, and CFD modeling enhance evaluation accuracy, though climatic variability, financial constraints, and retrofitting challenges persist. Improving thermal walking requires adaptive, context-specific strategies that combine climate-responsive design, real-time environmental data, and human-centric insights. As climate change accelerates, thermally responsive pedestrian environments will be critical for supporting active mobility, public health, and sustainable urban development.

DOI: 10.22034/ijumes.2024.737688

Running Title: Urban Thermal Walkability Enhancement by Mitigating Pedestrian Thermal Discomfort

NUMBER OF REFERENCES 83

NUMBER OF FIGURES 05

NUMBER OF TABLES 03

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INTRODUCTION

Urban spaces are vital to the daily life of city dwellers, serving as venues for commuting, leisure, and social interaction. The livability of these urban environments heavily relies on the thermal comfort of pedestrians, influencing both their ability to walk and their overall well-being. Thermal walking refers to the experience pedestrians have as they navigate through continuously changing thermal environments in cities a phenomenon that has gained increased attention in recent years (Lai et al., 2019). At a macro level, the growing challenges posed by climate change, urban heat islands, and the push for sustainable transportation systems are making thermal walkability a critical concern for urban planners, architects, and policymakers. The effects of climate change, particularly the rise in urban temperatures, underscore the need for urban environments that are not only resilient but also adaptable to thermal changes. This broad context brings forth the necessity of addressing pedestrian thermal comfort within urban design to mitigate the adverse effects of extreme temperatures. On a micro level, thermal comfort is determined by a complex interplay of environmental variables such as air temperature, humidity, wind speed, and solar radiation, as well as the architectural and landscape features that shape these microclimates. This article explores how various design elements, including urban geometry, surface materials, and vegetation, can modify thermal conditions and improve pedestrian comfort. By focusing on these microclimatic factors, the paper aims to propose actionable design strategies that contribute to enhancing pedestrian thermal experiences. The primary purpose of this review is to synthesize existing research on thermal walking in urban spaces and identify the key indicators and design strategies that can improve pedestrian comfort. The research question guiding this review is: How can urban design principles be integrated to enhance thermal walkability and pedestrian comfort in the face of climate change and urban heat island effects? This paper aims to bridge the gap between scientific research and practical urban design, offering valuable insights into creating more walkable, comfortable, and sustainable cities.

RESEARCH BACKGROUND

Thermal comfort in urban environments

Thermal comfort is a critical factor influencing human well-being in urban environments, especially for pedestrians, arises from (Fig. 1) a complex interaction of meteorological variables. It is defined as a state of mind that conveys contentment with the thermal environment (ASHRAE, 2017). Fanger (1970) introduced a broader definition, focusing on the surrounding environment as a whole. Thermal comfort in urban settings arises from the interaction of meteorological variables (air temperature, humidity, wind velocity, and solar radiation) and physiological and psychological factors (Johansson et al., 2014). Unlike indoor spaces, where thermal conditions are controlled, outdoor urban environments present unique challenges due to dynamic meteorological conditions and pedestrian activity.

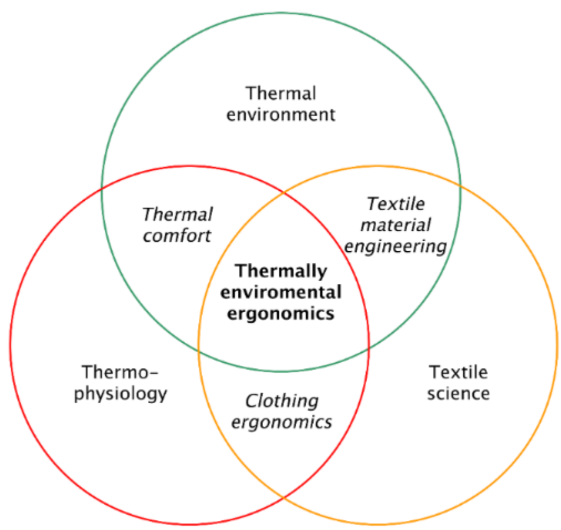

Figure 1: Concepts of thermally environmental ergonomics (Chen et al., 2020)

The concept of thermal walking

The concept of thermal walking (Fig. 2) extends the notion of thermal comfort to the dynamic experience of pedestrians as they move through urban spaces, encountering a succession of microclimates. It considers how varying thermal properties across different parts of a pedestrian's route influence their comfort, behavior, and overall experience (Vasilikou and Nikolopoulou, 2020). Urban form, material composition, and environmental factors like urban morphology, surface materials, vegetation, and temporal variations significantly influence the thermal conditions that pedestrians experience during walking (Krüger et al., 2011; Santamouris et al., 2011; Kong et al., 2017; Tsitoura et al., 2014). Personal factors such as age, gender, attire, and physical activity further modulate perceptions of thermal comfort (Lai et al., 2019).

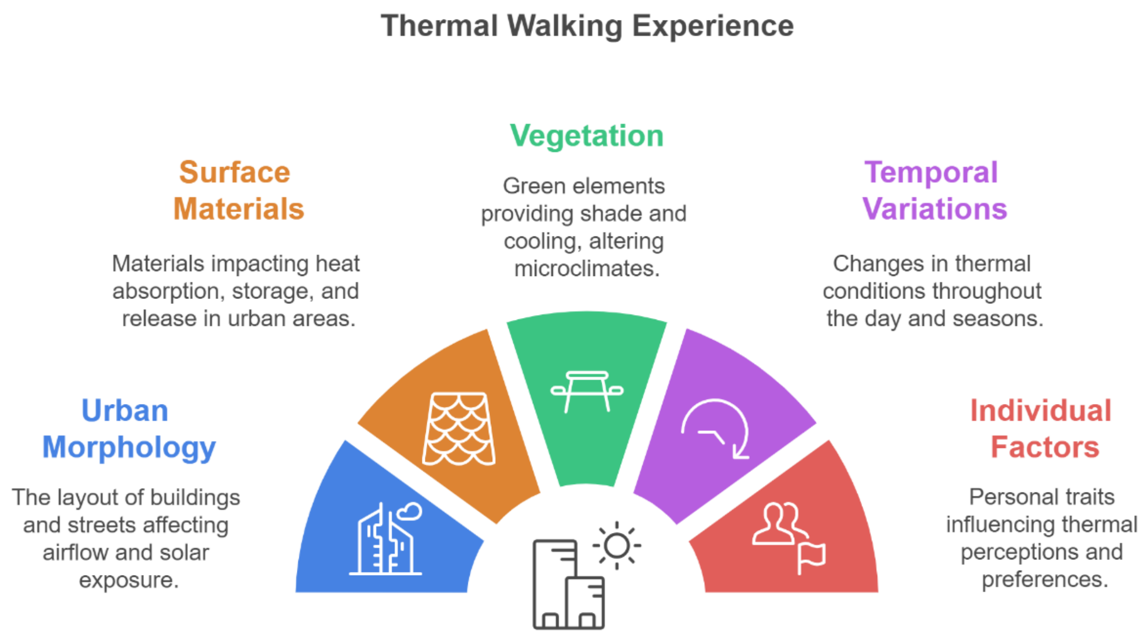

Figure 2: Factors that influence thermal walking experience

The Evolution of Thermal Comfort: From Foundational Studies to Smart Technologies

The study of thermal comfort has evolved significantly, from foundational physiological studies to sophisticated, personalized models integrated with smart technologies (Fig. 3). Early research (1920s-1930s) primarily focused on enhancing worker safety in industrial settings, with Fanger's PMV and PPD models serving as foundational tools for indoor comfort standards. By the 1980s, adaptive thermal comfort models emerged, recognizing the importance of individual preferences and the ability to adjust to the environment. The 1990s and 2000s marked a shift toward outdoor thermal comfort, focusing on urban microclimates and introducing models like Physiological Equivalent Temperature (PET) to assess thermal conditions in open spaces. Recently, research has emphasized thermal walking, recognizing the dynamic nature of thermal comfort during pedestrian movement. The integration of smart cities and wearable sensors has enabled real-time monitoring of thermal comfort, allowing cities to adapt to dynamic environmental conditions (Bröde et al., 2012; Sadeghian et al., 2024).

The evolution of thermal comfort research, as outlined above, evidences a paradigm shift from the static, universally applicable PMV model to a dynamic, context-aware understanding of thermal walking (Table 1). While foundational studies established the physiological baseline (Fanger, 1970; Höppe, 1999), contemporary work has underscored the inadequacy of these static models for the heterogeneous urban environment (Nikolopoulou and Lykoudis, 2006). The literature is clear that the instantaneous thermal experience of a pedestrian is a function of both microclimatic inputs and the continuous, transient nature of their movement, which is profoundly modulated by urban morphology (Vasilikou and Nikolopoulou, 2020). The current body of research successfully identifies the primary physical and subjective factors influencing thermal walkability (Lai et al., 2019). However, a consolidated, systematic framework that translates the fragmented empirical findings (e.g., Lee et al., 2020) into an accessible, actionable set of design principles for urban designers remains underdeveloped. This article is therefore justified as it moves beyond mere factor identification to provide the urgently needed systematic synthesis of design principles derived from this specialized literature. (Tab. 1)

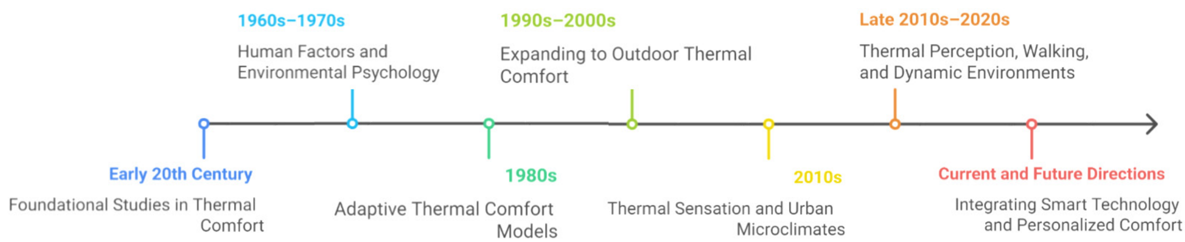

Figure 3: Evolution of thermal comfort from basics to smart technology

The evolution of thermal comfort research, as outlined above, evidences a paradigm shift from the static, universally applicable PMV model to a dynamic, context-aware understanding of thermal walking (Table 1). While foundational studies established the physiological baseline (Fanger, 1970; Höppe, 1999), contemporary work has underscored the inadequacy of these static models for the heterogeneous urban environment (Nikolopoulou and Lykoudis, 2006). The literature is clear that the instantaneous thermal experience of a pedestrian is a function of both microclimatic inputs and the continuous, transient nature of their movement, which is profoundly modulated by urban morphology (Vasilikou and Nikolopoulou, 2020). The current body of research successfully identifies the primary physical and subjective factors influencing thermal walkability (Lai et al., 2019). However, a consolidated, systematic framework that translates the fragmented empirical findings (e.g., Lee et al., 2020) into an accessible, actionable set of design principles for urban designers remains underdeveloped. This article is therefore justified as it moves beyond mere factor identification to provide the urgently needed systematic synthesis of design principles derived from this specialized literature. (Tab. 1)

Table 1: Research Background

Author(s)/ Year	Purpose	Findings/Results	Impression
ASHRAE, 2017	Define thermal comfort	Thermal comfort is a state of mind related to contentment with the thermal environment.	Establishes the baseline definition for thermal confort.
Fanger, 1970	Define the surrounding environment in terms of thermal comfort	Expands thermal comfort to include the total environmental context.	Classic model that laid the foundation for later studies.

Nikolopoulou and Steemers, 2003	Explore the interaction of meteorological variables and thermal comfort	Identifies key meteorological variables influencing thermal comfort.	Crucial for understanding the broader environmental factors affecting comfort.
Johansson et al., 2014	Investigate physiological and psychological factors affecting thermal comfort	Shows that subjective factors must be considered alongside objective meteorological variables.	Important for recognizing the holistic nature of confort.
Vasilikou and Nikolopoulou, 2020	Define thermal walkability	Thermal walkability extends thermal comfort to dynamic pedestrian experiences in urban spaces.	Introduces a new perspective on comfort, focusing on pedestrian movement.
Krüger et al., 2011	Study urban morphology's influence on thermal comfort	Urban morphology significantly impacts airflow, shading, and solar radiation.	Highlights the importance of urban design in thermal confort.
Santamouris et al., 2011	Study the role of surface materials in thermal comfort	Materials used in urban infrastructure affect heat absorption, retention, and dissipation.	Important for understanding how urban surfaces contribute to thermal conditions.
Kong et al., 2017	Investigate vegetation's impact on thermal comfort	Vegetation helps provide shade and promotes evaporative cooling, modifying the microclimate.	Emphasizes the role of green infrastructure in improving confort.
Lai et al., 2019	Examine individual factors in thermal comfort	Personal attributes significantly affect individual perceptions of thermal confort.	Important for developing personalized solutions in thermal comfort research.
Bröde et al., 20212	Develop the Universal Thermal Climate Index (UTCI)	UTCI provides a comprehensive method for assessing outdoor thermal comfort across climates.	A major advancement in quantifying outdoor thermal confort.
Sadeghian et al., 2004	Investigate urban form's influence on thermal comfort	Urban form, particularly sun exposure and mean radiant temperature, plays a critical role.	Supports the argument for considering urban design when assessing thermal confort.
Lee et al., 2020	To quantify the impact of tree crown spacing and street canyon geometry on reducing pedestrian heat stress.	Reducing tree crown spacing lowers Tmrt and PET, with a stronger effect in shallow canyons (H/W = 0.5).	Provides design-relevant evidence for the synergy between canopy structure and urban geometry, crucial for landscape architecture.

MATERIALS AND METHODS

This study employed a systematic literature review to synthesize the latest research on thermal walking in urban environments. The literature search was conducted across Web of Science, Scopus, and Google Scholar, focusing on peer-reviewed articles published between 2013 and 2024 to ensure coverage of recent developments (Fig. 4). Inclusion criteria targeted studies that examine the relationship between outdoor thermal comfort, pedestrian movement, and urban design strategies. The data extracted from these studies focused on three main areas:

•Microclimatic factors (e.g., air temperature, mean radiant temperature).

•Biometeorological indices (e.g., PET, UTCI, SET).

•Design interventions (e.g., street geometry, tree canopy density).

The data were thematically synthesized, allowing for a comparative analysis across different climatic contexts. This process helped to distill a set of validated design principles aimed at improving thermal walking conditions in urban spaces, addressing the central research question.

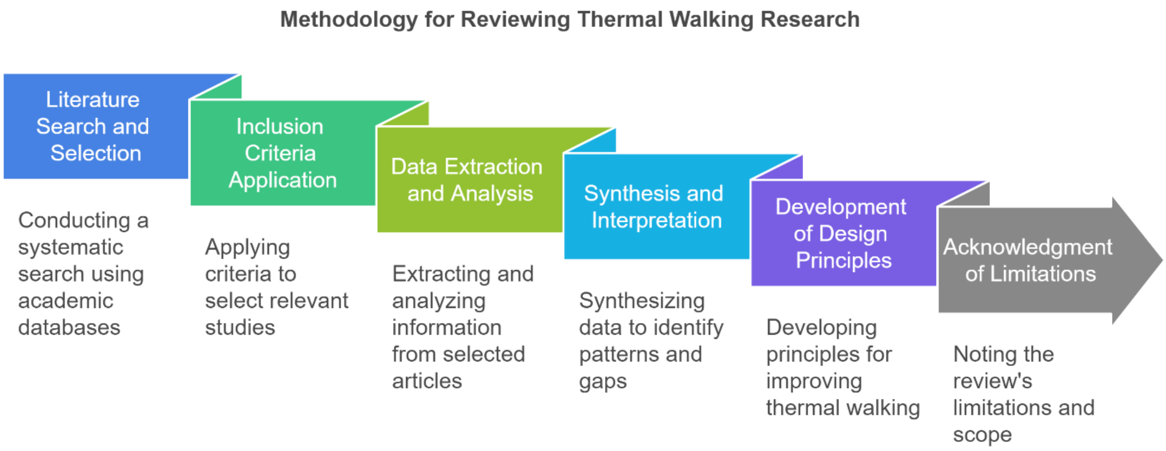

Figure 4: Methodology for reviewing thermal walking research

THEORICAL FRAMEWORK

Urban morphology and thermal comfort

Urban morphology plays a crucial role in shaping thermal comfort for pedestrians. The design and layout of urban spaces including factors like building density, street aspect ratio, orientation, and green area ratio have significant effects on microclimatic conditions, which directly influence pedestrian thermal perception (see Bedra et.al., 2023; Yi et.al., 2023; da Silva et al., 2023; Ma et al., 2022). Key aspects of urban morphology that affect thermal comfort include (Vasilikou and Nikolopoulou, 2019):

•Spatial Sequences: The sequence and continuity of spaces, such as streets and squares, influence thermal experiences for pedestrians. High-density spaces tend to create differences in thermal comfort between different urban areas.

•Aspect Ratio: The height-to-width ratio (H/W) of streets affects the distribution of solar radiation and ventilation, with higher ratios typically providing cooler conditions during hot seasons.

•Complexity and Materiality: The combined effect of urban form and the materials used in buildings significantly shapes pedestrian thermal comfort. Material choices affect heat absorption and retention, which in turn impact the thermal experience during movement.

Indicators of Thermal Walking; Microclimatic Conditions

Microclimatic conditions such as air temperature, humidity, wind speed, and solar radiation are fundamental to pedestrian comfort. While thermal comfort indices like Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), and Standard Effective Temperature (SET) offer objective measures, they do not fully capture the subjective nature of thermal walking. Recent studies highlight that dynamic interactions between pedestrians and their surroundings must be considered to truly understand thermal experiences in urban environments (Vasilikou and Nikolopoulou, 2019). The following microclimatic factors have been identified as significant contributors to thermal confort :

•Air Temperature: A moderate temperature range is ideal for pedestrian comfort. Extreme heat or cold can make walking uncomfortable and reduce pedestrian activity (Eliasson et al., 2007).

•Humidity: High humidity can increase the sensation of heat, while low humidity can intensify the feeling of cold (Spagnolo and de Dear, 2003).

•Wind Speed: Wind can both cool pedestrians in hot weather and increase discomfort in cold weather (Ali-Toudert and Mayer, 2006).

•Solar Radiation: Direct exposure to sunlight is a significant factor affecting thermal comfort, especially in hot climates (Lai et al., 2010).

Thermal comfort indicators for pedestrians

Thermal indices were originally formulated through empirical equations to provide a holistic assessment of thermal environmental effects on human populations (Chen et al., 2020). In the context of evaluating thermal comfort for pedestrians, it is imperative to incorporate specific indicators that reflect the dynamic characteristics inherent to outdoor environments (Tab. 2). Several indices have been formulated and employed in contemporary research.

Table 2: Comparison of thermal comfort indicators

Indicator	Advantages	Limitations	References
PET	Widely used and validated	May not fully account for adaptation in different climates	Qi et al., 2023; Arif and Yola, 2020; Lai et al., 2019; Salata et al., 2016; Matzarakis et al., 1999
	Considers all basic thermoregulatory processes		
UTCI	Applicable in all climate coditions	Complex calculation process	Lee et al., 2020; Di Napoli et al., 2018; Bröde et al., 2012
	Based on advanced human thermoregulation model	Requires specialized software	
SET	Accounts for humidity effects well	Less commonly used in outdoor studies	Fang et al., 2021; Nazarian et al., 2017
	Useful for comparing diverse thermal environments		
TSV	Captures subjective perceptions	Subjective nature limits comparability across studies	Çeter et al., 2022; das Neves Almeida et al., 2022; Li et al., 2021; de Arêa Leão Borges et al., 2020; Broday and de Paula Xavier, 2019; Cheung and Jim, 2018; Zhou et al., 2014
	Useful for understanding psychological adaptation		
TCV	Directly measures overall comfort	Highly subjective	Sunagawa et al., 2023; Yuan et al., 2023; Afelt et al., 2022; Ahsan et al., 2022; Du, 2019; Remoaldo et al., 2016; Zhou et al., 2014
	Can capture non-thermal factors affecting comfort	May vary significantly between individuals and cultures	

Urban design elements affecting thermal walking

Thermal comfort in urban environments is influenced by a combination of behavioral, psychological, and urban design factors. Pedestrian clothing and activity level play a crucial role in shaping thermal perceptions. For example, light clothing and moderate activity tend to enhance comfort in warm conditions, while the insulation of clothing can impact neutral temperature (Makvandi et al., 2021). Psychological adaptation also plays a significant role, as individuals' expectations, prior experiences, and perceived control over their environment can modify their comfort thresholds (Nikolopoulou and Steemers, 2003;

Xu and Li, 2021). Psychological factors, such as the interplay between visual stimuli (e.g., lighting conditions) and thermal comfort, emphasize the importance of integrating behavioral factors into the understanding of thermal experiences (Pigliautile et al., 2023).

In addition, urban design elements significantly impact thermal walking conditions. Key factors include:

•Street Geometry: The height-to-width ratio (H/W) of streets influences air circulation, shading, and solar radiation, affecting thermal comfort (Shafaghat et al., 2016; Sharmin et al., 2017). Narrower streets (higher H/W) tend to offer more shade but may reduce ventilation.

•Building Arrangement: The spatial configuration of buildings affects solar exposure and airflow, impacting thermal conditions. Building orientation and layout can optimize sunlight and enhance air circulation, thus improving thermal comfort (Abreu-Harbich et al., 2014; Friedman, 2021).

•Surface Materials: The choice of materials influences heat absorption and retention. High-albedo materials can reduce heat buildup, helping to mitigate the Urban Heat Island effect and improve pedestrian comfort (Santamouris et al., 2011).

•Vegetation and Water Features: Urban greenery and water bodies provide shade and facilitate cooling through evaporative processes, significantly improving thermal comfort (Kong et al., 2017; Kleerekoper et al., 2017).

•Shading Devices: Artificial shading devices, such as canopies and pergolas, can further enhance comfort by blocking solar radiation and improving shading efficiency (Coutts et al., 2016).

Overall, these design elements demonstrate the pivotal role of urban form, materials, and nature-based interventions in shaping microclimatic conditions and influencing pedestrian thermal experience.

Finally, advancements in measurement tools have provided valuable insights into thermal walking conditions. These include mobile measurements, 3D thermography, thermal imaging (Fox et al., 2015; Zhao et al., 2020), and Computational Fluid Dynamics (CFD) (Ghorbanian, 2024; Toparlar et al., 2017). These tools enable researchers to assess spatial variations in thermal conditions and understand the complex interactions between urban design and thermal comfort (Nakayoshi et al., 2015; Zhao et al., 2020).

Integration of Indicators into a Thermal Walking Model

The study of thermal comfort in urban environments reveals that no single indicator can fully explain the complex dynamics of pedestrian thermal experience. Instead, a holistic approach is essential one that combines various microclimatic factors, such as temperature, humidity, and solar radiation, with urban design elements, including street geometry, material properties, and the presence of greenery. Thermal walking is shaped by these continuously changing environmental factors along a pedestrian's route. Therefore, an integrated model of thermal comfort must consider the interplay between these elements, taking into account both objective environmental conditions and subjective human experiences. Recent advancements in urban design highlight the potential of adaptive strategies that respond dynamically to local climate conditions and pedestrian needs. These strategies utilize real-time environmental data to optimize urban spaces, ensuring that pedestrian environments remain comfortable and sustainable under varying thermal conditions.

FINDINGS AND DISCUSSION

The findings of this review highlight that thermal comfort in urban environments is not governed by any single indicator, but rather by a complex interaction of various microclimatic factors, urban design elements, and individual perceptions (Fig. 5). The research emphasizes the importance of considering these elements in an integrated, holistic model for understanding thermal walking.

Figure 5: Design principles for thermal walking

Urban morpholog, including street geometry, building density, material properties, and the presence of greenery, plays a pivotal role in shaping pedestrian comfort. The aspect ratio of streets and the orientation of buildings, for example, directly affect solar radiation exposure, air circulation, and the availability of shade, all of which significantly impact pedestrian thermal experiences. Moreover, the spatial sequences and complexity of urban environments—ranging from narrow, shaded streets to open, sunlit squares—introduce dynamic variations in thermal conditions that pedestrians encounter during movement. The following strategies are not presented as prescriptive design guidelines; rather, they synthesize recurring principles reported across peer-reviewed studies to illustrate how different urban design decisions influence thermal walking conditions (Tab. 3):

Table 3: Various Design strategies

A. Microclimate modification strategies	
Strategies	Description
Optimize street orientation	Align streets to balance solar exposure and prevailing winds, improving shading and ventilation (Jamei and Rajagopalan, 2017; Sylliris et al., 2023).
Create diverse thermal environments	Combine shaded, semi-shaded, and sunlit areas using vegetation, cool materials, and water features to support thermal choice (Vasilikou and Nikolopoulou, 2020; Zeeshan and Ali, 2022).
Implement cool pavement technologies	Use reflective or porous pavements to lower surface temperatures and reduce Tmrt (Peluso et al., 2022; Detommaso et al., 2021; Sen et al., 2019).
B. Urban geometry and layout strategies	
Strategies	Description
Vary building heights and setbacks	Adjust vertical profiles to enhance airflow, reduce heat accumulation, and improve microclimate performance (Yuan et al., 2023; Yang et al., 2023).
Design compact urban forms with adequate spacing	Balance density with ventilation corridors to mitigate heat buildup and maintain airflow (Ma et al., 2022; Javanroodi et al., 2018).
Incorporate pocket parks and small green spaces	Introduce small distributed green areas to provide localized cooling and reduce UHI intensity (Saaroni et al., 2018; Malcoti et al., 2023).
C. Materials and surfaces	
Strategies	Description
Use cool roofing materials	Apply high-albedo, low-heat-capacity materials to reduce solar gain and surface temperatures (Ben Ratmia et al., 2023; Santamouris, 2015; Santamouris et al., 2011).

Incorporate green walls and facades	Utilize vertical greenery to lower surface temperatures through shading and evapotranspiration (Bozdogan Sert et al., 2021; Besir and Cuce, 2018).
Select appropriate paving materials	Choose reflective, low-heat-retention paving (e.g., grass pavers, terracotta) to reduce pedestrian-level heat (Yang et al., 2023; Senevirathne et al., 2021; Sangkertadi et al., 2023).
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Strategies	Description
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Select appropriate paving materials	Choose reflective, low-heat-retention paving (e.g., grass pavers, terracotta) to reduce pedestrian-level heat (Yang et al., 2023; Senevirathne et al., 2021; Sangkertadi et al., 2023).

Together, the strategies summarized above reflect recurring themes in the literature, highlighting how coordinated design decisions can meaningfully enhance thermal walking conditions in diverse urban settings.

The accumulation of findings from various studies indicates that adaptive urban design strategies can be highly effective in improving thermal comfort. These strategies should not only focus on passive environmental features such as vegetation and surface materials, but also integrate real-time environmental data to continuously adjust the urban environment according to local climate conditions and pedestrian needs. Technologies such as smart sensors, wearable devices, and mobile measurements are becoming increasingly essential in monitoring and adjusting urban spaces to create more comfortable, sustainable environments.

Furthermore, the findings highlight the importance of understanding subjective experiences of thermal comfort. Psychological factors, such as perceived control over the environment and cultural adaptation, play a significant role in how individuals assess thermal comfort. People accustomed to specific climates may have different thresholds for comfort, underscoring the need for more personalized and context-sensitive urban design solutions.

In expanding the scope of thermal walking research, it is clear that future studies should focus on refining integrated models that combine objective thermal indicators (like PET, UTCI) with subjective measures such as thermal sensation votes and comfort votes. These models should also take into account the dynamic nature of pedestrian movement and the varying conditions encountered along walking routes.]

CONCLUSION AND RESULTS

The Thermal Walkability Synthesis: An Interpretive Summary

At the core of this review, the findings reveal that thermal comfort in urban environments is influenced by a dynamic interplay of multiple factors, including urban morphology, microclimatic conditions, and behavioral factors. These elements collectively shape the thermal walking experience, which is continuously impacted by changes in the urban environment as pedestrians move through different spaces.The systematic analysis of the literature yields five major, interconnected findings that define the contemporary thermal walkability paradigm:Urban Morphology and Radiant Flux Control: The geometrical configuration of urban space, including street geometry, building density, aspect ratio, and the thermal properties of surface materials, is the primary control layer for regulating the Mean Radiant Temperature (Tmrt) and thus thermal comfort. Specifically, streets with a higher height-to-width ratio (H/W) demonstrably offer better shading but necessitate careful evaluation to ensure adequate ventilation, illustrating the complex tradeoff between solar protection and airflow dynamics. The orientation of streets, moreover, plays a crucial and predictive role in controlling solar radiation access and facilitating beneficial wind dynamics.Microclimatic Drivers of Discomfort: The key environmental variablesair temperature (Ta), relative humidity (RH), wind speed (Va), and critically, solar radiationare the essential inputs for determining the instantaneous comfort of pedestrians. These physical factors must be quantitatively modeled and considered alongside urban design elements to systematically create environments that promote pedestrian comfort across diverse diurnal and seasonal cycles.Behavioral and Psychological Adaptation: Pedestrian variables such as clothing insulation, activity level, and inherent psychological adaptation significantly influence how the objective thermal conditions are perceived. Crucially, the perception of personal control over the environment (e.g., choice of path or resting spot), along with cultural acclimatization, plays a pivotal and often mitigating role in shaping the final thermal experience, challenging purely deterministic physical models (Nikolopoulou and Lykoudis, 2006).Adaptive Urban Design Imperative: Recent advancements emphatically emphasize the need for adaptive urban design strategies that move beyond static solutions, incorporating real-time data from environmental sensors to respond dynamically to the local climate and immediate pedestrian needs. Urban spaces equipped with smart technologies can be adjusted in real-time for instance, through automated water features or dynamic shading systems significantly improving pedestrian comfort under rapidly varying thermal conditions.Integrated Thermal Walking Models: The most rigorous approach to assessing pedestrian comfort demands the comprehensive integration of both subjective metrics (TSV, TCV) and objective biometeorological measures (PET, UTCI, and SET) into a single Thermal Walking Model. While current indices provide useful foundational tools, a more integrated approach that explicitly accounts for the transient changes encountered during movement and utilizes real-time environmental data is the recommended direction for future urban design evaluation.

The findings of this review underscore the complex interplay between urban design and pedestrian thermal comfort. While a robust set of design principles has been identified, their implementation is fraught with challenges, and significant opportunities for future research remain.

Challenges in Implementation

Translating climate-responsive thermal walking principles into professional practice is hampered by systemic and logistical obstacles. Chief among these is the challenge of integrating complex thermal comfort initiatives within the constraints of the existing urban fabric, where the retrofitting of established areas involves considerable logistical and financial hurdles (Sailor, 2014). Furthermore, the effectiveness of any intervention is critically dependent on context-specificity, where climate variability and shifting long-term climate patterns complicate robust planning (Sharifi and Lehmann, 2014). Economically, the adoption of advanced materials, complex green infrastructure, and smart technologies is often restricted by prohibitive initial costs and the necessity for long-term municipal maintenance (Norton et al., 2015; Roy et al., 2012). Finally, effective implementation relies on robust interdisciplinary coordination across diverse stakeholders and requires ensuring public acceptance and behavioral adaptation, a process that is inherently complex and gradual (Lenzholzer and Brown, 2016).

Future Research Directions

To address these gaps and advance the field of thermal walkability, future research must prioritize the development of dynamic, human-centric, and economically validated solutions. Longitudinal studies are urgently needed to robustly evaluate the sustained efficacy of interventions against evolving climate and urban development scenarios, driving the development of flexible, adaptive design solutions (Santamouris, 2020; Sadeghian et al., 2024). A crucial technological frontier is the rigorous investigation of IoT, big data, and Artificial Intelligence (AI) to facilitate the dynamic management of urban microclimates and provide real-time comfort data directly to both designers and pedestrians (Nochta et al., 2019). From a methodological perspective, new frameworks must be established to integrate fine-grained human behavior, perception, and cultural context into design models. Concurrently, establishing credible methodologies for quantifying the economic benefits of improved thermal comfort such as public health savings or increased commercial vitality is essential to strengthen the case for increased urban investment (Estrada et al., 2017). Ultimately, the creation of sophisticated, interdisciplinary computational tools that seamlessly merge high-resolution climate modeling with urban planning processes is necessary to optimize thermal comfort across the city scale (Naboni et al., 2019).

This review synthesizes contemporary knowledge on thermal walking and demonstrates that pedestrian thermal comfort arises from the interaction of microclimatic variables, urban morphology, materiality, vegetation, and subjective human responses. Evidence across the literature confirms that no single metric adequately captures these dynamics; instead, meaningful assessment requires a combination of objective biometeorological indices such as PET and UTCI and subjective measures including TSV and TCV. Urban design elements, particularly street geometry, surface materials, vegetation, and water features consistently emerge as powerful levers for moderating radiant flux, shading, ventilation, and heat storage along pedestrian routes.

At the same time, operationalizing these principles in real urban contexts remains challenging. Constraints related to retrofitting existing urban fabrics, climatic variability, financial limitations, and multi-stakeholder coordination all hinder the implementation of thermal-responsive design. Nonetheless, technological advances such as thermal imaging, mobile sensing, and CFD modelling offer unprecedented precision for diagnosing thermal conditions and guiding intervention strategies. Looking forward, the enhancement of thermal walkability depends on context-specific, adaptive, and data-driven approaches. Future research should focus on integrating real-time environmental sensing with human-centric design models, assessing long-term performance of interventions, and clarifying the economic and health benefits of improved thermal comfort. As climate change intensifies and urban populations continue to grow, designing thermally comfortable pedestrian environments becomes an essential condition for creating livable, resilient, and sustainable cities.

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HOW TO CITE THIS ARTICLE

Ghorbanian,M. (2026). Mitigating Pedestrian Thermal Discomfort: A Systematic Review of Design Strategies for Urban Thermal Walkability. (e738225). International Journal of Urban Management and Energy Sustainability, ( ), e738225

DOI: 10.22034/ijumes.2024.737688