Assessing Outdoor Thermal Comfort Indicators and Their Influence on Pedestrian Behaviour in Indian Urban Streets: A Systematic Review

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Abstract
The accelerating pace of urban expansion across Indian cities has placed mounting pressure on the built environment, leading to a contraction of outdoor public spaces and a measurable decline in microclimatic quality. As urban streets function as primary sites of pedestrian activity and public life, developing a robust understanding of outdoor thermal comfort has become indispensable to sustainable urban planning and design. The importance of this question is amplified in the Indian context by the country's remarkable climatic diversity, which encompasses extreme summer heat in northern and western plains, humid tropical conditions along the southern coasts, and severe winter cold in the Himalayan belt. This study presents a critical review of research conducted over the last decade on outdoor thermal comfort and its influence on pedestrian behaviour in urban areas. Relevant studies were systematically selected from major academic databases through a rigorous screening and filtering process, covering both developed and developing countries. The review focuses on four key dimensions influencing outdoor thermal comfort: physical, physiological, psychological, and behavioural factors. A comprehensive assessment of indicators and sub-indicators used across the selected studies was undertaken, followed by the identification and consolidation of overlapping parameters to establish a refined set of indicators.The findings reveal that, alongside physical, physiological, and psychological considerations, behavioural factors have received increasing attention in both developed and developing countries due to their significant role in shaping pedestrian responses to outdoor thermal environments. The study highlights the most frequently adopted and prioritized indicators for assessing thermal comfort and pedestrian behaviour. These findings provide a valuable framework for future urban street studies and can support planners, designers, and policymakers in developing thermally comfortable and pedestrian-friendly urban environments.

Keywords: Outdoor thermal comfort; Pedestrian behaviour; Urban heat stress; Thermal comfort indicators; Behavioural adaptation; Urban morphology; Indian cities; Climate-responsive urban design.

1. Introduction

Against this background, the present study aims to critically analyse the indicators used to evaluate outdoor thermal comfort and their influence on pedestrian behaviour in urban streets. By reviewing studies conducted in both developed and developing countries over the past decade, the research identifies and compares physical, physiological, psychological, and behavioural indicators used in thermal comfort assessment. The study further examines the prioritization of these indicators across different contexts and highlights research gaps relevant to Indian cities. The findings are expected to contribute to the development of context-sensitive frameworks for designing thermally comfortable, pedestrian-friendly, and sustainable urban streets.

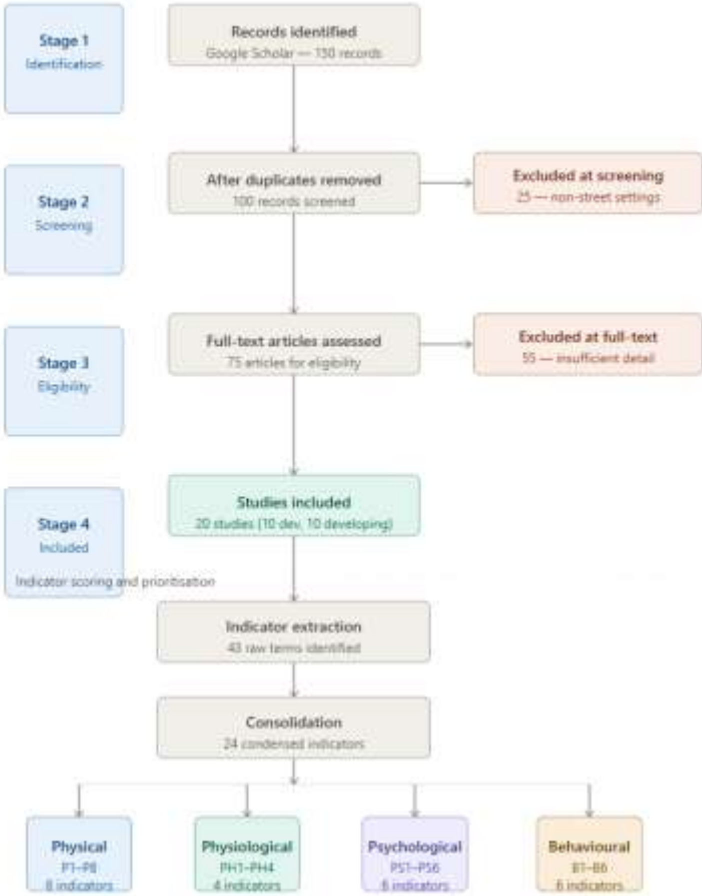
2. Method

The method adopted for this study involves four steps: (1) Literature study and data extraction; (2) Data processing; (3) Analysis and results; (4) Discussion and conclusion.
Research papers were selected from the published literature assessing outdoor thermal comfort in urban areas. These were further narrowed by selecting studies that adopted urban streets as their primary spatial context. The identified studies were classified across four factors: Physical, Physiological, Psychological, and Behavioural. The identified indicators were scored in relation to the shortlisted studies. Each study was scored as per its distribution across the four criteria and vice-versa.

2.1 Literature Searches

Outdoor thermal comfort as a research domain has attracted sustained scholarly interest across multiple continents, generating a substantial body of peer-reviewed evidence. For this review, a structured literature search was conducted across Google Scholar to retrieve relevant peer-reviewed publications comprising an assessment of outdoor thermal comfort in relation to urban street environments. Papers were evaluated against the four-criterion indicator framework (physical, physiological, psychological, and behavioural) and shortlisted on the basis of their specificity to urban street conditions. Ten studies covering both developed and developing national contexts were ultimately selected. These were then classified according to three secondary criteria: (i) indicators assessed; (ii) research context — developed or developing country; and (iii) pedestrian behaviour criteria addressed.

Outdoor thermal comfort assessment involving climatic, urban morphological, and human-related factors can be broadly classified into two quantitative groups of empirical and numerical methods. The empirical models are based on observations, measurements, and data collection by the researcher. The numerical methods use computational power and modelling techniques to address research questions. The shortlisted studies are therefore classified as per their context — developed and developing countries. Although this study is primarily a literature review, it also highlights research gaps across different climatic regions of India. Many areas beyond metropolitan cities remain underexplored, particularly smaller urban centres that represent the majority of India's urban growth. A framework for future research should therefore include tier-2 and tier-3 cities and cover diverse climate zones, ensuring a more representative understanding of outdoor thermal comfort.



"Figure 1. Literature review and indicator prioritisation process."

2.2 Identified Indicators

The performance of a particular system requires certain measurements which determine its effectiveness and efficiency. Indicators are one of the components which are measurable and required for any assessment study. These assessments are primarily focused on outdoor thermal comfort along with pedestrian behaviour. A comprehensive list of indicators was developed, including 8 Physical, 4 Physiological, 6 Psychological, and 6 Behavioural factors. The list was categorised according to the criteria, indicator, and unit of measurement. Table 1 shows the categorisation for one of the studies from the comprehensive list.

Table 1: Categorised Indicator List — Study 1 (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016)

Criteria	Indicator	Unit
Physical Factors	Temperature	°C / °F
	Relative Humidity	%
	Wind Velocity	m/s
	Mean Radiant Temperature	MRT (W/m²)
	Radiation	1 rad
Physiological Factors	Age	
	Gender	
	Active thermoregulation	

	Passive thermoregulation	
Psychological Factors	Naturalness of climate	
	Expectations	
	Experience	
	Time of exposure	
	Perceived control	
	Environmental Stimuli	
Behavioural Factors	Clothing insulation	
	Activity level & metabolic rate	
	Type of activity / Human Posture and position	
	Culture	
	Social (individual or Companion)	
	Metabolic Rate	Met or W/m

The total number of indicators in all the studies amounts to 43, amongst which 58.14% belong to the Physical category, 9.38% to the Physiological factor, 13.95% to the psychological category, and 18.60% to the Behavioural category.

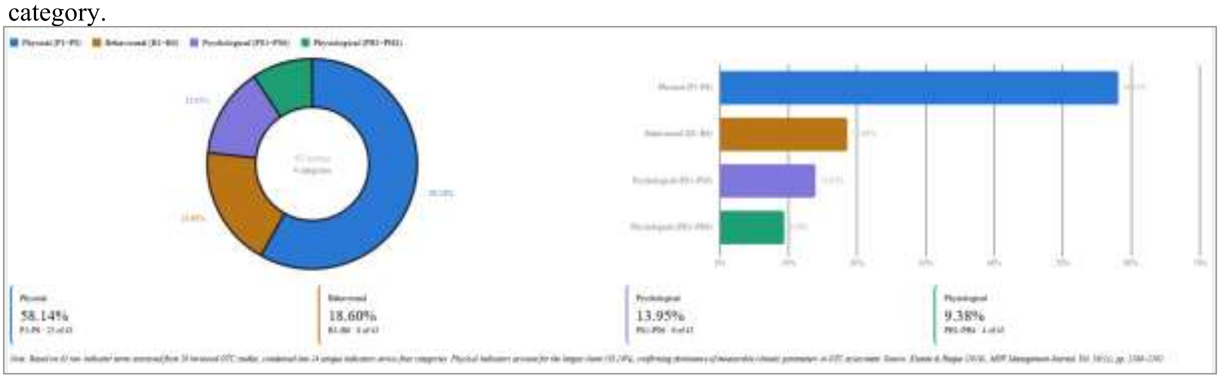


Figure 2. Distribution of indicators across the four assessment criteria (percentage-wise).

The subjective criteria account for 67% of the indicators, while the objective criteria account for 23%. Twenty-two of the shortlisted studies used a comprehensive list of indicators and sub-indicators further filtered according to the four criteria — physical, physiological, psychological, and behavioural. The list was further condensed by combining similar indicators (see Table 2). The condensed list contained 8 Physical, 4 Physiological, 6 Psychological, and 6 Behavioural indicators abbreviated according to the criteria. The climatic and physiological assessment consists of objective factors — i.e., measurable climatic atmospheric parameters, biometeorological conditions, and physiological factors that can be measured using instrumentation and other quantitative assessment methods. The way we experience thermal environments is also affected by subjective physiological and socio-behavioural factors such as thermal history, cultural background, and acclimatisation (Chen and Ng, 2012).

Physical factors: Physical factors in research studies often refer to physical parameters that can be measured directly using sensors such as air temperature, solar radiation, wind speed, and humidity.

Physiological factors: The temperature on human skin and sweat rate are used to assess the human reaction to ambient temperature. The response generated by the human body constitutes the physiological factors assessed. These factors influence the thermal comfort of people in the region.

Psychological factors: Psychological factors are non-climatic and non-physiological factors that affect the comfort sensation in the human brain. Research studies have often considered thermal experience, thermal expectations, perceived control, mood, and emotion as psychological factors during thermal comfort studies (Chen, Wen, Zhang, and Xiang, 2015; Holland, 2016; Jendritzky et al., 2012).

Behavioural factors: There are some social factors that influence thermal comfort, such as position in space, number of companions, and the socio-economic variable which directly affects the type of clothing worn. The activity undertaken by the individual also influences thermal comfort, including jogging, walking, workouts, and shopping (Coccolo, Kämpf, Scartezzini, and Pearlmutter, 2016).

Table 2: Condensed List of Similar Indicators							
Physical (8)	**Physical (8)**	**Physiological (4)**	**Physiological (4)**	**Psychological (6)**	**Psychological (6)**	**Behavioural (6)**	**Behavioural (6)**
P1	Air Temperature (°C/°F)	PH1	Age	PS1	Naturalness of climate	B1	Clothing insulation
P2	Relative Humidity (%)	PH2	Gender	PS2	Expectations	B2	Activity level & metabolic rate
P3	Mean Radiant Temperature (MRT W/m²)	PH3	Active thermoregulation	PS3	Experience	B3	Type of activity / Human Posture
P4	Solar Radiation (W/m²)	PH4	Passive thermoregulation	PS4	Time of exposure	B4	Culture
P5	Wind Velocity (m/s)			PS5	Perceived control	B5	Social (individual or Companion)
P6	H/W Aspect Ratio			PS6	Environmental Stimuli	B6	Metabolic Rate (Met or W/m)
P7	Sky View Factor (SVF)						
P8	Thermal Sensation Vote (TSV)						

2.3 Data Processing

The analysis begins with the comparison of the condensed list of indicators with each study, as seen in Table 3. Each indicator was allotted a single point score if it was used for assessment in the respective study. To determine the importance given to each indicator by developed and developing countries, each study was scored respectively. To understand the overall priority for an indicator, a cumulative score that included studies from both developed and developing countries was calculated.

Indicator Score. The indicator score determines the importance of a particular indicator. The condensed list of indicators was individually scored on the basis of its use in the shortlisted studies (Equation 1). The developed and developing countries' scores were calculated separately to understand the difference in priority of indicator selection. To see the overall priority for an indicator, a cumulative score for each indicator was calculated (Equation 2).

Table 3: Factors Influencing Thermal Comfort

Environmental / Physical Factor	**Physiological Factors**	**Psychological Factors**	**Behavioural / Social Factors**
Physical factors in research studies often refer to physical parameters that can be measured directly using sensors such as air temperature, solar radiation, wind speed, and humidity.	The temperature on human skin and sweat rate are used to assess the human reaction to ambient temperature. The response generated by the human body constitutes the physiological factors assessed.	Psychological factors are non-climatic and non-physiological factors that affect the comfort sensation in the human brain, including thermal experience, expectations, perceived control, mood, and emotion.	Social factors such as the position in the space, number of companions, and socio-economic variables directly affect the type of clothing and activity undertaken by the individual.
Temperature	Age	Naturalness of climate	Clothing insulation
Relative Humidity	Gender	Expectations	Activity level & metabolic rate
Wind Velocity	Active thermoregulation	Experience	Type of activity

Environmental / Physical Factor	Physiological Factors	Psychological Factors	Behavioural / Social Factors
Mean Radiant Temperature	Passive thermoregulation		Culture
		Perceived control	Social (individual or companion)
		Environmental stimuli	
References: Coccolo, Kämpf, Scartezzini, & Pearlmutter (2016); Nikolopoulou & Steemers (2003); ASHRAE (2013)	References: Coccolo, Kämpf, Scartezzini, & Pearlmutter (2016); Nikolopoulou & Steemers (2003); ASHRAE (2013)	References: Coccolo, Kämpf, Scartezzini, & Pearlmutter (2016); Nikolopoulou & Steemers (2003); ASHRAE (2013)	References: Coccolo, Kämpf, Scartezzini, & Pearlmutter (2016); Nikolopoulou & Steemers (2003); ASHRAE (2013)

Source: Nikolopoulou and Steemers (2003); ASHRAE (2013)

$I(i) = \Sigma\, s(i,n)$, for $n = 1$ to N …(1)
$Ic(i) = Idx(i) + Idy(i)$ …(2)

where I is the indicator score, s is the point score given to the study, n is the respective study number, Ic is the cumulative score for each indicator, Idx is the indicator score for developed countries, and Idy is the indicator score for developing countries.

Criteria Score. The prioritisation for outdoor thermal comfort criteria is equally important. Therefore, the score for each study was calculated individually to understand the importance given to each behaviour criterion by studies conducted in developed countries and India.

Where SP, SPH, SPS and SB are the cumulative scores of each study in the Physical, Physiological, Psychological, and Behavioural criteria respectively; n is the respective indicator, and Pi, PHi, PSi and Bi are the point scores given to the study for using an indicator in the Physical, Physiological, Psychological, and Behavioural criteria respectively.

3. Results and Discussion

3.1 Analysis of Outdoor Thermal Comfort Indicators

To understand the influence of thermal comfort conditions on pedestrian behaviour in urban areas, an indicator score was calculated by comparing the condensed list of indicators with the shortlisted studies. The indicator score represents the relative importance and frequency of use of various indicators in both developed and developing countries. The percentage share of indicators under four major criteria — physical, physiological, psychological, and behavioural — was determined for each study.

The analysis revealed that methods for assessing physical and physiological aspects of outdoor thermal comfort are well established and widely adopted. In contrast, approaches for evaluating behavioural responses remain less developed and lack standardised frameworks. Although numerous urban indicators exist for measuring thermal comfort and street usability, only a limited number specifically address pedestrian behavioural responses to thermal conditions. Consequently, behavioural indicators compatible with urban street studies were identified and analysed separately.

3.2 Prioritisation of Physical Indicators

A majority of the reviewed studies prioritised physical indicators over physiological, psychological, and behavioural indicators regardless of geographical context. Physical criteria consistently achieved the highest scores among all categories. This dominance can be attributed to the availability of measurable environmental variables and the existence of well-established simulation and modelling techniques.

The most frequently used physical indicators in both developed and developing countries include:

- Air Temperature (°C/°F)
- Relative Humidity (%)
- Mean Radiant Temperature (MRT)
- Solar Radiation
- Wind Velocity (m/s)
- Height-to-Width Ratio (H/W Ratio)
- Sky View Factor (SVF)
- Thermal Sensation Vote (TSV)
- Urban Geometry and Street Canyon Characteristics

Developed countries reported a usage frequency of approximately 90.90% for key physical indicators, while developing countries showed a similar frequency of 90.91%. The strong emphasis on parameters such as SVF, H/W ratio, and TSV reflects their ability to accurately represent the interaction between urban morphology and thermal conditions.

Furthermore, developed countries frequently integrate these indicators with advanced urban climate and morphological simulation models. In contrast, studies from developing countries, particularly India, rely more heavily on basic climatic measurements due to limitations in data availability, technological resources, and monitoring infrastructure.

3.3 Physiological and Behavioural Indicators

The relative neglect of physiological and behavioural indicators in the reviewed literature stands in contrast to their direct influence on pedestrian experience of outdoor thermal environments. The analysis confirms that both categories received comparatively lower attention despite their well-documented relevance to comfort and adaptive behaviour, and that behavioural assessment represents a particularly underdeveloped area of research in developing country contexts.

In developed nations, the most frequently used behavioural indicators include:

- Clothing Insulation
- Activity Level and Metabolic Rate
- Human Posture and Type of Activity
- Social Context (Individual or Companion Presence)
- Cultural Adaptation
- Thermal Preference and Adaptation Behaviour

Behavioural indicators B1, B2, and B3 were incorporated in approximately 54.55% of the reviewed studies from developing countries and at higher frequencies in developed countries.

Indian studies largely focus on clothing adaptation and activity type while rarely incorporating cultural, social, and metabolic variables into thermal comfort assessments. As a result, many studies may underestimate the complexity of pedestrian responses to outdoor thermal environments.

3.4 Psychological Responses and Thermal Perception

Among all four categories, psychological indicators recorded the lowest overall scores. Developed countries showed higher representation of psychological indicators, particularly acceptance, perception, and satisfaction measures. Indicators associated with thermal acceptance were commonly used across both developed and developing countries, suggesting a shared recognition of subjective thermal perception.

Developed countries demonstrated greater emphasis on understanding how individuals perceive and adapt to outdoor thermal conditions, whereas studies in developing countries were primarily concerned with generating baseline climatic and environmental information. This difference highlights a significant research gap, especially in the context of rapidly urbanising regions where pedestrian perception plays an important role in street usage and public-space vitality.

Table 4: Criteria Score — Developed and Developing Countries

Table 4: Criteria Score — Developed and Developing Countries																					
Developed Countries																					
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**	**Idx**
P1	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1	1	1	1	18
P2	1	1	1			1		1	1	1		1	1		1	1	1	1	1	1	15
P3		1		1	1	1				1	1	1		1	1	1		1	1		12
P4					1				1	1									1		4
P5	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1		1		1	17
P6						1	1	1		1				1	1	1			1		8
P7			1		1	1		1	1	1	1		1	1			1	1	1		12
P8			1			1			1											1	4
SP																					
PH1	1					1			1	1	1	1	1				1			1	9
PH2	1					1				1	1	1	1				1			1	8

PH3																					
PH4																					
SPH																					
PS1																					
PS2																					
PS3																					
PS4																					
PS5																					
PS6																					
SPS																					
B1		1	1	1		1		1	1	1			1				1			1	10
B2						1	1		1	1											4
B3		1	1	1				1	1								1			1	7
B4									1												1
B5																					
B6																					
SB																					
Developing Countries (including India)																					
	S 21	**S 22**	**S 23**	**S 24**	**S 25**	**S 26**	**S 27**	**S 28**	**S 29**	**S 30**	**S 31**	**S 32**	**S 33**	**S 34**	**S 35**	**S 36**	**S 37**	**S 38**	**S 39**	**S 40**	**Idy**
P1	1	1	1	1	1	1	1	1	1	1		1	1	1		1		1			15
P2	1	1	1	1	1		1	1	1			1	1	1	1	1					13
P3	1	1	1		1		1	1	1	1			1		1	1		1	1	1	14
P4	1	1	1	1	1		1	1	1			1	1	1	1	1					13
P5																					
P6	1	1	1		1			1						1	1	1		1	1	1	11
P7					1			1													2
P8								1	1						1	1					4
SP																					

P H1					1			1	1							1					4
P H2					1			1	1							1					4
P H3									1												1
P H4									1												1
SP H																					
PS 1					1																1
PS 2																					
PS 3																					
PS 4																					
PS 5																					
PS 6					1											1			1		3
SP S																					
B1	1	1			1			1	1						1	1					7
B2	1	1	1		1			1	1							1					7
B3	1	1						1	1						1	1					6
B4								1				1				1					3
B5	1							1								1					3
B6	1	1																			2
SB																					

3.5 Relationship Between Urban Morphology and Pedestrian Thermal Comfort

The review confirms a strong relationship between urban form, microclimate, and pedestrian behaviour. Most studies investigating outdoor thermal comfort focused on factors such as:

- Street Geometry
- Canyon Orientation
- Neighbourhood Morphology
- Vegetation Coverage
- Shading Devices
- Water Bodies
- Surface Materials and Albedo

The findings indicate that full vegetation cover, increased street aspect ratios, and shading canopies are among the most effective strategies for improving outdoor thermal comfort. Water bodies, wet surfaces, grass cover, and high-albedo materials also contribute positively to thermal moderation. However, the effectiveness of these interventions remains highly dependent on local climatic conditions and urban morphology.

The growing adoption of bottom-up planning approaches demonstrates increasing recognition of microclimate-sensitive urban design as a tool for enhancing pedestrian comfort and reducing urban heat stress.

3.6 Research Gap and Implications for Indian Cities

Although substantial progress has been made in evaluating physical aspects of outdoor thermal comfort, current assessment methods remain largely generic and often fail to capture the social, cultural, and behavioural realities of Indian urban environments. Existing studies frequently overlook localised adaptation mechanisms that influence pedestrian behaviour under varying climatic conditions.

The review identifies a critical need for more comprehensive behavioural assessment frameworks tailored to Indian cities. Future research should integrate region-specific factors such as traditional clothing practices, cultural adaptation strategies, socio-economic characteristics, and pedestrian activity patterns.

To strengthen behavioural assessment in urban thermal comfort studies, the following approaches are recommended:

- Clothing Adaptation Surveys reflecting local and seasonal attire patterns.
- Wearable Sensor Technologies for monitoring personal thermal exposure and physiological responses.
- Mobile-Based Tracking and Behavioural Mapping to examine pedestrian movement between shaded and unshaded environments.
- Community-Level Assessments investigating the influence of socio-economic and cultural factors on thermal perception and adaptive behaviour.

3.7 Discussion

The review demonstrates that physical indicators remain the dominant approach for evaluating outdoor thermal comfort due to their quantifiable nature and ease of measurement. However, thermal comfort is inherently a human-centred phenomenon that cannot be fully understood through environmental variables alone. Behavioural and psychological responses significantly influence how pedestrians experience and adapt to outdoor thermal conditions.

While developed countries are increasingly integrating behavioural dimensions into thermal comfort assessments, research in India and other developing countries remains focused primarily on environmental monitoring. Bridging this gap will require multidisciplinary approaches that combine climatic measurements with behavioural science, urban design, and social research. Such integration will enable the development of more realistic and context-sensitive models for evaluating pedestrian comfort and supporting climate-responsive urban planning.

4. Conclusion

This study critically reviewed the indicators used to assess outdoor thermal comfort and examined their influence on pedestrian behaviour in urban areas. The findings demonstrate that outdoor thermal comfort is a multidimensional phenomenon shaped by the interaction of physical, physiological, psychological, and behavioural factors. Among these, physical indicators such as air temperature, relative humidity, mean radiant temperature (MRT), sky view factor (SVF), height-to-width ratio (H/W ratio), and thermal sensation vote (TSV) remain the most widely adopted due to their measurability and the availability of established assessment frameworks.

The review further reveals that thermal comfort conditions significantly influence pedestrian behaviour by affecting route selection, duration of outdoor activities, use of public spaces, social interactions, and adaptation strategies such as seeking shade or modifying activity levels. While physical parameters continue to dominate thermal comfort assessments, behavioural and psychological dimensions remain comparatively underexplored, particularly in developing countries. This limitation restricts a comprehensive understanding of how pedestrians experience and respond to outdoor thermal environments.

Cross-contextual comparison between studies from developed and developing nations reveals that while physical indicators hold primacy in both settings, the treatment of behavioural and psychological dimensions is markedly asymmetric. Developed country research increasingly incorporates structured behavioural assessment — including thermal preference surveys, activity mapping, and cultural adaptation analysis — as a standard component of OTC studies. By contrast, the Indian literature remains largely confined to environmental and climatic measurement, with behavioural complexity — ranging from traditional clothing conventions and household-level adaptation strategies to the socio-economic determinants of outdoor activity — afforded limited systematic attention. India's climatic diversity, rapid rate of urbanisation, and distinctive socio-cultural landscape make this asymmetry a significant constraint on the development of context-appropriate OTC frameworks.

The study highlights the need for context-specific approaches that integrate pedestrian behaviour into outdoor thermal comfort evaluation. Factors such as clothing adaptation, activity patterns, thermal preferences, cultural practices, and social interactions should be considered alongside conventional climatic measurements. The incorporation of behavioural mapping, wearable sensing technologies, pedestrian movement analysis, and community-based surveys can provide a more comprehensive understanding of thermal comfort experiences in urban environments.

From an urban planning and design perspective, the findings emphasise the importance of climate-responsive street design. Urban morphology parameters such as SVF, H/W ratio, vegetation cover, shading elements, and water features play a critical role in improving pedestrian thermal comfort and encouraging outdoor activities. Integrating these design strategies with behavioural evidence can contribute to the development of more inclusive, walkable, and thermally comfortable urban streets.

Future research should expand beyond metropolitan cities and investigate thermal comfort conditions in tier-2 and tier-3 cities across diverse climatic regions. Furthermore, interdisciplinary studies combining quantitative environmental measurements with qualitative assessments of pedestrian perception and behaviour are essential for developing holistic thermal comfort models. Such efforts will enhance the understanding of pedestrian-environment interactions and support the creation of healthier, climate-resilient, and people-centred urban spaces.

Overall, the study concludes that improving outdoor thermal comfort is not solely a matter of modifying environmental conditions but also of understanding and accommodating pedestrian behaviours. A balanced integration of physical, physiological, psychological, and behavioural indicators is therefore essential for designing urban environments that promote comfort, well-being, and sustainable urban living.

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