Energy & Buildings 303 (2024) 113758

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Outdoor thermal comfort in built environment: A review of studies in India

Jayesh Dashrath Khaire *, Leticia Ortega Madrigal, Begona Serrano Lanzarote

Department of Architecture, Building, Urban Planning, and Landscape, Universitat Politècnica de València, 46022, Spain

A R T I C L E I N F O

Keywords:
Thermal comfort review
Neutrality
Thermal indices
Climatic zones
Indian studies

A B S T R A C T

The increasing population in Indian cities is leading to an increased load on the built environment in urban areas which is prone to effects such as the reduction of outdoor open spaces and decline of environmental quality. In this line, focus on outdoor thermal comfort studies has become an important aspect. The current status of outdoor thermal comfort in India and its comparative scenario are not available to researchers. In this paper, a critical review is performed on the studies published in the past 10 years, those focused on a built environment from micro-scale to macro scale. For the review, 18 papers were finally selected after performing the searches in major databases and filtering out irreverent studies. Following this, the shortcomings and gaps are identified and the future scope is stated. Most importantly, future studies are necessary to cover missing climatic regions and urban areas which are not yet been explored. The review also seeks the focus on the standardization of thermal comfort indices and the range of neutral values as per climatic regions. Along with the quantitative studies, a qualitative approach is also required in the research. Furthermore, future studies need to include psychological aspects such as adaptation and acclimatization. This review is the foremost study of the Indian context. It will act as a reference for researchers, architects, planners, and urban designers to improve their knowledge of outdoor thermal comfort and understand the gaps that need to be addressed.

1. Introduction

The estimated world population in cities will be 81% by 2030 [19] whereas, 91% of the population will be in cities of developing countries [20]. In India, the annual growth rate of the urban population is 3.35% [21], which is vulnerable to the built environment and the change in the built morphology of the existing urban areas; also there are cities in India that are proposed to be built [22]. This growth is leading to an increased load on the built environment in urban areas which is prone to effects such as the reduction of outdoor open spaces and decline of environmental quality. Urban built form alters the thermal environment significantly [23]. One of the concerns related to this is the outdoor thermal comfort level. The users tend to stay indoors for most of the duration of the day to get refuge from the thermal discomfort [24] that also results in the decline in outdoor space use.

The increasing population in the Indian cities is resulting into the decline of the open spaces and the increasing issues of outdoor thermal comfort. [25] conducted the study at Delhi, India, and found that the neighborhoods with high population density have a comparatively low proportion of outdoor open spaces. It was also found that the neighborhoods did not match the criteria of WHO and UN for per capita availability of public open spaces. Outdoor thermal comfort is one of the major concern at these spaces due to the ambient temperature level at the Indian urban areas especially during the summer season.

Traditionally outdoor open spaces India were used for various day today activities. The outdoor spaces were not just limited to the circulation paths, playgrounds or any type of recreation activity but extended to the social interaction that gave a certain character to the open spaces. These activities are getting affected due to the level of outdoor thermal comfort. It is vulnerable to the society since the time spent by the user at the outdoor spaces is getting declined and the quality of life is getting affected.

Thermally comfortable urban open spaces can attract the citizens to the outdoors [26–28]. These spaces are important for the physical and social well-being of the user [29]. In this regard, an in-depth understanding of outdoor thermal comfort is required among the stakeholders who can help to improve the quality of open spaces. One needs to understand the interaction between the user, the microclimatic parameters, and the built environment.

In this regard, numerous studies related to outdoor thermal comfort have been conducted around the world. The studies varied based on the scale of the site, climatic regions, use of the thermal comfort

* Corresponding author.
E-mail address: arjayeshkhaire@gmail.com (J.D. Khaire).

https://doi.org/10.1016/j.enbuild.2023.113758
Received 28 January 2023; Received in revised form 20 August 2023; Accepted 17 November 2023
Available online 23 November 2023

Nomenclature

✓	Topic studied
ANOVA	Analysis of variance
ANCOVA	Analysis of co-variance
ASV	Actual sensation vote
C	Convective heat flow
C_C	Cloud cover
Cl	Clothing value
CFD	Computational Fluid Dynamics
D	Globe diameter
d	Index of agreement
E_D	Latent heat flow to evaporate water into water vapor diffusing through the skin
DI	Discomfort index
e	Globe emissivity
E_{Re}	Sum of heat flows for heating and humidifying the inspired air
HSV	Humidity sensation vote
HSD	Honest significant difference
H/W	Height to width ratio
K↓	Short-wave radiant flux density from the upper hemisphere
K↑	Short-wave radiant flux density from the lower hemisphere
L↓	Long-wave radiant flux density from the upper hemisphere
L↑	Long-wave radiant flux density from the lower hemisphere
LCZ	Local climatic zone
LST	Land surface temperature
M	Metabolic rate
N/A	Data not available
NS	Not studied
OP	Operative temperature
PET	Physiological equivalent temperature
PMV	Predicted mean vote
R	Net radiation of the body
RMSE	Root mean square error
R_h	Relative humidity
R^2	Coefficient of determination
r	Correlation coefficient
S	Storage heat flow for heating or cooling the body mass.
SET	Standard effective temperature
OUT-SET	Outdoor standard effective temperature
SPSS	Statistical Package for the Social Sciences
SSV	Sun sensation vote
SVF	Sky view factor
E_{SW}	Heat flow due to evaporation of sweat
T_a	Air temperature
T_g	Globe temperature
T_s	Surface temperature
THI	Temperature humidity index
T_{mrt}	Mean radiant temperature
TSV	Thermal sensation vote
TC	Thermal comfort
TCPS	Thermal comfort perception survey
mTSV	Mean thermal sensation vote
T_W	Wet bulb temperature
UT	Union Territory
UTCI	Universal thermal climate index
V_a	Wind speed
W	Physical work output
WBGT	Wet bulb globe temperature
WSV	Wind sensation vote
N30˚E	Orientation aligned at an angle 30˚ from North
N60˚E	Orientation aligned at an angle 60˚ from North

Table 1
Studies selected for the review.

Study	Title
[1]	Evaluating outdoor thermal comfort in urban open spaces in a humid subtropical climate: Chandigarh, India.
[2]	Evaluating outdoor thermal comfort in “Haats” – The open-air markets in a humid subtropical region.
[3]	Assessing outdoor thermal comfort conditions at an urban park during summer in the hot semi-arid region of India.
[4]	Assessing The Thermal Comfort Conditions In Open Spaces: A Transversal Field Survey On The University Campus In India.
[5]	Evaluating the role of the albedo of material and vegetation scenarios along the urban street canyon for improving pedestrian thermal comfort outdoors.
[6]	Impact of building regulations on the perceived outdoor thermal comfort in the mixed-use neighborhood of Chennai.
[7]	Urban heat island intensity and evaluation of outdoor thermal comfort in Chennai, India.
[8]	Exploring the pattern of outdoor thermal comfort (OTC) in a tropical planning region of eastern India during summer.
[9]	Outdoor thermal comfort in different settings of a tropical planning region: A study on Sriniketan-Santiniketan Planning Area (SSPA), Eastern India.
[10]	Outdoor thermal comfort in various micro-entrepreneurial settings in hot humid tropical Kolkata: Human biometeorological assessment of objective and subjective parameters.
[11]	Quantitative outdoor thermal comfort assessment of street: A case in a warm and humid climate of India.
[12]	Semantics of outdoor thermal comfort in religious squares of composite climate: New Delhi, India.
[13]	Assessing outdoor thermal comfort of English Bazar Municipality and its surrounding, West Bengal, India.
[14]	Thermal comfort in urban open spaces: Objective assessment and subjective perception study in the tropical city of Bhopal, India.
[15]	Optimizing Street Canyon Orientation for Rajarhat Newtown, Kolkata, India.
[16]	Role of Built Environment on Factors Affecting Outdoor Thermal Comfort - A Case of T. Nagar, Chennai, India.
[17]	Impact of urban morphology on microclimatic conditions and outdoor thermal comfort – A study in a mixed residential neighborhood of Chennai, India.
[18]	Study on the Microclimatic Conditions and Thermal Comfort in an Institutional Campus in Hot Humid Climate.

index, method of evaluation, etc. The majority of the studies were carried out during the daytime since the questionnaire responses can be achieved when people are awake and using outdoor space [30]. The studies [31–34] performed the climatic study at a regional scale, on the other hand, studies [35,11] are conducted on a single street for a much smaller area. Studies have been performed under numerous climatic zones. Those studies referred to the Koppen climate classification whereas Indian studies have the option to refer to their classification in the climatic zones of India. Studies are mostly focused on a single climatic zone. But, there are studies [36,37] which performed the cross-climatic analysis. Most of the outdoor thermal comfort studies are based on on-site studies. The scale of such sites varied based on the scope of the studies. Some studies [38,39] compared two or more neighborhoods to have a comparative understanding or studied [40] a single street or open space in depth to evaluate the thermal comfort level and impact of enclosing built masses. The majority of the stud-

Table 2
Summary of the studies.

Study	Year	Published in Journal	City (State)	Climatic region	Season studied
[1]	2022	Building and Environment	Chandigarh (UT)	Composite	Summer and winter
[2]	2021	Building and Environment	New Delhi (UT)	Composite	Summer
[3]	2021	Materials today: proceedings	Sofidon (Haryana)	Composite	summer
[4]	2021	International journal of built environment and sustainability	Sonepat (Haryana)	Composite	Winter
[5]	2021	Urban Climate	Roorkee (Uttarakhand)	Composite	Summer
[6]	2021	Frontiers of Architectural Research	Chennai (Tamil Nadu)	Warm-humid	Summer
[7]	2021	Environment, Development and Sustainability	Chennai (Tamil Nadu)	Warm-humid	Summer and winter
[8]	2020	Urban climate	Sriniketan-Santiniketan (West Bengal)	Warm-humid	Summer
[9]	2020	Sustainable Cities and Society	Chotanagpur (Jharkhand)	Warm-humid	Summer and winter
[10]	2020	Science of the Total Environment	Kolkata (West Bengal)	Warm-humid	Summer and winter
[11]	2020	Urban Climate	Vijayawada (Andhra Pradesh)	Warm-humid	Summer and winter
[12]	2019	International Journal of Biometeorology	New Delhi (UT)	Composite	Summer
[13]	2019	Advances in Space Research	English bazar (West Bengal)	Warm-humid	Summer, winter and post monsoon
[14]	2017	Urban climate	Bhopal (Madhya Pradesh)	Composite	Summer
[15]	2017	Environmental and Climate Technologies	Kolkata (West Bengal)	Warm-humid	Summer
[16]	2016	Indian Journal of Science and Technology	Chennai (Tamil Nadu)	Warm-humid	Winter
[17]	2015	ICUC9 Conference	Chennai (Tamil Nadu)	Warm-humid	Summer
[18]	2014	30th Plea Conference	Chennai (Tamil Nadu)	Warm-humid	Summer

ies focused on physical or geometrical parameters, for example, studies [41–43] used H/W ratio, SVF, and orientation to define the morphological character of the site and studied their impact on thermal comfort. Although numerous studies are focused on outdoor thermal comfort, these studies vary in terms of the focus. The studies either focus on the estimation of thermal neutrality, the existing thermal state, or the effect of physical and climatic parameters on the thermal comfort level. The studies are also focused on optimization [44,45] of urban form to achieve better thermal comfort levels. Various tools and techniques are being used to evaluate outdoor thermal comfort. Studies [46–48] used a CFD simulation technique to investigate the complex fluid flow patterns in urban thermal environments. Whereas, in the past few years studies used ENVI-met simulations steady-state analysis.

Due to the complexity and number of aspects involved in the outdoor thermal comfort studies, several researchers [49,30,50,51] around the world have performed review studies on the topic of outdoor thermal comfort. Shooshtarian et al. [52] conducted a critical review to examine the quality of thermal comfort assessment in Australia's cities whereas, Dunjic [53] reviewed the outdoor thermal comfort research in urban areas of 11 countries of Central and Southeast Europe in the past decade (2010-2019). Dissanayake and Weerasinghe [54], and Baruti et al. [55] reviewed the outdoor thermal comfort in warm humid climates. These studies are focused on the regions based on specific territories and climatic zones to better assess the thermal comfort scenario and to identify the gaps. Some reviews are also focused on the assessment methods, comfort parameters [56], numerical models [57] etc. The only review study in the Indian context by Kumar [58] performed meta-data analysis for the subject's thermal adaptation in various indoor environments.

The advancements in the outdoor thermal comfort studies worldwide have been done since decades. Since the 1970s, a series of thermal comfort models based on people's thermal sensation to environment have been developed [59]. Past 10 years research in outdoor thermal comfort in Indian context has gained momentum. The topic of research at Indian context is comparatively new an not yet explored in depth. For this reason, it is necessary to look into the current status of the Indian studies.

The topic of outdoor thermal comfort is vast, diverse, and multifaceted. Its scale varies from immediate outdoor spaces to buildings to the issues such as climate change and heat island effects. Since the review seeks the human involvement and related parameters, the study is limited to the outdoor open spaces ranging from the immediate open space to the buildings to the neighborhood scale. The broader scales such as climate change and urban heat island effect studies are not involved since those are not based on the human involvement and the effect of the specific entity of the built environment can not be visualized. Basically, the review is about the interaction of user- climate- built environment.

Due to the rising population in the Indian cities urbanization has taken a rapid pace, outdoor space use has been affected due to issues linked to the climate. But there seems to be missing attention by the researchers in most of the cities and their thermal comfort status. There are also the parameters that need necessary attention such as the standardized range of thermal comfort, mode or the index of its evaluation, etc. To give attention to the issues in Indian urban areas, it is necessary to see the gaps in the current research.

The current status of outdoor thermal comfort in India and its comparative scenario are not available for researchers in the field of thermal comfort. For this reason, in this paper, a critical review is performed, with the objectives broadly concerning the focus, type of built environments studied, thermal comfort indices used, parameters evaluated, thermal sensation scales used, and the results obtained by the studies. The review is focused on a micro-scale (single location such as a plaza or a street) to a macro-scale (two or more locations within an urban area). Studies that are concerned about the subjective and objective thermal comfort level that have used thermal indices are only considered for the review. The study is performed comparatively. Following this, the shortcomings and gaps are identified and the future scope is stated.

2. Materials and methods

2.1. Search procedure

The review is based on 18 research papers. The following procedure was followed to select appropriate studies for the review.

The search process was conducted multiple times; before writing the review, after completing the writing part to check if new papers have been published in between, and before submitting the manuscript to the journal.

As per the study by Falagas et al. [60], commonly used databases are Pubmed, Google Scholar, Scopus, and Web of Science. These databases were searched in this review. Publishers' websites such as Taylor and Francis, SAGE Publications, MDPI, Springer, Hindawi, Wiley, and Emerald were also searched. Other databases such as "Copernicus" were also searched but it did not result in any thermal comfort study from India. The Keywords used were "thermal comfort", "thermal perception", "urban thermal comfort", "outdoor thermal comfort", and "thermal comfort in India". The search was not limited to outdoor thermal comfort, since it is possible that the titles used related aspects such as affecting parameters, effect on the sensation, etc. For this reason, more keywords were used such as "urban canyon", "street", PET, "T_{mrt}", etc. The deci-

Table 3
Output of the search process.

Database/ Platform	Step 1- Search result of Indian studies	Step 2- Studies focused on outdoor environment	Step 3- Relevant studies obtained
Science Direct	112	42	11
Reasearchgate	68	26	9
Google Scholar	156	36	15
Semantic scholar	83	39	8
Pubmed	5	2	2
Taylor and Francis	5	0	0
Springer Nature	35	6	2
Total no. of selected articles			47
Finally selected articles after removing duplicates			**18**

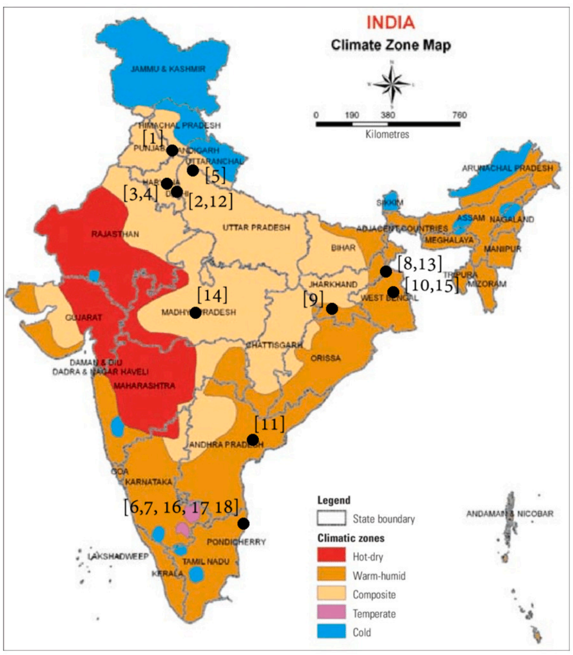

Fig. 1. Site locations concerning climatic zones of India.

sion to include thermal indices PET and T_{mrt} is due to the commonly used indices in thermal comfort studies.

The search used the typical syntax with standard boolean: "Outdoor AND Thermal comfort AND India", "Thermal comfort AND India", "Human AND Thermal comfort", "Outdoor thermal comfort" OR "Outdoor microclimate" and "User AND Thermal comfort". The search resulted in original journal articles, review articles, conference papers, and a Ph.D. thesis. Table 3 shows the broader steps involved in the search, filtration, and output in terms of the number of articles.

Screening and filtration were performed manually by reading the titles and abstracts to check whether the articles are in the scope of the review. Some studies focused on the climatic aspects at the meso scale to macro scale are excluded from the review. For example, [61] investigated the climate change impact and thermal comfort zones in semi-arid regions of Andhra Pradesh with the use of the Land Surface Temperature (LST) and Normalized Difference Built-up Index (NDBI). The study is not relevant to the review since it talks about climate change, a long-term phenomenon that occurs at the regional scale. Also, the study does not talk about human interference and the parameters linked to it. Some studies are conducted at an urban scale and involve people/users/respondents, still, they are not qualified for the review since they focused on the areas such as indoor activities. For example, [62] investigated summertime thermal comfort at residences of elderly people. The study is not relevant to this review because it has investigated indoor thermal comfort, and it is only focused on elderly people. Another study [63] that focused on a specific activity, and assessed the outdoor thermal comfort conditions of exercising people, was excluded.

The selection criteria are based on the limitation of this review: 1) The studies conducted at outdoor open spaces in India, 2) Studies conducted user surveys, 3) Addressed the issues of outdoor open spaces within the urban limit, 4) Considered the interaction of the user-climate- built environment. 5) Articles published in the past ten years.

To ensure all the relevant articles are gathered, at "Google" (www.google.com), one more method was used in which keywords were used with the extensions such as .pdf, .ppt, .docx, etc. For example, to find the available research in pdf format the search query was put as "Thermal comfort in India .pdf". The search query was repeated with a few more related keywords. The method also helped to search for any unpublished work, grey literature, notes, etc. Attempts were also made to search for unpublished works on digital platforms such as Scribd (www.scribd.com) and Academia (www.academia.edu). The search did not result in any relevant articles. The articles obtained through this method were the repeated results of previous stage searches and no fresh article was found. The authors did not find any article which is relevant for the review but not accessible. 18 articles were finally selected for the review (Table 1). Table 2 gives the summary of those studies.

2.2. Data extraction and classification

The finally selected studies were first gathered into the "Mendeley" which is a referencing application, that also helps to organize and sort the articles. The initial analysis was conducted using Microsoft Excel in which the data was classified into a number of tables. For example, in Table 6, the data extracted is arranged as the target population, sample size, and thermal parameters evaluated. The extract that was put in the tables helped to organize the data and to make sure the valuable information is not missed out. The results are organized into ten subsections. This number obtained due to the data extracted from the studies could be organized into these ten subsections, and there is no other idea that defines the specific number of subsections. The whole process was conducted manually and no other analytical method or software was used since the number of articles is limited to 18 only.

3. Results and discussion

3.1. The focus of the reviewed studies

Although Koppen climate classification [64,65] is one of the most widely used climate classification systems in the world, Indian studies tend to follow the Indian classification of climates that is the 'climatic zones of India' [66]. In this review, all the climatic zones are mentioned in terms of the climatic zones of India for ease of understanding. Studies have been conducted in ten cities from two climatic zones (composite, and warm and humid) whereas the remaining three climatic zones (hot and dry, temperate, and cold) are not yet studied. Fig. 1 shows the climatic zones of India with pointers showing the sites of the studies conducted.

Studies by Manavvi and Rajasekar [1] and Ali and Patnaik [14] evaluated thermal comfort levels at three different urban typologies: waterfront, green, and built open space to evaluate the biometeorological index PET at composite climate. The study by Manavvi and Rajasekar [2] evaluated the outdoor thermal comfort level at two "Haats" (open-air markets) in New Delhi. One more study [12] conducted in New Delhi evaluated outdoor thermal comfort at two religious squares. Kumar and Sharma [3] assessed the outdoor thermal comfort level by evaluating UTCI, PET, and WBGT at a public park in Sofison, Haryana. Another study by Kumar and Sharma [4] at Haryana focused on the university campus of DCRUST University to evaluate the neutral range of PET. Mohammad et al. [5] focused on the albedo of materials and vegetation along the urban canyon at Roorkee, Uttarakhand for the improvement of pedestrian thermal comfort level. It is the only study on the composite climate of India that focuses on the contribution of parameters such as materials and vegetation on the effect of thermal comfort level. In contrast, the rest of the studies (Table 4) focused on the evaluation of the thermal comfort level in various urban neighborhoods and typologies.

Amongst the studies conducted in warm and humid climates were studies conducted in Chennai [6,7,16–18], and West Bengal [8–10,13,15], whereas Deevi and Chundeli [11] conducted the study at Vijaywada. Among the studies from West Bengal, Das and Das [8] identified the variety of subjective and objective thermal sensations across the LCZs to evaluate PET whereas Das et al. [9] worked on similar aspects with similar LCZs to evaluate UTCI and THI. Bhaskar and Mukherjee [15] examined the influence of canyon orientation by generating the scenarios of canyon orientations with 15° increments. Optimum orientation was found by comparing various thermal parameters for all the explored orientations. Banerjee et al. [10] collected the data for summer and winter to understand the seasonal variations in outdoor thermal comfort in various neighborhoods and calculate the neutral temperature. Ziaul and Pal [13] analyzed the Spatiotemporal conditions by using DI and PET and evaluated the thermal comfort conditions for various seasons. Deevi and Chundeli [11] conducted the study at Vijayawada and investigated the factors (SVF and H/W ratio) influencing the thermal comfort level at an urban canyon. Studies by Amirtham et al. [18] and Amirtham et al. [17] investigated the influence of geometrical and morphological parameter SVF, building materials, and green cover on PET in Chennai during the summer season. Another study conducted in the built environment of Chennai by Horrison and Amirtham [16], analyzed the spatial variation of T_a and R_h during the winter season.

3.2. Study of built environment

Studies have classified the built environments based on land use, density, morphology, geometry, LCZs, streets, and marketplaces (Table 4). LCZ (local climatic zone) classification is proposed by Stewart and Oke [67], which provides a research framework for urban heat island studies and standardizes the worldwide exchange of urban temperature observations. This classification is based on the density of the built mass, the height of buildings, land cover, and vegetation. Some of the reviewed studies Rajan and Amirtham [6], Das and Das [8], Das et al. [9] used LCZ classification for differentiating the urban densities in their studies. Ziaul and Pal [13] classified built environments based on varying densities: Open mid rise, Compact low rise, and Open low rise densities which are similar to LCZ classification. Similarly, Banerjee et al. [10], and Amirtham et al. [17] also studied varying densities of the built environment.

LCZ classification just allows a basic assessment of the local climate and its accuracy is limited [68]. It can provide a valuable input for meso-scale models, but its reliability at the micro- scale is not yet tested. It is not a popular index in the Indian context. A review study [69] found that more than half of the published studies on LCZ are in Chinese cities. The study also highlights that the LCZ classification is more applicable to the UHI and climate change studies rather than the micro-climate studies.

Studies conducted in warm and humid climates by Manavvi and Rajasekar [1] and Ali and Patnaik [14] compared and evaluated the outdoor thermal comfort level in three different urban settings: Green space, waterfront, and plaza. Both studies considered vegetation present on the site. Canopy cover is the area of the ground covered by a vertical projection of the canopy, while canopy closure or canopy density is the proportion of the sky hemisphere obscured by vegetation when viewed from a single point [70]. Canopy cover is used by Manavvi and Rajasekar [1] whereas canopy density (recorded using spherical densiometer) is used by Ali and Patnaik [14]. Studies at New Delhi [2,12] evaluated thermal comfort by comparing urban squares, few studies [4,18] are performed in the educational campuses, whereas some studies [5,7,11,15,16] are focused on urban streets.

The commonly studied physical parameters are H/W and SVF along with orientation to understand the built morphology of their study areas. These parameters represent the geometrical aspects of the built environment. Several studies (Table 4) used SVF and H/W ratios in their studies. The traditional way of acquiring the SVF is taking a 180° fish-eye photograph of the surrounding area [71,72]. Besides taking photographs, Rayman [73] is the software tool that is commonly used. Chen et al. [74] concluded that the SVF is a useful and effective tool for planners and urban climatologists conducting studies in sub-tropical cities. The H/W ratio or aspect ratio is another commonly used method to understand and evaluate the built geometry. It is calculated by taking the ratio of the average height of the buildings surrounding the open space to the width of the open space. Orientation of buildings or open spaces is also considered in the studies. Bhaskar and Mukherjee [15] explored the seven alternative orientations of the street with a 15° increment to arrive at the appropriate street orientation for the optimum thermal comfort level.

SVF can be used to correlate thermal parameters at the micro scale as well as macro scale studies such as UHI [40,75]. There has been a mix opinion about which parameters defining the physical configuration is better among H/W ratio and SVF. Deevi and Chundeli [11] preferred SVF over H/W ratio. Whereas it is observed that the most of the studies where the linear configuration of open spaces such as streets is studied, the H/W ratio is given the preference. It can be said that the open spaces which are primarily enclosed from two opposite directions can use the H/W ratio.

It is observed that the orientation of the built masses plays a vital role along with the H/W ratio or SVF. The built environments with similar values of SVF can have variations in the enclosing physical entities along with their orientation, due to which variation in the thermal environment may occur. Several studies [76] have encountered this point in which the orientation plays a vital role for the built environments having similar SVFs.

Other than physical/geometrical parameters, the studies have also differentiated the built morphologies in terms of materials [5,18]. The studies [3,4,8,9] made the thermal comfort evaluation based on the field survey by evaluating the subjective and objective parameters; these studies did not focus on the physical parameters of the built environment.

3.3. Micro meteorological measurements

On-site micrometeorological measurements can be used directly for thermal analysis, as an input for the calculation of T_{mrt}, or as an input for ENVI-met. These measurements are also used to validate the simulation outcome. T_a (°C), R_h (%), V_a (m/s), and T_g (°C) are commonly measured indices on site (Table 5).

The globe temperature (T_g) is indicated by a temperature sensor placed in the center of a globe. It is measured by a globe thermometer

Table 4
Built environment classification with physical parameters.

Study	Built environment	Physical/ Geometrical parameters
[1]	Plaza, green and waterfront	SVF, percentage of tree cover
[2]	The open air markets at 2 locations	SVF, frequency of shade
[3]	City park	-NS-
[4]	University campus of DCRUST	-NS-
[5]	Single linear street	SVF
[6]	Various morphologies defined with LCZs	SVF, H/W
[7]	Streets and open spaces	SVF
[8]	Various morphologies defined with LCZs	-NS-
[9]	Various morphologies defined with LCZs	-NS-
[10]	Various morphologies of varying heights	SVF, H/W
[11]	Street with varying building heights	SVF, H/W, and orientation
[12]	two religious squares.	SVF
[13]	Morphologies of varying densities	Open mid rise, compact low rise and open low rise
[14]	Parks, lakefronts, open spaces	Tree canopy density
[15]	Street orientations	Seven alternative orientations with 15° increment
[16]	Streets and open spaces within the neighborhood	H/W, SVF, built density, and orientation
[17]	Various morphologies	H/W, SVF, built density
[18]	University campus of Satyabhama University	SVF, H/W, green cover, and orientation

developed by Vernon [77] that measures the combined effect of radiant heat, air temperature, and wind speed [78,79]. T_g along with T_a and V_a is used for the calculation of T_{mrt}. Studies [5–7,15] used measured T_a for the validation of the simulation outcome.

Some studies preferred one or two more indices other than commonly measured indices to help evaluate thermal comfort. Li and Becker [80] suggested that knowledge of the LST is necessary for environmental studies. It is one of the key parameters for the understanding of energy fluxes between the atmosphere and the ground [81]. Manavvi and Rajasekar [1], and Manavvi and Rajasekar [2] measured the incoming and outgoing short wave (K↓, K↑) and long wave (L↓ and L↑) radiant flux densities. Many studies evaluated these indices with the help of ENVI-met simulations. WBGT is a heat stress index and its value represents the thermal environment to which an individual is exposed [82]. The standard also recommends it as a screening method to establish the presence or absence of heat stress. Kumar and Sharma [3] measured WBGT (°C) with a WBGT meter and evaluated the range of neutral values.

The instruments placed on the site have to be placed as per certain protocols. Studies [3,10,11,8,9] preferred 1.1 m as suggested by previous studies [83–86] which is also in accordance with standards [87]. Some studies [1,2,12] preferred 1.2 m height as suggested in the study by [88], whereas [5] preferred 1.5 m height. In rare cases, studies used different heights due to site-specific challenges as can be seen in the study by Rajan and Amirtham [7] which used 2.5 m as the height for the placement of the instruments.

3.4. Use of software and its validation

Commonly used software among the revied studies is Rayman [89] and ENVI-met [90]. Only Deevi and Chundeli [11] used Ecotect for developing shadow patterns. Rayman is commonly used for the calculation of T_{mrt} and PET, whereas most of the climatic indices can be simulated using ENVI-met. Reviewed studies also used ENVI-met for simulating the T_{mrt} and PET (Table 5). Most of the studies preferred Rayman over ENVI-met. There are no studies that compare the output of Rayman and ENVI-met. The possible reason for the inclination towards the Rayman can be because of its open-source availability, whereas ENVI-met has a grid limitation of 50 * 50 cells for free users, and tools for bioclimatic indices such as PET and UTCI are available only for paid users. To calculate PET in Rayman, T_a, R_h, V_a, T_{mrt}, and personal characteristics are used. Several studies [91] found that ENVI-met is a more suitable tool for thermal comfort studies than Rayman.

Numerical models such as ENVI-met need to be validated before their results can be considered reliable and used for the analysis. Earlier studies [92,93] analyzed the performance of the ENVI-met model. Studies [94] have tried to understand the effectiveness of the ENVI-met tool for outdoor thermal comfort studies. The study also suggested the procedure to perform simulations in Envi-met. [95] conducted the validation study for ENVI-met. All of the reviewed studies which used ENVI-met simulations validated the results with on-site measurements. Rajan and Amirtham [6] and Rajan and Amirtham [7] performed validation with linear regression (R^2) between observed and simulated T_a. To improve the accuracy of the validation Willmott [96] suggested root mean square error (RMSE) and index of agreement (d) to determine the model performance. Bhaskar and Mukherjee [15] used R^2, RMSE and d to validate simulated T_a with observed T_a. Mohammad et al. [5] performed validation with R^2 for T_a, V_a, R_h, and T_{mrt}. The outcome of validation for accepted values is shown in Table 5.

3.5. Thermal comfort indices

Thermal comfort indices were developed based on single-node, two-node, and multi-node models. A single node is based on the heat balance equation, calculated using six basic parameters, T_a, R_h, V_a, T_{mrt}, Cl, and metabolic rate. Two models include the effect of skin temperature and core temperature on heat balance. In the multi-node model, the whole human body was divided into many sections to consider the effect of skin temperature, core temperature, and rate of change of skin temperature on heat balance.

Numerous indices have been used for the evaluation of thermal comfort. It is observed that these indices get affected differently due to climatic and non-climatic parameters. for example, T_{mrt} is affected greatly by solar radiation whereas PET gets affected due to wind speed; for this reason, it is beneficial to use two or more indices in a single study so that the effect from various entities of the built environment can be accommodated in the study. It is observed that Indian studies have used more than two indices together for thermal comfort evaluation.

Number of multi-node models have been developed since last five decades [97]. The indices explained in the subsequent sections are the commonly used indices in the reviewed studies.

3.5.1. Physiological equivalent temperature (PET)

To date, various thermal comfort indices have been used. Potchter et al. [98] summarised the indices used in 117 studies from 2001 to 2017. Having a suitable model for the evaluation of thermal comfort is an important aspect. In this review, it can be seen that most of the studies used PET as a primary index and other indices to support the evaluation. Other review studies [52,88] also found that the PET is the widely used index to evaluate the thermal comfort of users.

Table 5
Micrometeorological measurements, software used, and indices evaluated.

Study	Micrometeorological measurements	Software used	Indices evaluated	Validation
[1]	T_a, R_h, V_a, T_g, T_s, K↓, K↑, L↓, L↑	Rayman	T_{mrt}, PET	-NS-
[2]	T_a, R_h, V_a, T_g, K↓, K↑, L↓, L↑	Rayman	T_{mrt}, PET	-NS-
[3]	T_a, R_h, V_a, T_g, WBGT	Rayman	UTCI, PET, WBGT	-NS-
[4]	T_a, R_h, V_a	Rayman	PET	-NS-
[5]	T_a, R_h, V_a, T_g, and T_s	Rayman, ENVI-met	T_{mrt}, PET	R^2 = 0.80 to 0.93
[6]	T_a, R_h	ENVI-met	T_{mrt}, PET	R^2 = 0.65 to 0.71
[7]	T_a, R_h	ENVI-met	T_{mrt}, PET	R^2 = 0.51 to 0.91
[8]	T_a, R_h, V_a, LST	-NS-	UTCI,THI	-NS-
[9]	T_a, R_h, V_a, LST	-NS-	PET, SET, DI	-NS-
[10]	T_a, R_h, V_a, T_g,	Rayman	PET	-NS-
[11]	T_a, R_h, V_a	Ecotect, Rayman	PET	-NS-
[12]	T_a, R_h, V_a, T_g,	Rayman	PET, UTCI, T_{mrt}	-NS-
[13]	T_a, R_h, V_a	Rayman	DI, PET, PMV, T_{mrt}	-NS-
[14]	T_a, R_h, V_a, T_g, Cc	Rayman	PET	-NS-
[15]	T_a, V_a	ENVI-met	T_{mrt}, PET	R^2 = 0.97, RMSE = 0.411 °C, d = 0.995
[16]	T_a, R_h	Rayman	T_a, R_h	-NS-
[17]	T_a, R_h, V_a, T_g	Rayman	T_{mrt}, PET	-NS-
[18]	T_a, R_h, V_a, T_g	Rayman	PET	-NS-

In this review paper, 16 out of 18 studies used PET for the evaluation of thermal comfort, which indicates the reliability and importance of the index in the field of thermal comfort. PET was introduced by [83]. It is based on a two-node Munich energy balance model [99,100]. The heat balance of PET is given by equation (1).

$$M + W + R + C + E_D + E_{Re} + E_{SW} + S = 0 \quad (1)$$

3.5.2. Mean radiant temperature (T_{mrt})

Out of reviewed studies, seven studies have used the T_{mrt} index. It is best suited for the evaluation of daytime thermal comfort since T_{mrt} values do not fluctuate in the absence of sunlight [78]. There are various methods to determine the T_{mrt} [101]. Studies Rajan and Amirtham [6], Ziaul and Pal [13], and Perera and Weerasekara [102] achieved T_{mrt} from the simulation outputs. T_{mrt} is recommended by ISO 7726: 1998 [103] and given by equations (2), (3) and (4). These equations are useful when a globe thermometer is used and combined with measurements of T_a and V_a. Equation (3) is used by Banerjee et al. [10] for the calculation using measured Tg with an emissivity of 0.95 and a globe diameter of 120 mm, whereas equation (4) is used by Ali and Patnaik [14] for the calculation using 40 mm globe thermometer. There are several other equations developed by the researchers. The equations vary due to the globe's mean convection coefficient (For example $3.42 * 10^9 Va^{0.119}$ is a mean convection coefficient in the case of equation (2)). Equation (4) is a simplified equation where a mean convection coefficient and globe emissivity are kept constant.

$$Tmrt = \left[(Tg + 273)^4 + \frac{3.42 * 10^9 Va^{0.119}}{eD^{0.4}} * (Tg - Ta) \right]^{0.25} - 273.15 \quad (2)$$

$$Tmrt = \left[(Tg + 273)^4 + \frac{1.1 * 10^8 Va^{0.6}}{eD^{0.4}} * (Tg - Ta) \right]^{0.25} - 273.15 \quad (3)$$

$$Tmrt = Tg + 273 * Va^{0.5} * (Tg - Ta) \quad (4)$$

3.5.3. Universal thermal climate index (UTCI)

The UTCI is defined as the air temperature of the reference condition causing the same model response as actual conditions [104]. It is based on Fiala's [105] advanced multinode model. The index provides an assessment of the outdoor thermal environment. Several studies [106,107] around the world validated the index.

UTCI is very sensitive to changes in temperature, solar radiation, wind, and humidity. [108] found the effect of direct solar radiation on UTCI. It depicts temporal variability of thermal conditions better than other indices [109,97]. It can be computed using the software developed by Brode et al. [110]. It can also be evaluated with the equation (5). Kumar and Sharma [3], Das and Das [8], Manavvi and Rajasekar [12] used UTCI in their studies.

$$UTCI = f(Ta; Tmrt; Va; Rh) \quad (5)$$

According to Blazejczyk et al. [109], the present indices express bioclimatic conditions reasonably only under specific meteorological situations, while the UTCI represents specific climates, weather, and locations much better. Also, according to the study, similar to the human body, the UTCI is very sensitive to changes in ambient stimuli: temperature (Ta and Tmrt), solar radiation, wind, and humidity. UTCI depicts the temporal variability of thermal conditions better than other indices.

3.5.4. Temperature humidity index (THI)

THI is a measure of the reaction of the human body to a combination of heat and humidity [111,112]. According to Eludoyin and Adelekan [113], and Eludoyin [114] for tropical climates, THI is the most relevant thermal comfort index. It is evaluated with the equation (6). Das and Das [8] used THI along with UTCI for warm and humid West Bengal.

$$THI = 0.8 * Ta + (Rh * Ta)/500 \quad (6)$$

3.5.5. Discomfort index (DI)

DI is a physiological thermal stress indicator that was developed by Thom [111]. It is based on the T_a and R_h and evaluated with equation (7). Das et al. [9] and Ziaul and Pal [13] used DI.

$$DI = Ta - 0.55(1 - 0.01Rh)(Ta - 14.5) \quad (7)$$

3.5.6. Standard effective temperature (SET)

SET [115] and OUT-SET [116] use two-node models. SET is defined as the air temperature in which, in a given reference environment, the person has the same skin temperature and wetness as in the real environment. Das et al. [9] used SET.

3.5.7. Wet bulb globe temperature (WBGT)

WBGT [117] is an outdoor heat stress index in a hot environment [118]. It is a thermo-physiological index that measures the heat stress of an individual under direct sunlight [119]. Equation (8) [120] shows the index without direct solar radiation whereas equation (9) [120] shows the index with direct solar radiation. Kumar and Sharma [4] used equation (9).

$$WBGT = 0.7Tw + 0.3Tg \quad (8)$$

$$WBGT = 0.7Tw + 0.2Tg + 0.1Ta \quad (9)$$

Table 6
Parameters evaluated from questionnaire.

Study	Target population	Sample size	TSV	SSV	WSV	HSV	TC	Acceptability	Preference
[1]	Plaza, green and waterfront	2585	✓	-NS-	✓	✓	✓	✓	✓
[2]	Marketplaces	392	✓	✓	✓	✓	-NS-	✓	✓
[3]	City park	55	✓	-NS-	-NS-	-NS-	✓	-NS-	-NS-
[4]	University campus	185	✓	✓	✓	✓	✓	✓	✓
[5]	Street	73	✓	-NS-	-NS-	-NS-	-NS-	-NS-	✓
[8]	23 sites	200	✓	✓	✓	✓	-NS-	-NS-	-NS-
[9]	23 sites	200	✓	✓	✓	✓	-NS-	-NS-	-NS-
[10]	Neighborhoods	318	✓	-NS-	✓	-NS-	✓	✓	-NS-
[11]	Local street vendor	94	✓	-NS-	-NS-	-NS-	-NS-	-NS-	-NS-
[12]	Religious squares	353	✓	✓	✓	✓	-	✓	✓
[13]	Various densities	250	✓	-NS-	-NS-	-NS-	-NS-	-NS-	-NS-
[14]	Visitors and vendors	240	✓	-NS-	-NS-	-NS-	✓	-NS-	-NS-
[17]	Residential neighborhood	-NA-	✓	-NS-	-NS-	-NS-	-NS-	-NS-	-NS-
[18]	University campus	-NA-	✓	-NS-	-NS-	-NS-	-NS-	-NS-	-NS-
	% of studies used the parameter		100	27.78	38.89	33.33	27.78	27.78	27.78

WBGT replaces ambient temperature and humidity indexes, the index responds to solar access and wind [121]. The study also highlights the limitation of the index. WBGT requires careful evaluation of people's activity, clothing, and many other factors, all of which can introduce large errors in any predictions of adverse effects. The index can provide only a general guide to the likelihood of adverse effects of heat. This index is best suited for active people such as outdoor workers, athletes, etc. [122]

3.5.8. Predicted mean vote (PMV)

Ziaul and Pal [13] used predicted mean vote (PMV) [123] along with other indices T_{mrt}, PET and DI. PMV is based on six factors: T_a, V_a, R_h, T_{mrt}, M, and Cl. It was originally developed for indoor climates. It was first applied to the outdoor environment by Jendritzky and Nübler [124], and developed a model called as Klima-Michel Model (KMM). Later on, several other studies adopted PMV in outdoor environments. The PMV overestimates/underestimate of thermal sensation in warm and cool conditions respectively because the PMV model does not consider the psychological and behavioral adaptations in the real world [127]. It also overestimates the thermal sensation experienced by Indians, since Indians may have a wider thermal comfort range, especially concerning hotter temperatures [125]. For this reason, though it is widely used in the last ten years all over the world [126], Indian studies did not rely on this index.

3.6. On-site questionnaire survey

Table 6 shows the summary of the parameters included in the questionnaire. Most of the reviewed studies evaluated and compared thermal comfort at two or more locations of varying characteristics whereas some studies are focused on a single location such as a street [5], university campus [4,18], and city park [3]. The sample size of the studies typically ranged between 200 to 400 users. Kumar and Sharma [3] cited the reason as the COVID pandemic for only 55 respondents in its study.

The data collected was usually divided into three sections. The first section is about personal parameters such as age, gender, clothing, metabolic rate, demographic information, and socio-cultural value. The second section deals with subjective thermal perceptions, and the third section is about preference and acceptance. Manavvi and Rajasekar [1] adopted the questionnaire from Johansson et al. [88] which has a higher potential to rescale the thermal indices. The questionnaire utilized by Mohammad et al. [5] is based on previous research [86,128] and ASHRAE 55 standard [87,129]. Kumar and Sharma [4] designed the questionnaire based on ISO 2001 [130].

Current studies generally neglect psychological, socio-economic, and cultural factors [131,51], and assume steady-state conditions for outdoor subjects [132]. Ali and Patnaik [14] done the demographic profiling based on the Kuppuswamy scale [133]. Ali and Patnaik [14] considered parameters such as socio-economic status, ethnic groups, and demography and evaluated the impact on thermal sensation using various data analysis methods. The study used the Kruskal-Wallis test to estimate the relationship of thermal sensation votes with socio-economic status, Tuckey's HSD to confirm the differences that occurred among the groups, and Mann-Whitney U to evaluate the relationship of thermal sensation votes with gender. The effect of gender was also analyzed by Manavvi and Rajasekar [12] who found that gender has a weak influence on thermal perception which agrees well with Shooshtarian and Ridley [134] but contradicts with Lam et al. [135]. Thermal perception can vary as per age also. Manavvi and Rajasekar [12] found that the age of 20-40 showed higher acceptability of PET. Clothing value is another personal parameter that can affect thermal sensation. It is scaled from 0 (no clothing) to 1 (complete/100% clothing). Clothing values for various garments are given by the standards [136–138]. Studies [1,12] calculated clothing values concerning [138,139] whereas, Banerjee et al. [10] adopted clothing values from the study [140] which suggest the clothing values for the traditional Indian subcontinent.

3.7. Thermal comfort evaluation parameters and measurement scales

Table 6 gives the overview of the parameters evaluated from the questionnaire and Fig. 2 shows the measurement scales used to evaluate those parameters.

Three types of scales used in the thermal comfort evaluation are 1) descriptive, 2) affective, and 3) preferential [51]. The study [141] first used the descriptive and affective scales. The combination of these three scales explains the thermal comfort level in a better manner [142].

3.7.1. Descriptive scales

Descriptive scales explain the present thermal state of the users. Reviewed studies evaluated TSV, WSV, SSV, and HSV using various scales. The commonly used parameter in the questionnaire is thermal sensation/thermal sensation vote (TSV) (Table 6). It is different from the thermal comfort level. Thermal sensation and thermal comfort describe two different attitudes towards microclimate [143,144]. The thermal sensation is a conscious feeling generally evaluated on the seven-point scale [87,145,146].

As per ASHRAE 55 [87], the thermal sensation scale is a seven-point ordinal scale. Zhang and Zhao [147] and Schweiker et al. [148] recommended a seven-point scale for temperate climates whereas a nine-point scale (added 'very cold' (-4) and 'very hot' (+4) categories) for extreme climates. Manavvi and Rajasekar [1], and Manavvi and Rajasekar [2] evaluated the thermal sensation on a nine-point ordinal scale for the composite climate of New Delhi where extreme climate situation is observed. [11] followed a seven-point scale, whereas [14] used a four-point scale for the ASV referred from the international standard [149] (later on revised [130]) to measure thermal sensation level.

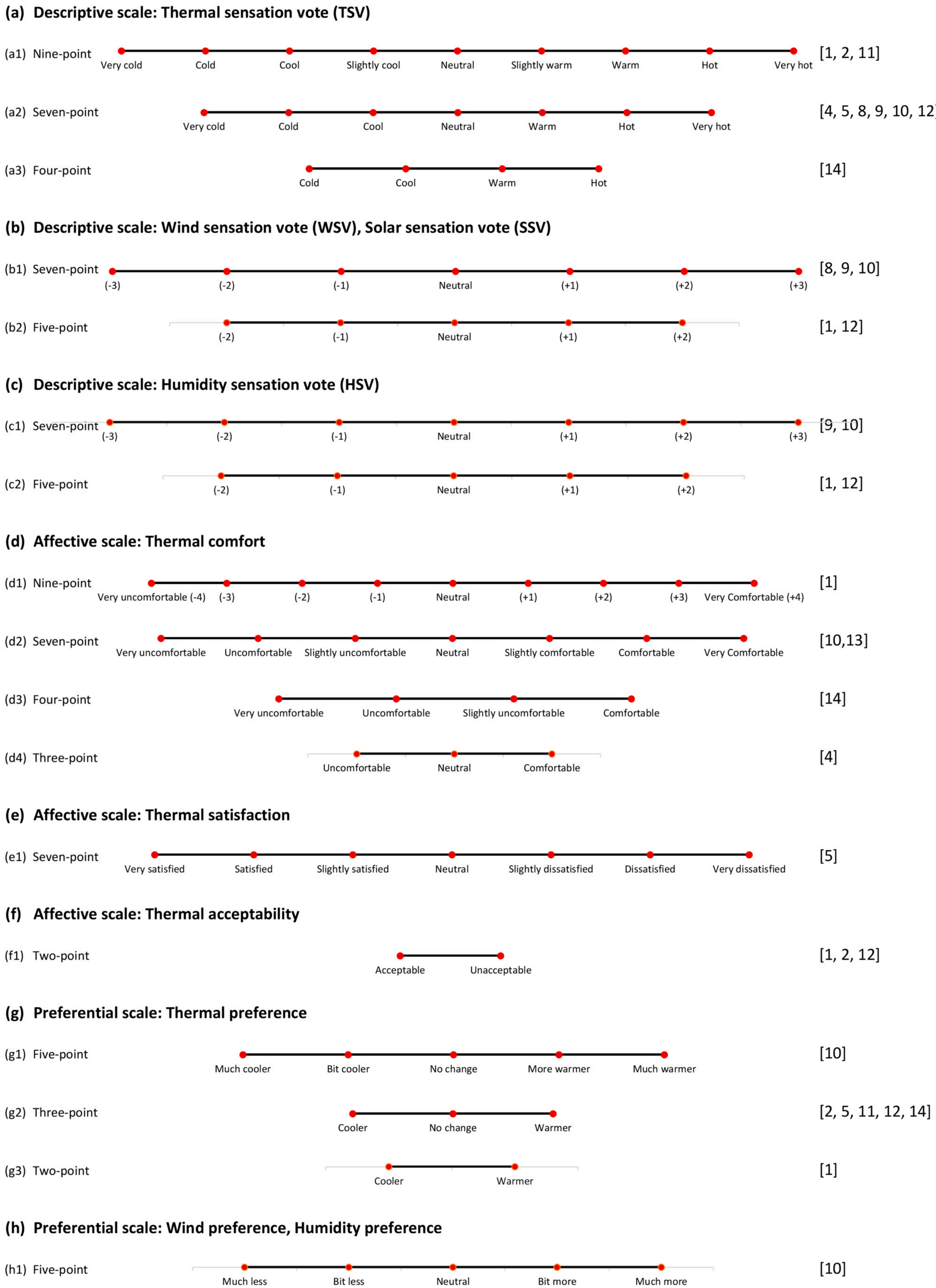

Fig. 2. Measurement scales used in the studies.

HSV, WSV, and SSV were evaluated on a five-point Likert scale by Manavvi and Rajasekar [1], and Manavvi and Rajasekar [2], whereas Banerjee et al. [10] and Das et al. [9] evaluated HSV on a seven-point scale (dry to very humid). Banerjee et al. [10] taken SSV on a seven-point scale (very soothing to very harsh). [14] Highlighted that the socio-economic factors affect the thermal sensation.

3.7.2. Affective scales

Thermal comfort, thermal satisfaction, and acceptance are measured on affective scales. Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation [87]. Ali and Patnaik [14] used a four-point thermal comfort scale [149] where comfortable (0) is the point of origin followed by slightly uncomfortable (1), uncomfortable (2), and very uncomfortable (3). The scale does not account for neutral sensation.

A match of thermal expectations with actual conditions results in thermal satisfaction [150]. Mohammad et al. [5] used seven-point scale (Fig. 2 e). As per ASHRAE 55 standards, if the temperature is accepted by at least 80% of the users then it can be termed as acceptable. Studies [1,2,12] used a two-point scale for thermal acceptability.

3.7.3. Preference scales

Thermal preference is an ideal condition an individual would favor in the thermal environment [51,151,150]. Studies [2,5,11,12,14] used three-point McIntyre scale ((-1) Prefer warmer; (0) No change; (+1) Prefer cooler). Manavvi and Rajasekar [1] used a two-point scale: want cooler and want warmer whereas a five-point scale is used by Banerjee et al. [10].

Mohammad et al. [5], and Ali and Patnaik [14] used a three-point scale with more humid (+1), same (0), and less humid (-1). [10] added two more points on the scale on either side (much more and much less) to make it a five-point scale for humidity and wind preference whereas the study used a three-point scale for shade preference.

3.8. Acclimatization and adaptation

Acclimatization is one of the determinants of outdoor thermal comfort level [86,152–155]. Studies [151,86] have observed the behavioral adaptation during strong sunshine. People in public places was seeking shade, either under trees or man-made shading devices such as caps and umbrella.

Nikolopoulou and Steemers [156] defines three kinds of adaptation: physiological, physical, and psychological. Nikolopoulou [157] included two more kinds of adaptations: reactive and interactive. Psychological adaptation promotes the presence of people in an urban space [158]. Manavvi and Rajasekar [12] found that the purpose of the visit to the site affects the PET level, which can be understood as an example of psychological adaptation. Manavvi and Rajasekar [1] also highlights the psychological adaptability to naturalness since the study observed a wider range of acceptable PET in a green space compared to a plaza. The study by Manavvi and Rajasekar [2] at marketplaces in New Delhi, found that 80% of the subjects accept a PET value of 38.6 °C, and users are found to be more tolerant of higher PET. The study observed an instant reactive adaptation in one of the marketplaces. From the above observations, it can be said that the acclimatization or adaptation to the site affects the thermal comfort perception of the user.

de Dear and Brager [159] proposed a framework for adaptive comfort based on three dimensions: behavior adaptation, physiological acclimatization, and psychological adaptation. Adaptive thermal behaviors can be patterned by the user's behavior towards thermal comfort; such as changing posture, clothing value, avoiding heat sources, etc. [160,150,159].

Very few reviewed studies talked about acclimatization. Banerjee et al. [10] found that during the summer season, people responded to an increase in comfort at one of the study sites with an annual neutral PET 3.82 °C higher than the other site. [14] Highlighted the significance of psychological adaptation

3.9. Thermal neutrality

Thermal neutrality is the mean vote on the thermal sensation scale that indicates neutral [87]. Since equivalent temperature is not directly related to thermal sensation, it is associated with the thermal sensation data (TSV, mTSV) obtained from the field surveys. Most of the reviewed studies have used PET to establish neutrality (Table 7).

Linear regression (R^2) is the most commonly used method for the determination of neutral value. Although there are no such standards that state the acceptable value for R^2 while establishing the thermal neutrality, based on Table 7, it can be said that the lowest acceptable R^2 value is 0.41 for T_a, 0.42 for UTCI and 0.60 for PET.

Linear regression has limitations in terms of accuracy [161,162]. Even increments are permitted in linear regression, whereas uneven increments are permitted in probit regression [163]. Manavvi and Rajasekar [1] is the only study from the reviewed studies that used 2 probit regression to compare the results of linear regression. The study achieved a neutral temperature of 24.05 °C which is very close to the neutral value obtained from linear regression (24.09 °C). These results do not prove the inaccuracy of the linear regression and further studies are necessary to check the accuracy.

A huge variation could be observed in the neutral values (Table 7). The possible reasons could be the tolerance, acclimatization, and adaptation of the user to the variation in weather conditions, differences in the built environments, and the activities they are involved in. It is also concluded by [164] that the PET values vary with climate as people from a specific place develop equilibrium with the conditions of that climate which develops differential thermal perception from place to place. Manavvi and Rajasekar [1] estimated different values of neutral T_a for different wind speeds. Users were found to be more tolerant of higher wind velocity ($V_a > 1.5$ m/s), which gave a neutral value of 0.5 °C higher than lower wind velocity ($V_a < 0.5$ m/s). Similarly, the difference was also achieved between summer and winter. Thermo-neutral PET value was higher in summer (29.5 °C) than during winter (23.2 °C). Manavvi and Rajasekar [2] achieved 24.7 °C as a neutral PET value, however 80% of the subjects accepted a PET value of up to 38.6 °C. The neutral range of DI evaluated by [13] is 21 °C-24 °C with a comfort range of 18 °C-21 °C whereas the comfort range defined by Thom [111] is 15 °C -19.5 °C. Very few respondents reported a neutral thermal sensation during the summer out of the reviewed studies.

The neutral values estimated by the studies belong to the specific sites where on-site measurements and questionnaire surveys took place. For this reason, the same neutral value can not be considered the neutral value of that whole city or climatic region. There are studies around the world that have estimated neutral values on a broader scale. Neutral PET range achieved by Lin et al. [165] is 26 °C - 30 °C for Taiwan, Matzarakis and Mayer [166] achieved 18 °C - 23 °C for Europe whereas, Cohen et al. [167] achieved 20 °C - 25 °C for the Mediterranean climate of Israel. Studies are therefore required in the Indian context to estimate the neutral temperature either as per climatic region or as per the cities, which will act as a reference point for the researchers in the related fields.

It is interesting to note that Fagner's seven-point scale shows the neutral scale and the comfortable scale as two different points on the sensation scale. 'Neutral' is the point between comfortable and uncomfortable; so the question arises whether the neutral state means the user is slightly less comfortable. The user may vote for slightly comfortable or slightly uncomfortable; under which situation will he vote for neutral? vote cast by the user can affect the calculations of the neutral value. Future studies should bring more clarity to the definition of the points on the sensation scales.

Table 7
Thermal neutrality achieved by studies.

Study	City	Indices correlated	Values of R^2	Neutral value	Acceptable range
[1]	Chandigarh	mTSV vs T_a (V_a < 0.5 m/s)	R^2 = 0.91	19.60 °C (T_a)	-*NS*-
		mTSV vs T_a (V_a > 1.5 m/s)	R^2 = 0.98	20.10 °C (T_a)	-*NS*-
		mTSV vs PET	R^2 = 0.92	24.09 °C (PET)	20.20 °C to 36.60 °C
[2]	New Delhi	mTSV vs PET	R^2 = 0.63	24.70 °C (PET)	-*NS*-
[12]	New Delhi	mTSV vs PET	R^2 = 0.60	24.70 °C (PET)	-*NS*-
		mTSV vs UTCI	R^2 = 0.42	22.90 °C (UTCI)	-*NS*-
[3]	Sofidon	mTSV vs PET	R^2 = 0.67	30.80 °C (PET)	24.04 °C to 37.50 °C
		mTSV vs UTCI	R^2 = 0.68	31.80 °C (UTCI)	28.03 °C to 35.60 °C
		mTSV vs WBGT	R^2 = 0.97	24.80 °C (WBGT)	23.50 °C to 26.10 °C
[4]	Sonepat	mTSV vs PET	R^2 = 0.65	21.89 °C (PET)	18.42 °C to 25.37 °C
[5]	Roorkee	mTSV vs PET	R^2 = 0.91	19.91 °C (PET)	17.27 °C to 22.56 °C
[10]	Kolkata	mTSV vs PET	R^2 = 0.64 to 0.77	23.58 °C (PET)	19.48 °C to 27.59 °C
		mTSV vs T_a	R^2 = 0.41 to 0.78	-*NS*-	22.10 °C to 27.56 °C

Table 8
Relationship between physical parameters and thermal comfort indices.

Study	Influence	Effect on Index	Method (Relationship)	Key results
[1]	SVF	PET (Summer)	R^2 = 0.81 (Strong)	SVF > 0.5 is 3.8 °C higher than SVF < 0.5
[1]	SVF	PET (Winter)	R^2 = 0.64 (Strong)	SVF > 0.5 is 5.3 °C higher than SVF < 0.5
[5]	SVF	PET	R^2 = 0.80 (Strong)	Higher relationship is observed after 2 pm till 12 am
[11]	SVF	PET	(Strong)	Up to 3 °C difference across the locations
[12]	SVF	PET	R^2 = 0.83 (Strong)	Spatial and temporal variation observed
[2]	SVF	PET	R^2 = 0.90	Thermal characteristics are predominantly driven by SVF
[6]	SVF	PET	R^2 = 0.92 (High)	Increase in SVF by 0.2 increases PET by 4.15 °C
[2]	SVF	T_{mrt}	R^2 = 0.80	Thermal characteristics are predominantly driven by SVF
[6]	SVF	T_{mrt}	R^2 = 0.83 (High)	Increase in SVF by 0.2 increases T_{mrt} by 1.06 °C
[12]	SVF	Tmrt	R^2 = 0.76 (Strong)	Spatial and temporal variation observed
[5]	SVF	TC	-*N*/*A*-	SVF is not a precise indicator for thermal comfort conditions.
[12]	SVF	mTSV	R^2 = 0.75	An increase of 0.5 in SVF value contributed to an increase of 1.5 in MTSV
[11]	H/W	PET	-*N*/*A*-	H/W is less effective than SVF in achieving thermal comfort.
[18]	H/W	T_a, PET	-*N*/*A*-	Up to 3.7 °C reduction in PET due to higher H/W ratio
[11]	Orientation	PET	-*N*/*A*-	EW oriented streets perform poorly, even with high aspect ratios.
[18]	Orientation	PET	-*N*/*A*-	E-W orientation of the street are 6.6 °C higher than N-S oriented streets.
[15]	Orientation	T_a	-*N*/*A*-	N30°E to N60°E perform better during the afternoon when heat stress is higher.
[15]	Orientation	V_a	-*N*/*A*-	Orientation oblique to wind direction improves cross ventilation.
[17]	Orientation	T_a	-*N*/*A*-	Higher temperature at E-W and at E-W and N-S street intersection.
[18]	Orientation	T_a	-*N*/*A*-	E-W orientation of the street are 3.7 °C higher than N-S oriented streets.
[14]	Tree canopy	T_{mrt}	R^2 = 0.35	10% tree canopy cover lowers T_{mrt} by 0.7 °C and 70% canopy cover lowers T_{mrt} by 2.2 °C
[14]	Tree canopy	PET	R^2 = 0.28	10% tree canopy cover lowers PET by about 0.8 °C and 70% canopy cover lowers PET by 2.6 °C
[18]	Vegetation	PET	-*N*/*A*-	Up to 3.28 °C reduction in PET
[2]	Albeo	T_s	-*N*/*A*-	An increase in albedo of 0.1 can reduce the T_s by 7.9 °C
[2]	Albeo	PET	-*N*/*A*-	An increase in the albedo of 0.1 can reduce the PET by 4.9 °C

Table 9
Relationship between climatic parameters and thermal comfort indices.

Study	Influence	Effect on Index	Method (Relationship)	Key results
[1]	T_a	PET	r = 0.81 (summer), 0.74 (winter)	-*N*/*A*-
[1]	T_a	mTSV	R^2 = 0.95 (Exposed), 0.94 (shaded)	T_a was found to be the most decisive determinant of thermal sensation
[8]	T_a	LST	r = 0.98 (Strong)	-*N*/*A*-
[8]	T_a	UTCI	r = 0.98 (Strong)	-*N*/*A*-
[8]	T_a	THI	r = 0.96 (Strong)	-*N*/*A*-
[9]	T_a	SET	R^2 = 0.96, r = 0.98 (Strong)	-*N*/*A*-
[9]	T_a	DI	R^2 = 0.96, 0.89	The areas with > 32 °C temperature fall under the category of state of a medical emergency.
[9]	T_a	PET	R^2 = 0.99	-*N*/*A*-
[9]	T_a	TSV	R^2 = 0.90(Strong)	-*N*/*A*-
[13]	T_a	LST	R^2 = 0.70 to 0.87	-*N*/*A*-
[2]	T_a	TSV	r = 0.43	-*N*/*A*-
[9]	R_h	DI	R^2 = -0.70, -0.43	-
[9]	R_h	T_a	R^2 = -0.92 (Strong correlation)	-*N*/*A*-
[9]	V_a	T_a	R^2 = -0.72	-*N*/*A*-
[17]	V_a	T_{mrt}, PET	-*N*/*A*-	The higher wind speeds during noon reduced the T_{mrt} and PET values significantly.
[10]	T_{mrt}	PET	R^2 = 0.65 to 0.77	-*N*/*A*-
[12]	T_{mrt}	PET	R^2 = 0.82 (Strong)	-*N*/*A*-
[14]	T_g	ASV	(Significant impact)	-*N*/*A*-
[5]	T_s	PET	R^2 = 0.45 (High)	The building and tree shading has a considerable effect on T_s

3.10. Effect of physical and climatic parameters on thermal comfort

Table 8 shows the relationship between physical parameters and thermal comfort indices. Physical parameters can also be called geometrical parameters, since the physical parameters represent the geometrical aspects of the built environment such as SVF, H/W, orientation, and density. Most of the reviewed studies established the relationship between SVF and comfort indices with R^2 and found a strong correlation. Thus, it can be said that the thermal comfort level is highly dependent on the SVF of that location. Deevi and Chundeli [11] also found that the SVF is more effective than H/W to assess thermal comfort.

Variation in thermal comfort was observed in various built environments such as vegetated spaces/parks, waterfronts, urban squares, and streets. Studies [1,9,13,14] observed lower PET in vegetated spaces. The density of the built environment also affects the thermal comfort level. [15] found that densely built areas reduced the T_a up to 0.7C. On the contrary, density negatively affected the thermal comfort in the study [16] even though the SVF is only 0.22. [9] also found the lower temperature at compact low-rise areas.

Variations in the temperature can be observed due to the orientation of the open space. Even for the higher H/W Amirtham et al. [17] found higher values of T_{mrt} and PET. This is due to the orientation of open space having a higher H/W ratio oriented E-W which is open to direct solar radiation for a maximum duration of the day. Other studies [11,17,18] also achieved similar results. Appropriate orientation can improve the thermal comfort level by improving the ventilation of that open space. Orientation oblique to wind direction improves cross-ventilation [15].

The effect of solar access could be observed in several studies. Manavvi and Rajasekar [1] observed more significant variation in sun-exposed spaces than shaded spaces. Ali and Patnaik [14] found that the tree canopy density significantly affected the thermal comfort index PET. Results thus highlight the importance of shade and radiation reduction in attaining thermal comfort in urban open spaces during the afternoon.

The effect of material can also be seen in the variation of thermal comfort. Das and Das [8] found higher THI at high-density built-up areas due to impervious surfaces and high density. similarly, [13] found that the impervious surface is very uncomfortable (more than 30 °C) in the summer season, and partially uncomfortable (24 °C -27 °C) in post-monsoon. [2] studied the effect of albedo on T_s and PET.

Studies have identified the influence of climatic parameters such as T_a, R_h, V_a, and T_g on thermal comfort indices with correlation coefficient (r) and coefficient of determination (R^2) (Table 9). T_a is the most commonly used parameter. [1] also found that the T_a is the most decisive determinant of thermal sensation.

The lowest value of R^2 that represents as 'high' is 0.45 by Mohammad et al. [5] whereas correlation (r) is accepted for the lowest value of 0.43 by Manavvi and Rajasekar [2]. Since there are no such scales evolved for r and R^2 in the topic of thermal comfort, Table 8 and Table 9 can be refereed for the strength levels of the relationships between various parameters.

Researchers typically use various data analysis methods to establish the relationships between two or more parameters.

To estimate thermal neutrality, ordinal probit regression is widely used [152,168]. Ali and Patnaik [14] used SPSS [169] to perform various analysis. The study used one-way ANOVA [170] to compare perceived thermal comfort and thermal sensation, along with HSD test [171] to confirm the differences. Ordinal Logistic Regression was carried out to find which environmental parameters were affecting the perception of thermal comfort and thermal sensation by the people. The relationship between tree canopy density and PET was performed with linear regression. Mann-Whitney U [172] and Kruskal-Wallis H non-parametric tests were performed to analyze the relationship of the thermal sensation votes with gender and socio-economic status of the respondents. Das et al. [9] also used the Kruskal-Wallis test to assess whether a significant difference exists or not between various parameters.

4. Gaps, limitations and future scope

The reviewed studies have presented comprehensive work on various aspects of outdoor thermal comfort. Various built environments were focused on to evaluate and estimate their interaction with thermal parameters. Most of the studies estimated thermal neutrality whereas some studies evaluated the effect of physical and climatic parameters on thermal parameters. To achieve these, studies also conducted on-site micro-meteorological measurements and questionnaire surveys. To achieve subjective votes, various measurement scales were used by the studies after referring to relevant standards and past studies. In-depth work has been carried out by past studies; however, several gaps and shortcomings are identified which demand further research in this field.

There are five climatic zones in India out of which only two have been explored to date. Most of the studies focused on major cities Kolkata, Chennai, New Delhi, and towns nearby these cities. Studies done at Bhopal and Vijayawada are the exceptions. There are still a lot of urban areas in these two climatic zones (composite and warm-humid) which are unexplored by researchers. There are important cities in the remaining three climatic zones that are vulnerable to climate-related issues. Future studies are required to explore the sites from these climatic regions.

Past studies have revealed that various morphologies such as vegetated areas, waterfronts, urban squares, and street canyons impact significantly the thermal sensation level of the user. Studies rarely discussed the material characteristics of these entities and their thermal behavior. Each morphological entity can have a varying effect on the thermal comfort level within that urban area. For this reason, future studies are required to estimate the effect of each entity and their contribution to the thermal comfort level.

LCZ is a comprehensive climate-based classification of urban and rural sites for temperature studies Stewart and Oke [67]. In this review, studies [8,9] used LCZ classification to differentiate 23 sites. Studies [173,102] from other parts of the world also used LCZ for differentiating various urban neighborhoods. Past studies revealed that the LCZ classification can be applied to have a comparative idea of various urban neighborhoods, but its application within the same neighborhood (at the micro-scale) is not justified.

Besides climatic zones and type of built environment, future studies should also consider the cultural and ethnic background of the users. More technically, it can be explained in terms of their activity level, and their clothing value which can affect the thermal perception level.

Studies followed almost similar methods to conduct the on-site micrometeorological measurements. The weather station used by the studies usually carries measuring instruments with a data logger which gives the measurement of climatic parameters such as T_a, R_h, and V_a. Some studies also used a black globe thermometer to measure T_g, so that the T_{mrt} can be calculated. Studies placed these instruments at measuring heights of 1.1 m to 1.5 m. In rare cases, heights were significantly changed due to site-specific challenges. Studies often took measurements at multiple locations at the same time; in that case, they required multiple instruments and volunteers who can operate these instruments. To overcome these problems researchers have looked into the development of miniature weather stations which can be worn by users [174–176] or can be placed on the top of vehicles [177,178] so that a single set-up of measuring instruments can capture the measurements at multiple locations within short time difference which will also improve the accuracy of measurements when two or more locations are compared.

Currently, a quantitative approach is being followed by studies for the evaluation of subjective as well as objective responses to thermal comfort. An on-site survey with a questionnaire is the common practice for subjective thermal comfort; these questions are based on the thermal comfort scales suggested by various standards. The scales varied from two points to nine points. The questionnaire responses can be subjective due to several reasons such as the interpretation of the question by the respondent. Also, in most of the cases, it is observed that the responses ranged between two to three points on the scale (Fig. 2). The subjective variation of thermal comfort is difficult to observe under such responses. The qualitative approach to the survey can help improve the understanding of subjective thermal comfort. Earlier studies have suggested qualitative methods such as photographic comparison [179] and thermal walk [180]. Employing qualitative and quantitative approaches together can improve the outcome of subjective thermal comfort.

The need for standardization of thermal indices was suggested by various studies [88,24]. Candido et al. [181] suggested a Brazilian Standard on Thermal Comfort. For Mediterranean climates, the MOCI index (Mediterranean Outdoor Comfort Index) was proposed by Golasi et al. [182]. Currently, there are no such standards in Indian climatic zones. Indian studies have been following universal standards for all the parameters related to thermal comfort. The applicability of those parameters in the Indian context is not proven by any study. Also, the universal standards for the Indian subcontinent may not be applicable, since various climatic regions have their climatic characteristics and the response from the local population in terms of clothing and adaptation. Hence, there is a huge potential to develop local thermal comfort standards for the outdoor environment. These standards will act as a benchmark for future thermal comfort and related studies.

5. Conclusion

This study presented a critical review of outdoor thermal comfort within urban areas of India. The focus on Indian studies derived from the change in the built morphology caused due to population growth in Indian cities, rapid urbanization, and the decline of outdoor space use. The selected papers for the review resulted broadly from two stages. In the first stage, major databases were searched based on various keywords, the resulting papers were further then filtered to finally achieve 18 valid papers from India that are published in the past 10 years. The foremost thing observed from the search process is that the outdoor thermal comfort research in the Indian context is limited to certain cities and climatic regions whereas there is still a huge part of India that is unexplored.

Built environments were represented with various geometrical parameters such as SVF, H/W, and orientation; some studies even used LCZ classification. Studies followed on-site campaigns for micrometeorological measurements to collect climatic parameters such as T_a, R_h, V_a, and T_g. To understand subjective thermal comfort levels and on-site, questionnaires were also collected by some studies. Amongst various parameters, the thermal sensation was the most commonly evaluated parameter. These parameters were evaluated based on various scales ranging from two-point to nine-point. Thermal comfort indices T_{mrt} and PET have commonly evaluated indices whereas UTCI, DI, THI, and SET are also evaluated by some studies. RayMan and ENVI-met are the commonly used software that was used to estimate the thermal parameters which were not obtained from on-site micrometeorological measurements. Most of the studies estimated the thermal neutral values along with the neutral range whereas some studies focused on the effect of physical and climatic parameters on thermal comfort level. The studies used various data analysis methods out of which linear regression was used for validation, identifying thermal neutrality, and it was also used to identify the relationship between two parameters. A correlation method was also commonly used. Studies rarely discussed the topics such as acclimatization and adaptation.

The review also highlights the gaps and limitations in the current research and highlights the future scope. First, and most importantly, the climatic zones and cities which are not yet studied; second, the improvement in the approaches of the study such as qualitative understanding, focus on the personal parameters, the consideration of acclimatization and adaptation during the study; lastly, the possibility of developing the local thermal comfort index.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] S. Manavvi, E. Rajasekar, Evaluating outdoor thermal comfort in urban open spaces in a humid subtropical climate: Chandigarh, India, Build. Environ. 209 (2022) 108659.
[2] S. Manavvi, E. Rajasekar, Evaluating outdoor thermal comfort in “haats” – the open air markets in a humid subtropical region, Build. Environ. 190 (2021).
[3] P. Kumar, A. Sharma, Assessing outdoor thermal comfort conditions at an urban park during summer in the hot semi-arid region of India, in: Materials Today: Proceedings, 2021.
[4] P. Kumar, A. Sharma, Assessing the thermal comfort conditions in open spaces: a transversal field survey on the university campus in India, Int. J. Built Environ. Sustain. 8 (2021) 77–92.
[5] P. Mohammad, S. Aghlmand, A. Fadaei, S. Gachkar, D. Gachkar, A. Karimi, Evaluating the role of the albedo of material and vegetation scenarios along the urban street canyon for improving pedestrian thermal comfort outdoors, Urban Clim. 40 (2021) 100993.
[6] E.H.S. Rajan, L.R. Amirtham, Impact of building regulations on the perceived outdoor thermal comfort in the mixed-use neighbourhood of Chennai, Front. Archit. Res. 10 (2021) 148–163.
[7] E.H.S. Rajan, L.R. Amirtham, Urban heat island intensity and evaluation of outdoor thermal comfort in Chennai, India, Environ. Dev. Sustain. 23 (2021) 16304–16324.
[8] M. Das, A. Das, Exploring the pattern of outdoor thermal comfort (OTC) in a tropical planning region of eastern India during summer, Urban Clim. 34 (2020) 100708.
[9] M. Das, A. Das, S. Mandal, Outdoor thermal comfort in different settings of a tropical planning region: A study on Sriniketan-Santiniketan Planning Area (SSPA), Eastern India, Sustain. Cities Soc. 63 (2020) 102433.
[10] S. Banerjee, A. Middel, S. Chattopadhyay, Outdoor thermal comfort in various microentrepreneurial settings in hot humid tropical Kolkata: human biometeorological assessment of objective and subjective parameters, Sci. Total Environ. 721 (2020) 137741.
[11] B. Deevi, F.A. Chundeli, Quantitative outdoor thermal comfort assessment of street: a case in a warm and humid climate of India, Urban Clim. 34 (2020) 1–10.
[12] S. Manavvi, E. Rajasekar, Semantics of outdoor thermal comfort in religious squares of composite climate, New Delhi, India, Int. J. Biometeorol. 64 (2019) 253–264.
[13] S. Ziaul, S. Pal, Assessing outdoor thermal comfort of English Bazar municipality and its surrounding, West Bengal, India, Adv. Space Res. 64 (2019) 567–580.
[14] S.B. Ali, S. Patnaik, Thermal comfort in urban open spaces: objective assessment and subjective perception study in tropical city of Bhopal, India, Urban Clim. 24 (2017) 954–967.
[15] D. Bhaskar, M. Mukherjee, Optimizing street canyon orientation for Rajarhat Newtown, Kolkata, India, Environ. Clim. Technol. 21 (2017) 5–17.
[16] E. Horrison, L.R. Amirtham, Role of built environment on factors affecting outdoor thermal comfort - A case of T, Nagar, Chennai, India, Indian J. Sci. Technol. 9 (2016) 3–6.
[17] L.R. Amirtham, E. Horrison, S. Rajkumar, L. Rose, Impact of urban morphology on microclimatic conditions and outdoor thermal comfort – a study in mixed residential neighbourhood of chennai, India, in: ICUC9 - 9th International Conference on Urban Climate Jointly with 12th Symposium on the Urban Environment, 2015.
[18] L.R. Amirtham, E. Horrison, S. Rajkumar, Study on the microclimatic conditions and thermal comfort in an institutional campus in hot humid climate, in: 30th International PLEA Conference: Sustainable Habitat for Developing Societies: Choosing the Way Forward - Proceedings 2, 2014, pp. 361–368.
[19] UNFPA, The state of the world population 2007: unleashing the potential of urban growth, in: United Nations Population Fund, United Nations Publications, vol. 1, 2007, pp. 1–108.
[20] UN-HABITAT, State of the World’s Cites 2012/2013, United Nations Human Settlements Programme, United Nations Human Settlements Programme (UN-HABITAT), 2012, pp. 1–152.
[21] Census, Provisional Population Totals, India, 2011.
[22] D. Bhaskar, M. Mukherjee, Urban physics for tomorrow’s, Urban Des. (2017) 1028–1037.
[23] T. Oke, The distinction between canopy and boundary-layer urban heat islands, Atmosphere 14 (1976) 268–277.
[24] I. Golasi, F. Salata, E. de Lieto Vollaro, M. Coppi, Complying with the demand of standardization in outdoor thermal comfort: a first approach to the Global Outdoor Comfort Index (GOCI), Build. Environ. 130 (2018) 104–119.

[25] Shahfahad, B. Kumari, M. Tayyab, H.T. Hang, M.F. Khan, A. Rahman, Assessment of public open spaces (POS) and landscape quality based on per capita POS index in Delhi, India, SN Appl. Sci. 1 (2019).

[26] D. Lai, Z. Lian, W. Liu, C. Guo, W. Liu, K. Liu, Q. Chen, A comprehensive review of thermal comfort studies in urban open spaces, Sci. Total Environ. 742 (2020) 140092.

[27] D. Lai, C. Zhou, J. Huang, Y. Jiang, Z. Long, Q. Chen, Outdoor space quality: a field study in an urban residential community in central China, Energy Build. 68 (2014) 713–720.

[28] G. Lin, S.P. Low, Influential criteria for building adaptation potential from the perspective of decision makers, in: 48th ASC Annual International Conference Proceedings, 2012.

[29] H. Woolley, Urban open spaces, Taylor and Francis (2003), https://doi.org/10.4324/9780203402146, https://www.taylorfrancis.com/books/9781135802295.

[30] R.F. Rupp, N.G. Vásquez, R. Lamberts, A review of human thermal comfort in the built environment, Energy Build. 105 (2015) 178–205.

[31] W. Heldens, T. Esch, H. Taubenböck, Climate Change in Cities – Can Remote Sensing Help to Optimise Mitigation Strategies?, Proceedings REAL CORP (2012) 121–128.

[32] M.S. Wong, J.E. Nichol, Spatial variability of frontal area index and its relationship with urban heat island intensity, Int. J. Remote Sens. 34 (2013) 885–896.

[33] D. Taleb, B. Abu-Hijleh, Urban heat islands: potential effect of organic and structured urban configurations on temperature variations in Dubai, UAE, Renew. Energy 50 (2013) 747–762.

[34] R. Emmanuel, H.J. Fernando, Urban heat islands in humid and arid climates: role of urban form and thermal properties in Colombo, Sri Lanka and Phoenix, USA, Clim. Res. 34 (2007) 241–251.

[35] T. Sharmin, S. Kabir, M. Rahaman, A study of thermal comfort in outdoor urban spaces in respect to increasing building height in Dhaka, AIUB J. Sci. Eng. 11 (2012).

[36] A. Krishan, Habitat of two deserts in India: hot-dry desert of Jaisalmer (Rajasthan) and the cold-dry high altitude mountainous desert of Leh (Ladakh), Energy Build. 23 (1996) 217–229.

[37] J. Natanian, P. Kastner, T. Dogan, T. Auer, From energy performative to livable Mediterranean cities: an annual outdoor thermal comfort and energy balance cross-climatic typological study, Energy Build. 224 (2020) 110283.

[38] K. Villadiego, M.A. Velay-Dabat, Outdoor thermal comfort in a hot and humid climate of Colombia: a field study in Barranquilla, Build. Environ. 75 (2014) 142–152.

[39] K. Axarli, A. Chatzidimitriou, Redesigning urban open spaces based on bioclimatic criteria: two squares in Thessaloniki, in: Greece, Proceedings - 28th International PLEA Conference on Sustainable Architecture + Urban Design: Opportunities, Limits and Needs - Towards an Environmentally Responsible Architecture, PLEA 2012, 2012.

[40] G. Baghaeipoor, N. Nasrollahi, The effect of sky view factor on air temperature in high-rise urban residential environments, J. Daylighting 6 (2019) 42–51.

[41] F. Ali-Toudert, H. Mayer, Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate, Build. Environ. 41 (2006) 94–108.

[42] S. Ali, B. Li, Evaluating the impact of the morphological transformation of urban sites on the urban thermal microenvironment, Buildings 8 (2018) 1–20.

[43] O.M. Galal, D.J. Sailor, H. Mahmoud, The impact of urban form on outdoor thermal comfort in hot arid environments during daylight hours, case study, New Aswan, Build. Environ. 184 (2020) 107222.

[44] X. Xu, Y. Liu, W. Wang, N. Xu, K. Liu, G. Yu, Urban layout optimization based on genetic algorithm for microclimate performance in the cold region of China, Appl. Sci. (Switzerland) 9 (2019).

[45] S. Mirzabeigi, M. Razkenari, Design optimization of urban typologies: a framework for evaluating building energy performance and outdoor thermal comfort, Sustain. Cities Soc. 76 (2022) 103515.

[46] K. Setaih, N. Hamza, M.A. Mohammed, S. Dudek, T. Townshend, CFD modeling as a tool for assessing outdoor thermal comfort conditions in urban settings in hot arid climates, J. Inf. Tech. Constr. 19 (2014) 248–269.

[47] J. Allegrini, V. Dorer, J. Carmeliet, Influence of morphologies on the microclimate in urban neighbourhoods, J. Wind Eng. Ind. Aerodyn. 144 (2015) 108–117.

[48] L. Chen, J. Hang, M. Sandberg, L. Claesson, S. Di Sabatino, The influence of building packing densities on flow adjustment and city breathability in urban-like geometries, Proc. Eng. 198 (2017) 758–769.

[49] P. Kumar, A. Sharma, Study on importance, procedure, and scope of outdoor thermal comfort –a review, Sustain. Cities Soc. 61 (2020) 102297.

[50] M.H. Elnabawi, N. Hamza, Outdoor thermal comfort: coupling microclimatic parameters with subjective thermal assessment to design urban performative spaces, Buildings 10 (2020) 238.

[51] Y. Dzyuban, G.N.Y. Ching, S. Kang, A.J. Tan, S. Banerjee, P.J. Crank, W.T.L. Chow, Landscape and urban planning outdoor thermal comfort research in transient conditions: a narrative literature review, Landsc. Urban Plan. 226 (2022) 104496.

[52] S. Shooshtarian, C.K.C. Lam, I. Kenawy, Outdoor thermal comfort assessment: a review on thermal comfort research in Australia, Build. Environ. 177 (2020) 106917.

[53] J. Dunjic, Outdoor thermal comfort research in urban areas of central and southeast Europe: a review, Geogr. Pannon. 23 (2019) 359–373.

[54] C. Dissanayake, U.G.D. Weerasinghe, Urban microclimate and outdoor thermal comfort of public spaces in warm-humid cities: a comparative bibliometric mapping of the literature, Am. J. Clim. Change 10 (2021) 433–466.

[55] M.M. Baruti, E. Johansson, J. Åstrand, Review of studies on outdoor thermal comfort in warm humid climates: challenges of informal urban fabric, https://doi.org/10.1007/s00484-019-01757-3, 2019.

[56] R. Aghamolaei, M.M. Azizi, B. Aminzadeh, J. O'Donnell, A comprehensive review of outdoor thermal comfort in urban areas: effective parameters and approaches, Energy Environ. (2022).

[57] L.M. Monteiro, Review of numerical modelling of outdoor thermal comfort, in: World Sustainable Building Conference 2005, 2005, pp. 2252–2259.

[58] S. Kumar, Subject's thermal adaptation in different built environments: an analysis of updated metadata-base of thermal comfort data in India, J. Build. Eng. 46 (2022) 103844.

[59] Q. Zhao, Z. Lian, D. Lai, Thermal comfort models and their developments: a review, Energy Built Environ. 2 (2021) 21–33.

[60] M.E. Falagas, E.I. Pitsouni, G.A. Malietzis, G. Pappas, Comparison of PubMed, scopus, web of science, and Google scholar: strengths and weaknesses, FASEB J. 22 (2008) 338–342.

[61] B. Pradeep Kumar, B.N. Anusha, K. Raghu Babu, P. Padma Sree, Identification of climate change impact and thermal comfort zones in semi-arid regions of AP, India using LST and NDBI techniques, J. Clean. Prod. 407 (2023) 137175.

[62] N. Sudarsanam, D. Kannamma, Investigation of summertime thermal comfort at the residences of elderly people in the warm and humid climate of India, Energy Build. 291 (2023) 113151.

[63] P. Kumar, A. Sharma, Assessing the outdoor thermal comfort conditions of exercising people in the semi-arid region of India, Sustain. Cities Soc. 76 (2022) 103366.

[64] W. Koppen, The thermal zones of the Earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world, Meteorol. Z. 20 (2011) 351–360.

[65] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of the Koppen-Geiger climate classification updated, Meteorol. Z. 15 (2006) 259–263.

[66] Bureau of Indian Standards, National Building Code of India 2005, 2005.

[67] I.D. Stewart, T.R. Oke, Local climate zones for urban temperature studies, Bull. Am. Meteorol. Soc. 93 (2012) 1879–1900.

[68] N. Kaloustian, B. Bechtel, Local climatic zoning and urban heat island in Beirut, Proc. Eng. 169 (2016) 216–223.

[69] W. Feng, J. Liu, A literature survey of local climate zone classification: status, application, and prospect, Buildings 12 (2022).

[70] S.B. Jennings, N.D. Brown, D. Sheil, Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures, Forestry 72 (1999) 59–73.

[71] P. Littlefair, Daylight, sunlight and solar gain in the urban environment, Sol. Energy 70 (2001) 177–185.

[72] A. Matzarakis, O. Matuschek, Sky view factor as a parameter in applied climatology - rapid estimation by the SkyHelios model, Meteorol. Z. 20 (2011) 39–45.

[73] A. Matzarakis, F. Rutz, H. Mayer, Modelling radiation fluxes in simple and complex environments—application of the RayMan model, Int. J. Biometeorol. 51 (2007) 323–334.

[74] L. Chen, E. Ng, X. An, C. Ren, M. Lee, U. Wang, Z. He, Sky view factor analysis of street canyons and its implications for daytime intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: a GIS-based simulation approach, Int. J. Climatol. 32 (2012) 121–136.

[75] M. Dirksen, R. Ronda, N. Theeuwes, G. Pagani, Sky view factor calculations and its application in urban heat island studies, Urban Clim. 30 (2019) 100498.

[76] Y. Lin, Y. Jin, H. Jin, Field study on the microclimate of public spaces in traditional residential areas in a severe cold region of China, Int. J. Environ. Res. Public Health 16 (2019) 2986.

[77] H.M. Vernon, The measurement of radiant heat in relation to human comfort, J. Ind. Hyg. 14 (1932) 95–111.

[78] C.L. Tan, N.H. Wong, S.K. Jusuf, Outdoor mean radiant temperature estimation in the tropical urban environment, Build. Environ. 64 (2013) 118–129.

[79] A.V.M. Oliveira, A.M. Raimundo, A.R. Gaspar, D.A. Quintela, Globe temperature and its measurement: requirements and limitations, Ann. Work Expo. Health 63 (2019) 743–758.

[80] Z.-L. Li, F. Becker, Feasibility of land surface temperature and emissivity determination from AVHRR data, Remote Sens. Environ. 43 (1993) 67–85.

[81] H. Mannstein, Surface energy budget, surface temperature and thermal inertia, in: Remote Sensing Applications in Meteorology and Climatology, Springer Netherlands, Dordrecht, 1987, pp. 391–410, http://link.springer.com/10.1007/978-94-009-3881-6_21.

[82] ISO 7243, Ergonomics of the Thermal Environment — Assessment of Heat Stress Using the WBGT (Wet Bulb Globe Temperature) Index, International Standard Organization, Geneva, 2017.

[83] H. Mayer, P. Hoppe, Thermal comfort of man in different urban environments, Theor. Appl. Climatol. 38 (1987) 43–49.

[84] S. Thorsson, T. Honjo, F. Lindberg, I. Eliasson, E.M. Lim, Thermal comfort and outdoor activity in Japanese urban public places, Environ. Behav. (2007).

[85] Z. Fang, Z. Lin, C.M. Mak, J. Niu, K.-T. Tse, Investigation into sensitivities of factors in outdoor thermal comfort indices, Build. Environ. 128 (2018) 129–142.

[86] E. Johansson, M.W. Yahia, I. Arroyo, C. Bengs, Outdoor thermal comfort in public space in warm-humid Guayaquil, Ecuador, Int. J. Biometeorol. 62 (2018) 387–399.
[87] ASHRAE-55, Thermal Environemental Condition for Human Occupancy, 2010.
[88] E. Johansson, S. Thorsson, R. Emmanuel, E. Krüger, Instruments and methods in outdoor thermal comfort studies - the need for standardization, Urban Clim. 10 (2014) 346–366.
[89] A. Matzarakis, H. Mayer, M.G. Iziomon, Applications of a universal thermal index: physiological equivalent temperature, Int. J. Biometeorol. 43 (1999) 76–84.
[90] M. Bruse, H. Fleer, Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model, Environ. Model. Softw. 13 (1998) 373–384.
[91] H. Lee, H. Mayer, L. Chen, Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, southwest Germany, Landsc. Urban Plan. 148 (2016) 37–50.
[92] S. Tsoka, A. Tsikaloudaki, T. Theodosiou, Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications–a review, Sustain. Cities Soc. 43 (2018) 55–76.
[93] P.J. Crank, D.J. Sailor, G. Ban-Weiss, M. Taleghani, Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies, Urban Clim. 26 (2018) 188–197.
[94] F. Salata, I. Golasi, R. de Lieto Vollaro, A. de Lieto Vollaro, Urban microclimate and outdoor thermal comfort. A proper procedure to fit ENVI-met simulation outputs to experimental data, Sustain. Cities Soc. 26 (2016) 318–343.
[95] A. Forouzandeh, Numerical modeling validation for the microclimate thermal condition of semi-closed courtyard spaces between buildings, Sustain. Cities Soc. 36 (2018) 327–345.
[96] C.J. Willmott, On the validation of models, Phys. Geogr. 2 (1981) 184–194.
[97] G. Jendritzky, R. de Dear, G. Havenith, UTCI—why another thermal index?, Int. J. Biometeorol. 56 (2012) 421–428.
[98] O. Potchter, P. Cohen, T.-P. Lin, A. Matzarakis, Outdoor human thermal perception in various climates: a comprehensive review of approaches, methods and quantification, Sci. Total Environ. 631–632 (2018) 390–406.
[99] P.R. Höppe, Heat balance modelling, Experientia 49 (1993) 741–746.
[100] P. Höppe, The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment, Int. J. Biometeorol. 43 (1999) 71–75.
[101] S. Thorsson, F. Lindberg, I. Eliasson, B. Holmer, Different methods for estimating the mean radiant temperature in an outdoor urban setting, Int. J. Climatol. 27 (2007) 1983–1993.
[102] N.G.R. Perera, W.M.S.B. Weerasekara, The Effect of Street Canyon Geometry on Outdoor Thermal Comfort in Colombo, in: International Conference on 'Cities, People and Places'- ICCPP-2014, 2014.
[103] Geneva, International Organization for Standardization, ISO 7726: Ergonomics of the thermal environment, instruments for measuring physical quantities, Technical Report, 1998.
[104] K. Błazejczyk, G. Jendritzky, P. Bröde, D. Fiala, G. Havenith, Y. Epstein, A. Psikuta, B. Kampmann, An introduction to the Universal Thermal Climate Index (UTCI), Geogr. Pol. 86 (2013) 5–10.
[105] D. Fiala, G. Havenith, P. Brode, B. Kampmann, G. Jendritzky, UTCI-Fiala multinode model of human heat transfer and temperature regulation, Int. J. Biometeorol. 56 (2012) 429–441.
[106] A. Psikuta, D. Fiala, G. Laschewski, G. Jendritzky, M. Richards, K. Błażejczyk, I. Mekjavič, H. Rintamäki, R. de Dear, G. Havenith, Validation of the Fiala multi-node thermophysiological model for UTCI application, Int. J. Biometeorol. 56 (2012) 443–460.
[107] N. Martínez, A. Psikuta, K. Kuklane, J.I.P. Quesada, R.M.C.O. de Anda, P.P. Soriano, R.S. Palmer, J.M. Corberán, R.M. Rossi, S. Annaheim, Validation of the thermophysiological model by Fiala for prediction of local skin temperatures, Int. J. Biometeorol. 60 (2016) 1969–1982.
[108] S. Park, S.E. Tuller, M. Jo, Application of Universal Thermal Climate Index (UTCI) for microclimatic analysis in urban thermal environments, Landsc. Urban Plan. 125 (2014) 146–155.
[109] K. Blazejczyk, Y. Epstein, G. Jendritzky, H. Staiger, B. Tinz, Comparison of UTCI to selected thermal indices, Int. J. Biometeorol. 56 (2012) 515–535.
[110] P. Brode, D. Fiala, K. Blazejczyk, Calculating UTCI equivalent temperature, 2009 1–5.
[111] E.C. Thom, The discomfort index, Weatherwise 12 (1959) 57–61.
[112] T.W. Schlatter, Temperature-humidity index, in: Climatology, Kluwer Academic Publishers, Dordrecht, 1987, pp. 837–838.
[113] O.M. Eludoyin, I.O. Adelekan, The physiologic climate of Nigeria, Int. J. Biometeorol. 57 (2013) 241–264.
[114] O.M. Eludoyin, A perspective of the diurnal aspect of thermal comfort in Nigeria, Atmos. Clim. Sci. 04 (2014) 696–709.
[115] A.P. Gagge, J.A.J. Stolwijk, Y. Nishi, An effective temperature scale based on a simple model of human physiological regularity response, in: Memoirs of the Faculty of Engineering, Hokkaido University, 1971, pp. 21–36.
[116] J. Pickup, R. de Dear, An Outdoor Thermal Comfort Index (Out-Set*) -Part I –the Model and Its Assumptions, in: 15th ICB and ICUC, 2000, pp. 1–7.
[117] C. Yaglou, D. Minard, Control of heat casualties at military training centers, A.M.A. archives of industrial health 16 (1957) 302–316.
[118] C.H. Lin, T.P. Lin, R.L. Hwang, Thermal comfort for urban parks in subtropics: understanding visitor's perceptions, behavior and attendance, Adv. Meteorol. 2013 (2013).
[119] W.T. Chow, S.N.A.B.A. Akbar, S.L. Heng, M. Roth, Assessment of measured and perceived microclimates within a tropical urban forest, Urban For. Urban Greening 16 (2016) 62–75.
[120] ISO 7933, Hot environments — Analytical determination and interpretation of thermal stress using calculation of required sweat rate, 1989.
[121] G.M. Budd, Wet-bulb globe temperature (WBGT)-its history and its limitations, J. Sci. Med. Sport 11 (2008) 20–32.
[122] N. weather service, Wet Bulb Globe Temperature Informational Guide, ????.
[123] P. Fagner, Thermal Comfort: Analysis and Applications in Environmental Engineering, McGraw-Hill, 1972.
[124] G. Jendritzky, W. Nübler, A model analysing the urban thermal environment in physiologically significant terms, Arch. Meteorol. Geophys. Bioklimatol. Ser. B 29 (1981) 313–326.
[125] A. Nutkiewicz, R.K. Jain, R. Bardhan, Energy modeling of urban informal settlement redevelopment: exploring design parameters for optimal thermal comfort in Dharavi, Mumbai, India, Appl. Energy 231 (2018) 433–445.
[126] R.C. Grifoni, G. Passerini, M. Pierantozzi, Assessment of outdoor thermal comfort and its relation to urban geometry, WIT Trans. Ecol. Environ. 173 (2013) 3–14.
[127] R. Yao, B. Li, J. Liu, A theoretical adaptive model of thermal comfort - adaptive Predicted Mean Vote (aPMV), Build. Environ. 44 (2009) 2089–2096.
[128] N. Nasrollahi, Y. Namazi, M. Taleghani, The effect of urban shading and canyon geometry on outdoor thermal comfort in hot climates: a case study of Ahvaz, Iran, Sustain. Cities Soc. 65 (2021) 102638.
[129] R.J. De Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE standard 55, Energy Build. 34 (2002) 549–561.
[130] ISO 2019, ISO 10551:2019 International Standard Ergonomics of the physical environment— Subjective judgement scales for assessing physical 2019, 2019, 1–28.
[131] N. Nazarian, J.K. Lee, Personal assessment of urban heat exposure: a systematic review, Environ. Res. Lett. 16 (2021) 033005.
[132] F. Aljawabra, M. Nikolopoulou, Influence of hot arid climate on the use of outdoor urban spaces and thermal comfort: do cultural and social backgrounds matter?, Intell. Build. Int. 2 (2010) 198–217.
[133] S. Oberoi, Updating income ranges for Kuppuswamys socio-economic status scale for the year 2014, Indian, J. Public Health 59 (2015) 156.
[134] S. Shooshtarian, I. Ridley, The effect of individual and social environments on the users thermal perceptions of educational urban precincts, Sustain. Cities Soc. 26 (2016) 119–133.
[135] C.K.C. Lam, M. Loughnan, N. Tapper, Visitors' perception of thermal comfort during extreme heat events at the royal botanic garden Melbourne, Int. J. Biometeorol. 62 (2018) 97–112.
[136] ASHRAE, ASHRAE Fundamentals Handbook 2001, American Society of Heating, Refrigerating, and Air-Conditioning Engineers SI Edition, 2001, 30.
[137] ASHRAE, ASHRAE 55:2004 Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 2004, p. 30.
[138] ASHRAE, ASHRAE Handbook: FUNDAMENTALS, American Society of Heating, Refrigerating, and Air-Conditioning Engineers SI Edition, 2013, p. 1134.
[139] M. Indraganti, R. Ooka, H.B. Rijal, Thermal comfort in offices in India: behavioral adaptation and the effect of age and gender, Energy Build. 103 (2015) 284–295.
[140] J. Nicol, I.A. Raja, A. Allaudin, G.N. Jamy, Climatic variations in comfortable temperatures: the Pakistan projects, Energy Build. 30 (1999) 261–279.
[141] A. Gagge, J. Stolwijk, J. Hardy, Comfort and thermal sensations and associated physiological responses at various ambient temperatures, Environ. Res. 1 (1967) 1–20.
[142] S. Shahzad, J. Brennan, D. Theodossopoulos, J.K. Calautit, B.R. Hughes, Does a neutral thermal sensation determine thermal comfort?, Build. Serv. Eng. Res. Technol. 39 (2018) 183–195.
[143] A. Auliciems, Towards a psycho-physiological model of thermal perception, Int. J. Biometeorol. 25 (1981) 109–122.
[144] S. Shooshtarian, P. Rajagopalan, Study of thermal satisfaction in an Australian educational precinct, Build. Environ. 123 (2017) 119–132.
[145] G. Brager, M. Fountain, C. Benton, E.A. Arens, F. Bauman, A Comparison of Methods for Assessing Thermal Sensation and Acceptability in the Field, Proceedings, Thermal Comfort: Past, Present and Future, 1993.
[146] S. Shooshtarian, Theoretical dimension of outdoor thermal comfort research, Sustain. Cities Soc. 47 (2019) 101495.
[147] Y. Zhang, R. Zhao, Relationship between thermal sensation and comfort in non-uniform and dynamic environments, Build. Environ. 44 (2009) 1386–1391.
[148] M. Schweiker, X. Fuchs, S. Becker, M. Shukuya, M. Dovjak, M. Hawighorst, J. Kolarik, Challenging the assumptions for thermal sensation scales, Build. Res. Inf. 45 (2017) 572–589.
[149] ISO, International Standard 7726, Thermal Environment-Instruments and Method for Measuring Physical Quantities., International Standard Organization, Geneva, 1995.
[150] R. de Dear, G. Schiller Brager, The adaptive model of thermal comfort and energy conservation in the built environment, Int. J. Biometeorol. 45 (2001) 100–108.

[151] T.P. Lin, Thermal perception, adaptation and attendance in a public square in hot and humid regions, Build. Environ. 44 (2009) 2017–2026.
[152] A. Middel, N. Selover, B. Hagen, N. Chhetri, Impact of shade on outdoor thermal comfort—a seasonal field study in tempe, Arizona, Int. J. Biometeorol. 60 (2016) 1849–1861.
[153] E.L. Kruger, C.A. Tamura, P. Bröde, M. Schweiker, A. Wagner, Short- and long-term acclimatization in outdoor spaces: exposure time, seasonal and heatwave adaptation effects, Build. Environ. 116 (2017) 17–29.
[154] B. Yang, T. Olofsson, G. Nair, A. Kabanshi, Outdoor thermal comfort under subarctic climate of North Sweden – a pilot study in Umeå, Sustain. Cities Soc. 28 (2017) 387–397.
[155] N. Kantor, L. Egerhazi, J. Unger, Subjective estimation of thermal environment in recreational urban spaces-part 1: investigations in Szeged, Hungary, Int. J. Biometeorol. 56 (2012) 1075–1088.
[156] M. Nikolopoulou, K. Steemers, Thermal comfort and psychological adaptation as a guide for designing urban spaces, Energy Build. 35 (2003) 95–101.
[157] M. Nikolopoulou, Urban open spaces and adaptation to climate change, in: Applied Urban Ecology, Wiley, 2011, pp. 106–122.
[158] E. Zabetian, R. Kheyroddin, Comparative evaluation of relationship between psychological adaptations in order to reach thermal comfort and sense of place in urban spaces, Urban Clim. 29 (2019) 100483.
[159] R.J. de Dear, G.S. Brager, Developing an adaptive model of thermal comfort and preference, ASHRAE Trans. 104 (1998) 145–167.
[160] R.A. Nasir, S.S. Ahmad, A.Z. Ahmed, Psychological adaptation of outdoor thermal comfort in shaded green spaces in Malaysia, Proc., Soc. Behav. Sci. 68 (2012) 865–878.
[161] N. Kantor, A. Kovacs, A. Takacs, Seasonal differences in the subjective assessment of outdoor thermal conditions and the impact of analysis techniques on the obtained results, Int. J. Biometeorol. 60 (2016) 1615–1635.
[162] S.Q.d.S. Hirashima, E.S. de Assis, M. Nikolopoulou, Daytime thermal comfort in urban spaces: a field study in Brazil, Build. Environ. 107 (2016) 245–253.
[163] J. Spagnolo, R. de Dear, A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia, Build. Environ. 38 (2003) 721–738.
[164] T.P. Lin, Y.C. Chen, A. Matzarakis, Urban thermal stress climatic mapping: combination of long-term climate data and thermal stress risk evaluation, Sustain. Cities Soc. 34 (2017) 12–21.
[165] Y. Lin, Y. Jia, G. Alva, G. Fang, Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage, https://doi.org/10.1016/j.rser.2017.10.002, 2018.
[166] A. Matzarakis, H. Mayer, Another kind of environmental stress: thermal stress, WHO Newsl. 18 (1996) 7–10.
[167] P. Cohen, O. Potchter, A. Matzarakis, Human thermal perception of coastal Mediterranean outdoor urban environments, Appl. Geogr. 37 (2013) 1–10.
[168] M.H. Elnabawi, N. Hamza, S. Dudek, Thermal perception of outdoor urban spaces in the hot arid region of Cairo, Egypt, Sustain. Cities Soc. 22 (2016) 136–145.
[169] SPSS, SPSS base 20.0 for Windows user's guide, 2011.
[170] L. Stanberry, Analysis of Variance, Encyclopedia of Systems Biology, Springer New York, New York, NY, 2013, pp. 24–25.
[171] W. Haynes, Tukey's HSD Test, in: Encyclopedia of Systems Biology, Springer New York, New York, NY, 2013, pp. 2303–2304.
[172] H.B. Mann, D.R. Whitney, On a test of whether one of two random variables is stochastically larger than the other, Ann. Math. Stat. 18 (1947) 50–60.
[173] L. Liu, Y. Lin, Y. Xiao, P. Xue, L. Shi, X. Chen, J. Liu, Quantitative effects of urban spatial characteristics on outdoor thermal comfort based on the LCZ scheme, Build. Environ. 143 (2018) 443–460.
[174] M. Nakayoshi, M. Kanda, R. Shi, R. de Dear, Outdoor thermal physiology along human pathways: a study using a wearable measurement system, Int. J. Biometeorol. 59 (2015) 503–515.
[175] A. Chokhachian, D. Santucci, T. Auer, A human-centered approach to enhance urban resilience, implications and application to improve outdoor comfort in dense urban spaces, Buildings 7 (2017) 113.
[176] I. Pigliautile, A.L. Pisello, A new wearable monitoring system for investigating pedestrians' environmental conditions: development of the experimental tool and start-up findings, Sci. Total Environ. 630 (2018) 690–706.
[177] N. Rajkovich, L. Larsen, A bicycle-based field measurement system for the study of thermal exposure in cuyahoga county, Ohio, USA, Int. J. Environ. Res. Public Health 13 (2016) 159.
[178] G.A. OBrien, N.A. Ross, I.B. Strachan, The heat penalty of walkable neighbourhoods, Int. J. Biometeorol. 63 (2019) 429–433.
[179] J. Cortesao, F. Brandao Alves, K. Raaphorst, Photographic comparison: a method for qualitative outdoor thermal perception surveys, Int. J. Biometeorol. 64 (2020) 173–185.
[180] C. Vasilikou, M. Nikolopoulou, Outdoor thermal comfort for pedestrians in movement: thermal walks in complex urban morphology, Int. J. Biometeorol. 64 (2020) 277–291.
[181] C. Candido, R. Lamberts, R. de Dear, L. Bittencourt, R. de Vecchi, Towards a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability, Build. Res. Inf. 39 (2011) 145–153.
[182] I. Golasi, F. Salata, E. de Lieto Vollaro, M. Coppi, A. de Lieto Vollaro, Thermal perception in the Mediterranean area: comparing the Mediterranean outdoor comfort index (moci) to other outdoor thermal comfort indices, Energies 9 (2016) 550.