# Indian Studies on Outdoor Thermal Comfort: A Review

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| Received | Reviewed | Revised | Published |
|---|---|---|---|
| 21.09.2023 | 18.10.2023 | 24.10.2023 | 31.10.2023 |

https://doi.org/10.61275/ISVSej-2023-10-10-12

## Abstract

Climate change has a negative impact on outdoor livability. Particularly in metropolitan settings, a rise in temperature has an impact on human health and thermal comfort. As a result of urbanization, the temperature in Indian cities is rising at an alarming rate.

This paper intends to examine previous investigations into outdoor thermal comfort in Indian context. 35 papers are evaluated to provide a summary of the prior research and to look at the necessity and potential of outdoor thermal comfort studies in Indian cities. This review also emphasizes the procedures, data collection techniques, and software used.

The paper examines research gaps, suggestions, and the potential scope of future research while highlighting the necessity of studies on outdoor thermal comfort. Future research is especially needed to encompass a variety of geographic regions, climatic zones, and other outdoor areas that have not been taken into account in previous studies. Furthermore, tourism purpose studies are lacking in the Indian context. For a better knowledge of the perceived thermal environment, it is also advised to combine quantitative and qualitative investigation.

The results of this study can be used by urban planners and designers to improve the outdoor thermal environment. This study can also help researchers determine the scope of additional research on outdoor thermal comfort in the context of India.

**Keywords:** Heat stress, Outdoor thermal comfort, Outdoor thermal comfort indices, Thermal perception, India.

## Introduction

Climate and weather conditions affect the health and well-being of humans. It is predicted by climate scientists that the average temperature could be 1.1 to 5.4°C warmer in 2100 (Geneva, 2023). These have a negative effect on the livability of the outdoor environment. Outdoor spaces are important because they accommodate various outdoor activities, and pedestrian traffic which contributes to urban livability. Due to this temperature rise, people prefer to stay indoors which is not healthy for the occupants. To combat this heat stress people, prefer air-conditioned spaces for thermal comfort, which in turn significantly increases energy consumption. As a result, planners and designers must conduct further research to enhance the thermal environment of outdoor spaces, as this is one of the factors affecting the quality of the outdoor environment (Nikolopoulou, Baker and Steemers, 2001). Improving thermal conditions in outdoor spaces can attract more people to use the outdoor spaces. Thermally comfortable outdoor spaces will encourage the active involvement of people in various outdoor activities. For instance research proves that engaging children in outdoor activities can impact child's growth and development (Joyce, Chundeli and Vijayalaxmi, 2023). Therefore, researchers must evaluate various outdoor areas and create a comfortable thermal environment. "Thermal Comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ASHRAE-55, 2017). The built environment influences outdoor thermal comfort (Nikolopoulou, Baker and Steemers, 2001), and improving the social, physical, and environmental settings of the open space can make the space more livable and vital outdoor space (Aghamolaei *et al.*, 2022). To conduct studies on indoor thermal comfort, steady-state heat balance theory models and adaptive models were first created and employed. In outdoor areas, several factors can affect the level of thermal comfort (Aghamolaei *et al.*, 2022). Recently outdoor thermal comfort studies have gained popularity as there is a lack of studies about climate-related problems that affect OTC as well as human health (Buchin *et al.*, 2016).

India is a developing country and due to rapid urbanization, urban built forms in megacities are changing according to urban demand. There are temperature differences in urban and rural areas of 4.5 °C and 2.5 °C in winter and summer. This is due to a decrease in green spaces and pervious surfaces in urban locations, thermal storage in various building materials, and additional factors including canyon shapes and the effects of the sky view (Rajan and Amirtham, 2021). There are several urban landscape strategies which can mitigate urban heat island effect. Studies can be done to analyze these effects (Bhat, 2022). According to a study by CSE, temperature rise in most of India is an alarming issue but has largely been ignored. There is a lack of policy preparedness for mitigating rising heat on the issue addressed in SDG 13 under climate action (Anumita, 2022). As stated by many researchers, different outdoor spaces have not yet been studied in the Indian context (Ali and Patnaik, 2018; Manavvi and Rajasekar, 2020). However, studies on outdoor thermal comfort are becoming more popular now.

Heat waves are some of the natural disasters that impact on human health. Evidence shows that the number of human deaths is more due to exposure to heatwaves than any other climatological disaster (Murari and Ghosh, 2019). In India, heatwaves generally occur in the summer months from March to June. In plains, coastal areas, and hilly areas during heatwave days, the temperatures rise upto 40°C, 35°C, and 30°C, respectively (India Meteorological Department, no date). A large part of India reports high temperatures from early March. According to IMD data, a 34% rise in deaths was recorded due to heat waves between 2003-2012 and 2013-2022. The 1998 heatwave is worth mentioning. Heat wave days in India concerning the number of deaths, particularly in New Delhi and Odisha (Murari and Ghosh, 2019). Various studies show that the places that have already experienced heatwaves will face them in greater intensity soon and the places that are not familiar with heat waves will also face heatwaves. In a developing country like India, a large number of people work outdoors and are vulnerable to heat waves (Murari *et al.*, 2015; Murari and Ghosh, 2019).

In this context, this paper review outdoor thermal comfort research in the Indian context. is Its aim is to ascertain the scale and spread of outdoor thermal comfort studies conducted in Indian cities.

The objectives of the research are:

1. To evaluate the existing literature from 2013 to 2023.
2. To review the procedures used to acquire data and analyze it.
3. To study the software and thermal comfort indices that have been applied.

This paper also provides information on the bibliographic analysis of the reviewed articles, the spread of OTC studies in India, sample size and target populations, research gaps, and future scopes. This review can extend our understanding of different outdoor spaces in India and users' need for improving the thermal environment.

## Theoretical Framework

### Thermal comfort

The International Organization for Standardization (ISO) has published several international regulations for the assessment of thermal comfort. Thermal comfort is defined as the mental state that conveys contentment with the immediate surroundings, emphasizing that comfort is a physiological and psychological condition (International Standards Organization ISO 7730 (2005) (Olesen, 1995). The International Organization for Standardization (ISO) has published a number of worldwide regulations for the assessment of thermal comfort (ISO 10551, 1995; ISO 7726, 1998; ISO 8996, 2004; ISO 7730, 2005; ISO 9920, 2007) (Johansson *et al.*, 2014).

Apart from ISO, ASHRAE 55 specifies methods for calculating and evaluating thermal comfort (ASHRAE-55, 2017). However, they are mostly intended for indoor settings. Several authors states that the theoretical frameworks created to describe thermoregulation processes in the interior environment are insufficient to include the thermal comfort conditions in the outside environment (Nikolopoulou and Lykoudis, 2006; Shooshtarian, 2019). This is mostly due to the outdoor environment's higher complexity and its temporal and spatial variability (Nikolopoulou and Lykoudis, 2006). Thus, the need for empirical data from field surveys on subjective human perceptions of outdoor wellness is acknowledged, which should allow for a more comprehensive and accurate assessment of thermal comfort in outdoor spaces (Nikolopoulou and Lykoudis, 2006).

Haldane (1905) suggested that wet bulb temperature is the most suitable expression of heat stress (Haldane, 1905; Epstein and Moran, 2006). Since then, a set of thermal indices has been established, based mostly on the interaction of environmental elements. Other personal factors, such as human activity and clothing level, were included later. Table 1, summarizes the main thermal comfort indexes.

**Table 1:** Nomenclature of the main thermal comfort indexes
Source: Authors

| Abbreviation | Indexes |
|---|---|
| COMFA | Comfort Formula |
| ETU | Universal Effective Temperature |
| PET | Physiological Equivalent Temperature |
| PMV | Predicted Mean Vote |
| PT | Perceived Temperature |
| OUTSET | Out. Stand. Eff. Temp. |
| SET | New Standard Effective Temperature |
| UTCI | Universal Thermal Climate Index |
| ASV | Actual Sensation Vote |
| TS | Thermal Sensation |
| TSV | Thermal Sensation Vote |
| AT | Apparent Temperature |
| DI | Discomfort Index |
| ESI | Environmental Stress Index |
| ET | Effective Temperature |
| WCI | Wind Chill Index |
| WBGT | Wet Bulb Globe Temperature Index |

## Research Methodology

The method for literature screening using used was the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Liberati *et al.*, 2009). This process often begins with discovering pertinent information using keywords, followed by categorization and a review of the most pertinent sources. The literature screening process includes five steps as follows (Fig 1).

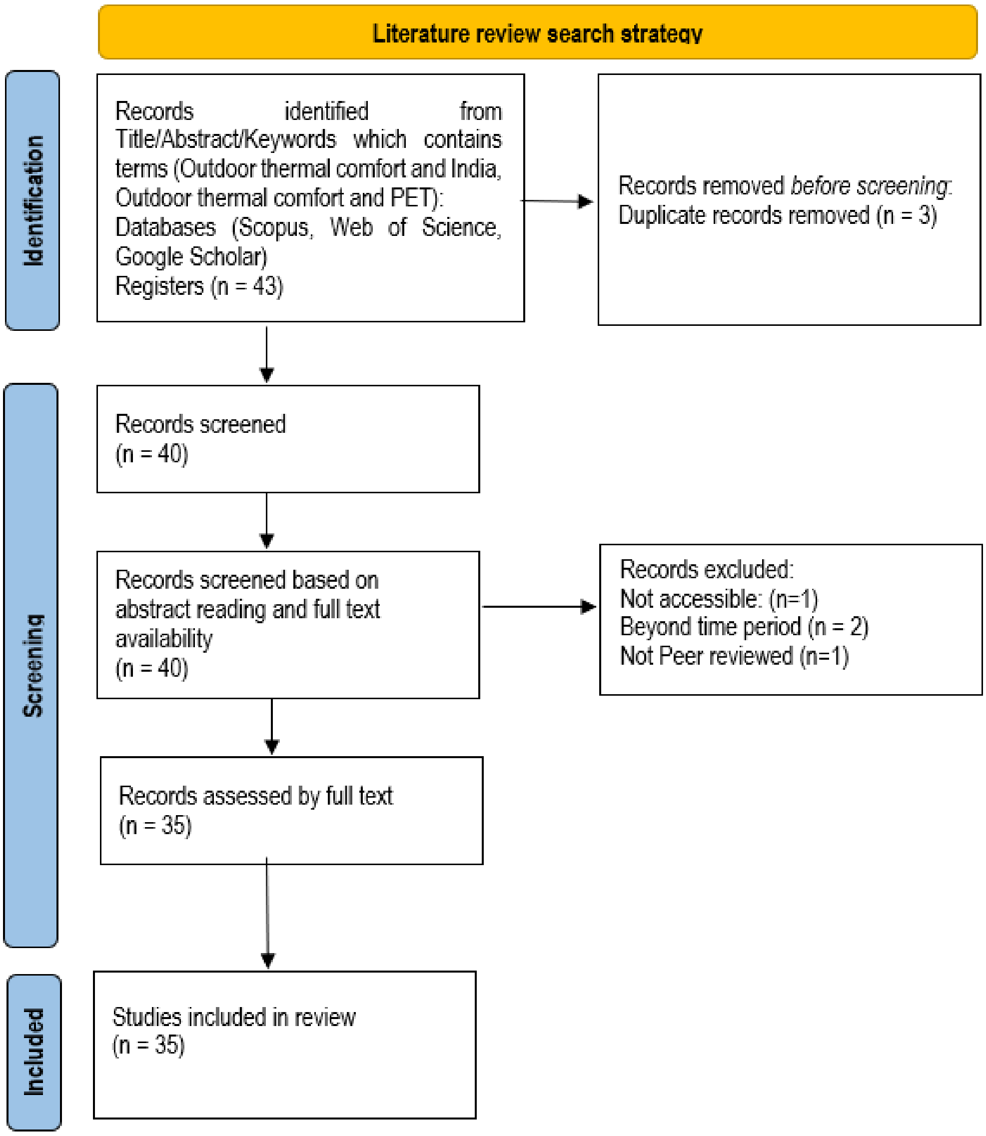


**Fig. 1:** Literature screening methodology using PRISMA framework
Source: Author

For this systematic review, major databases were used for desktop search like Scopus, Google scholar, Web of science, Sage, and Willy online library. Following keywords were used: outdoor thermal comfort, thermal perceptions, thermal sensation scale, outdoor thermal comfort indices, India. The search process yielded 43 research outputs which includes, journal articles, PhD thesis and conference papers. After removing duplicate records, 40 papers are accepted based on abstract reading, full text availability and journal details. After filtering these 40 papers, 5 articles were excluded based on full text not availability, limiting the time period from 2013-2023 and also excluding the non-peered reviewed papers. Finally, 35 articles were obtained for the review.

**Table 2:** List of papers with their categories
Source: Authors

| Sl No | Reference | Classification |
|---|---|---|
| 1 | (Horrison and Stephi, 2023) | Check the impact of different infrastructure on thermal comfort |
| 2 | (Manavvi and Rajasekar, 2023) | Understanding outdoor thermal comfort conditions |
| 3 | (Khaire *et al.*, 2023) | Heat mitigation strategies |
| 4 | (Pradeep Kumar *et al.*, 2023) | Understanding outdoor thermal comfort conditions |
| 5 | (Khaire, Madrigal and caLanzarote, 2023) | Heat mitigation strategies |
| 6 | (Kumar and Sharma, 2022c) | Understanding outdoor thermal comfort conditions |
| 7 | (Manavvi and Rajasekar, 2022) | Understanding outdoor thermal comfort conditions |
| 8 | (Kumar and Sharma, 2022b) | Understanding outdoor thermal comfort conditions |
| 9 | (Kumar and Sharma, 2022a) | Understanding outdoor thermal comfort conditions |
| 10 | (Prasad and Satyanarayana, 2022) | Understanding outdoor thermal comfort conditions |
| 11 | (Mohammad *et al.*, 2021) | Check the impact of different infrastructure on thermal comfort |
| 12 | (Kumar and Sharma, 2021) | Understanding outdoor thermal comfort conditions |
| 13 | (Manavvi and Rajasekar, 2021) | Understanding outdoor thermal comfort conditions |
| 14 | (Rajan and Amirtham, 2021) | Heat mitigation strategies |
| 15 | (Gopinath, no date) | Check the applicability of thermal comfort indices |
| 16 | (Raman, Kumar, Sharma, Froehlich, *et al.*, 2021) | Heat mitigation strategies |
| 17 | (Raman, Kumar, Sharma and Matzarakis, 2021) | Heat mitigation strategies |
| 18 | (Banerjee, Middel and Chattopadhyay, 2022) | Understanding outdoor thermal comfort conditions |
| 19 | (Salal Rajan and Amirtham, 2021) | Heat mitigation strategies |
| 20 | (Deevi and Chundeli, 2020) | Understanding outdoor thermal comfort conditions |
| 21 | (Das and Das, 2020) | Understanding outdoor thermal comfort conditions |
| 22 | (Das, Das and Mandal, 2020) | Understanding outdoor thermal comfort conditions |
| 23 | (Rahul, Mukherjee and Sood, 2020) | Check the impact of different infrastructure on thermal comfort |
| 24 | (Banerjee, Middel and Chattopadhyay, 2020) | Understanding outdoor thermal comfort conditions |
| 25 | (Kotharkar, Bagade and Agrawal, 2019) | Understanding outdoor thermal comfort conditions |
| 26 | (Gajjar and Jai Devi, 2019) | Check the impact of different infrastructure on thermal comfort |
| 27 | (Ziaul and Pal, 2019) | Understanding outdoor thermal comfort conditions |
| 28 | (Manavvi and Rajasekar, 2020) | Understanding outdoor thermal comfort conditions |
| 29 | (Ali and Patnaik, 2018) | Understanding outdoor thermal comfort conditions |
| 30 | (De and Mukherjee, 2018) | Heat mitigation strategies |
| 31 | (Bhaskar and Mukherjee, 2017) | Heat mitigation strategies |
| 32 | (Horrison and Amirtham, 2016) | Heat mitigation strategies |
| 33 | (Das, 2016) | Heat mitigation strategies |
| 34 | (De and Mukherjee, 2016) | Heat mitigation strategies |
| 35 | (Amirtham L.R., 2014) | Understanding outdoor thermal comfort conditions |

## Findings and Discussion

### Geographical Patterns

A total of 35 studies which are based on outdoor thermal comfort in Indian context, are selected for this review. Fig.2 and 3 show the distribution of OTC studies in various states and union territories of India. Among these, studies are focused mostly in metropolitan cities of West Bengal, New Delhi, Haryana and Tamil Nadu. Most of the studies are done in Rajarhat area, which is a planned city in eastern Kolkata. Cities which are facing severe heat stress in summer are mainly studied in India. Outdoor spaces like urban squares, urban parks in cities like New Delhi, Chandigarh are studied, which experiences good footfall.

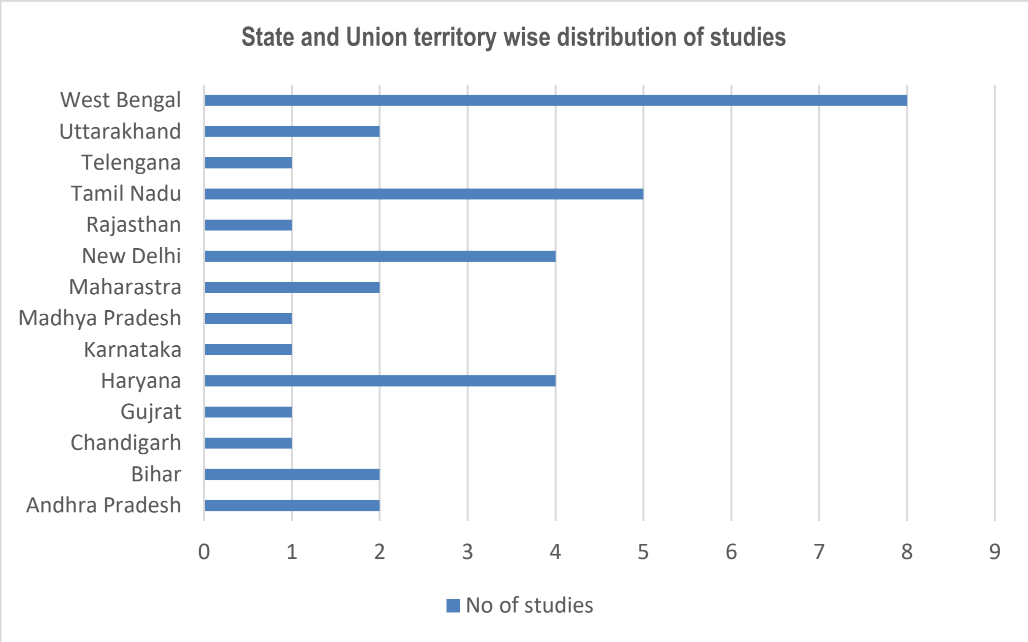


**Fig. 2:** State and Union territory wise distribution of studies
Source: Authors

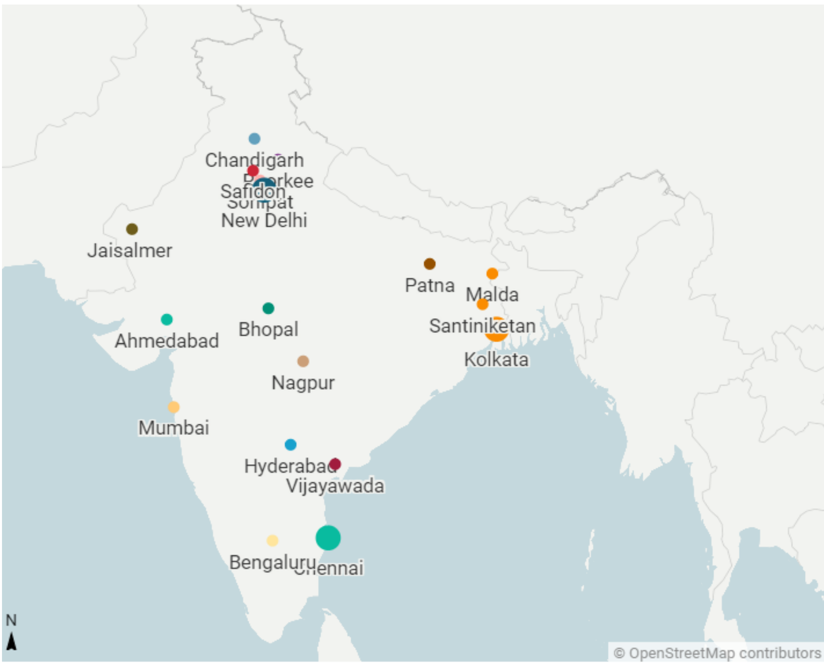


**Fig. 3:** locations of OTC studies in India
Source: Authors

**Spread of Outdoor Thermal Comfort studies in India**

The number of OTC studies in India increased 100% from 2019 to 2023. In this last 5 years, (Fig. 4) there is an increase in interest in OTC studies in India. From the reviewed research papers, 78% of the studies have been done from 2019 to 2023.

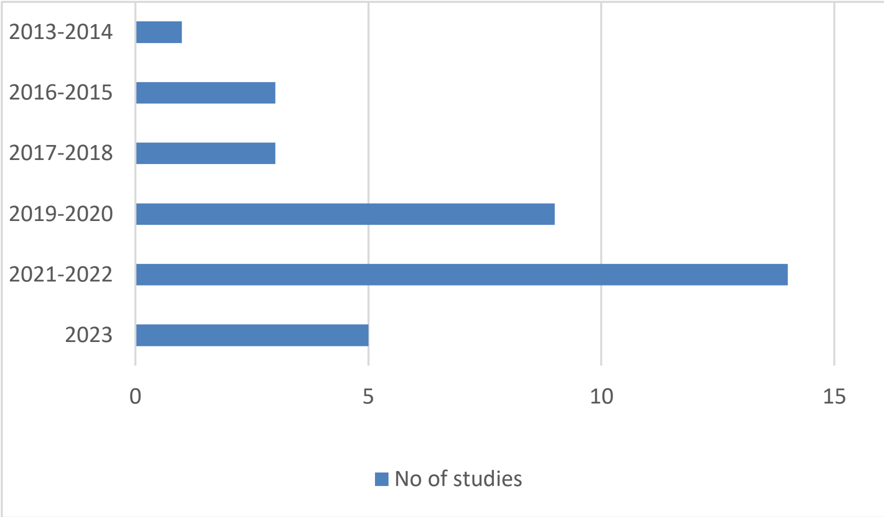


**Fig. 4:** Year wise distribution of OTC studies in India from 2013-2023
Source: Authors

## Contributing Journals

The most published articles (Table 3) among the reviewed papers are published on Urban climate (n=4), followed by Sustainable cities and society (n=3), Building and environment (n=3), International Journal of Biometeorology (n=3), Materials Today and Proceedings (n=2) in second, third, fourth and fifth place respectively.

**Table 3:** Publication Journal ranking
Source: Authors

| Name of the journals | No of studies |
|---|---|
| Urban Climate | 5 |
| Sustainable Cities and Society | 3 |
| Building and Environment | 3 |
| International Journal of Biometeorology | 3 |
| Materials Today: Proceedings | 2 |

## Article Citation Frequency

The research article entitled "Impact of green cover on improving outdoor thermal comfort in urban residential clusters" by Ali and Patnaik (2017) is the most cited paper in this list of top 10 from the reviewed paper (76 as of July, 2023). (Table 4)

**Table 4:** Top 10 cited papers in literature search
Source: Authors

| Title | Cited By |
|---|---|
| Thermal comfort in urban open spaces: Objective assessment and subjective perception study in tropical city of Bhopal, India | **76** |
| Evaluating the role of the albedo of material and vegetation scenarios along the urban street canyon for improving pedestrian thermal comfort outdoors | **35** |

| | |
|---|---|
| Optimisation of canyon orientation and aspect ratio in warm-humid climate: Case of Rajarhat Newtown | **29** |
| Outdoor thermal comfort in various microentrepreneurial settings in hot humid tropical Kolkata: Human biometeorological assessment of objective and subjective parameters | **26** |
| Role of Built Environment on Factors Affecting Outdoor Thermal Comfort - A Case of T. Nagar, Chennai, India | **23** |
| Outdoor thermal comfort in different settings of a tropical planning region: A study on Sriniketan-Santiniketan Planning Area (SSPA), Eastern India | **22** |
| Evaluating outdoor thermal comfort in urban open spaces in a humid subtropical climate: Chandigarh, India | **22** |
| Assessing outdoor thermal comfort of English Bazar Municipality and its surrounding, West Bengal, India | **19** |
| Semantics of outdoor thermal comfort in religious squares of composite climate: New Delhi, India | **18** |
| Quantitative outdoor thermal comfort assessment of street: A case in a warm and humid climate of India | **17** |
| Investigating local climate zones for outdoor thermal comfort assessment in an Indian city | **17** |

**Outdoor Thermal Comfort Indices**

The indicators which evaluate the thermal condition of the surrounding environment are thermal comfort indices. The thermal comfort index is calculated on the collective effect of various meteorological variables and two personal parameters. Over a period of time, many thermal comfort indices were developed for indoor and outdoor study. Amongst these OTC indices, some are used in Indian studies which are summarized in Table no. 5. Thermal comfort indices which are mostly applied in reviewed papers from 2013-2023 in India are plotted and shown in Fig. 5. As it is evident from Fig. 5 PET and UTCI are the two most used thermal comfort indices used in India. Besides PET and UTCI, other thermal comfort indices that are used are THI, WBGT, DI, and PMV. Although PMV is not reliable in outdoor thermal comfort analysis it assumes steady-state conditions. Some earlier studies (Das, 2016; Ziaul and Pal, 2019) in West Bengal only used PMV. SET is another index whose validity is high, however, only one study (Das, Das and Mandal, 2020) has used SET. Recently, PET or UTCI has been mostly used as an outdoor thermal comfort index. Outdoor thermal comfort indices distribution according to the climate can be observed in Fig. 6. PET is predominantly used in tropical areas followed by dry areas while UTCI is used mostly in dry areas followed by tropical areas.

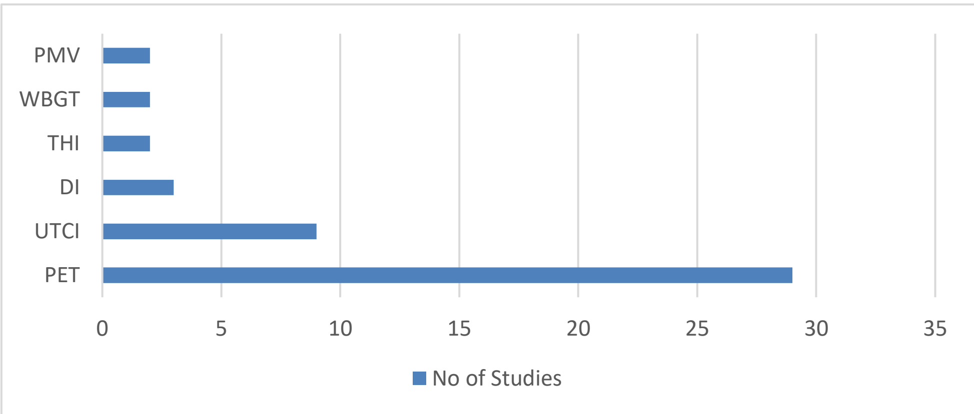


**Fig. 5:** Thermal comfort indices used in Indian studies from 2013-2023
Source: Authors

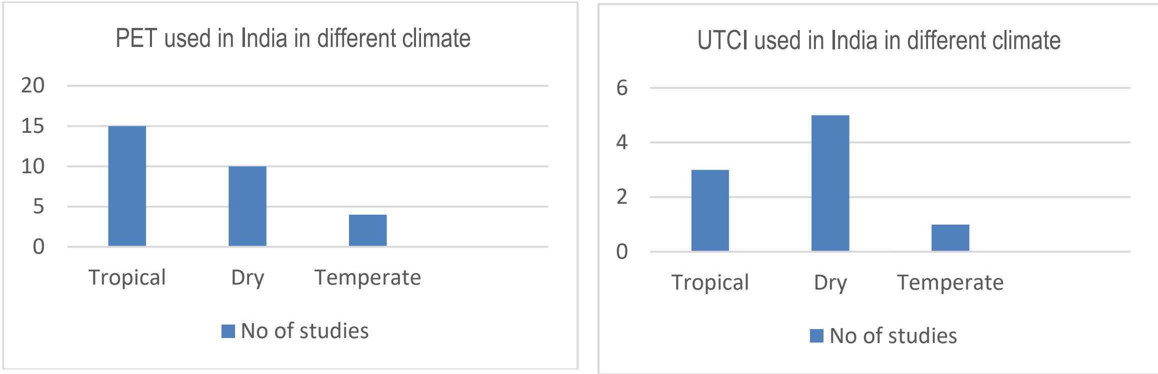


**Fig. 6:** PET and UTCI used in different climates
Source: Authors

**Table 5:** Thermal sensation of various thermal comfort indices
Source: Hoppe, 1999; Fiala et al., 2012; Toy and Yilmaz, 2010

| | PET (°C) | UTCI (°C) | WGBT (°C) | THI (°C) | PMV |
|---|---|---|---|---|---|
| **Frosty** | | <-27 | | -19.9--10 | |
| **Very Cold** | <4 | -27--13 | | -9.9—1.8 | <-3 |
| **Cold** | 4-8 | -13-0 | | -1.7-12.9 | -3--2 |
| **Cool** | 8-18 | 0-9 | | 13-14.9 | -2--1 |
| **Comfortable** | 18-23 | 9-26 | <18 | 15-19.9 | -1-1 |
| **Warm** | 23-35 | 26-32 | 18-24 | 20-26.4 | 1-2 |
| **Hot** | 35-41 | 32-48 | 24-28 | 26.5-29.9 | 2-3 |
| **Very Hot** | >41 | 38-46 | 28-30 | >30 | >3 |
| **Sweltering** | | >46 | >30 | | |

## Data Collection Methods

` Most of the Indian studies assessed thermal comfort, and the impact of urban heat island in different urban settings such as streets (Deevi and Chundeli, 2020), Open spaces (Kumar and Sharma, 2021), urban squares (Manavvi and Rajasekar, 2023) using PET and UTCI. These studies are done using microclimatic measurement and thermal comfort surveys. There are several studies in India, where thermal comfort is assessed by using only microclimatic measurement (Rahul, Mukherjee and Sood, 2020; Khaire, Madrigal and caLanzarote, 2023). Some studies that do not involve any microclimatic measurement and human subjects, where the extent of the study area is large like urban area these studies focus on heat stress risk and outdoor thermal stress on various morphological parameters in urban areas (Raman, Kumar, Sharma, Froehlich, *et al.*, 2021; Kumar and Sharma, 2022b).

## Questionnaire Surveys

Recently, studies are more focused on human based approaches. In this human- based OTC studies, questionnaires are used to collect data on human place relationship. These questionnaires can be equipped using ASHRAE standard 55 (ASHRAE-55, 2017) and ISO 10551. Generally, these questionnaires are grouped into three categories based on the research aim and focus of the study. First part of the questionnaire includes personal details like age, gender, weight, height, clothing, activity, time of exposure, status of residency etc. In the second part, questions are based on thermal perception like thermal sensation, overall comfort, thermal performance, thermal acceptance. Some of the studies, included thermal adaptive strategies.
In Table 6, a summary of the questions under each category is listed. Depending on the research aim and focus of the study, the structure of the questionnaire varies. However, some of the common parameters remain constant. In personal data, age, gender, clothing, activity level is

mostly analyzed by researchers in India. Most of the reviewed studies have used ASHRAE thermal sensational 7 point scale ('cold' (-3); 'cool' (-2); 'slightly cool' (-1); 'neutral' (0); 'slightly warm' (+1); 'warm' (+2), and 'hot' (+3)) (ASHRAE-55, 2017) except 3 studies that used thermal sensation 9 point scale (very cold; cold; cool; slightly cool, neutral; slightly warm; warm; hot; very hot) (Manavvi and Rajasekar, 2020, 2021, 2023). Ali and Patnaik, (2018) used a four point scale cold (−2), cool (−1), warm (+1), hot (+2) and Das and Das, (2020) used another 4 point scale (neutral (0); slightly warm (1); warm (2) and hot (3)). Out of these 4 scales of thermal sensation, ASHRAE 7 point and 9-point scale middle point is neutral, however, middle point is different in four-point scale.

Thermal preferences are recorded using 3-point McIntyre scale (5 studies) except two studies that used 5 point scale (Banerjee, Middel and Chattopadhyay, 2022; Banerjee, Middel and Chattopadhyay, 2020). Preference on microclimatic variables is recorded in some of the researches (5 studies). The most commonly requested variables are air temperature, wind speed, wind direction, relative humidity and solar radiation. In all the studies overall comfort level is recorded by three-point scale which is a very important parameter to record because whatever thermal sensation the user is feeling, they are comfortable or not should be recorded. 3 studies among the reviewed studies explored about thermal acceptability which is 2-point scale.

Some of the studies tried to explore user's choice of thermal adaptive strategies which includes, any change in clothing (Banerjee, Middel and Chattopadhyay, 2020), personal accessories, and behavioral changes. Studies like (Banerjee, Middel and Chattopadhyay, 2020; Manavvi and Rajasekar, 2020; 2021) have used questions about the choice of design attributes on 5 point Likert scale and measures to enhance overall thermal comfort and to reduce discomfort in summer.

**Table 6**: Structure of the questionnaires used in Indian studies
Source: Authors

| Reference | Personal details | Thermal perception scale | Thermal adaptive strategies | No of uestions |
|---|---|---|---|---|
| **(Manavvi and Rajasekar, 2023)** | Gender, age, Clothing, Education, purpose of visit, frequency of visit, activity level | **Thermal Sensation**<br>9-point scale<br>**Perception of individual climatic parameters**<br>5- point scale | | |
| **(Kumar and Sharma, 2022c)** | Gender, age, weight, and height, clothing, activity, heat symptoms | **Thermal Sensation**<br>ASHRAE 7-point<br>**Overall comfort** three-point scale | | 6 |
| **(S and Rajasekar, 2022)** | Gender, age, clothing, purpose and frequency of visit, time spent in the study area, activity level and residence time in the city | **Thermal Sensation**<br>9-point scale<br>**Perception of individual climatic parameters**<br>5- point scale<br>**Thermal acceptability**<br>2-point acceptability scale<br>**Thermal preference**<br>3-point McIntyre scale | | |
| **(Kumar and Sharma, 2022a)** | Height, weight, age gender, timing of the visit and activities, clothing | **Thermal Sensation**<br>ASHRAE 7-point<br>**Overall comfort** three-point scale | | |

| | | | |
|---|---|---|---|
| **(Mohammad *et al.*, 2021)** | Height, weight, gender and age | **Thermal Sensation** ASHRAE 7-point **Preference of individual climatic parameters** 3- point scale **Overall comfort** 7 -point scale | |
| **(Kumar and Sharma, 2021)** | Weight, height, age, gender, geographic data, clothing insulation and metabolic rate | **Thermal Sensation** ASHRAE 7-point **Overall comfort** three-point scale **Preference of individual climatic parameters** 3- point scale **Thermal preference** 3-point McIntyre scale | |
| **(Manavvi and Rajasekar, 2021)** | Gender, age, clothing, purpose and frequency of visit, time spent in the study area, activity level and residence time in the city | **Thermal Sensation** 9-point scale **Thermal acceptability** 2-point acceptability scale **Perception of individual climatic parameters** 5- point scale **Thermal preference** 3-point McIntyre scale | Question regarding the impact of design characteristics and related external stimuli on a **5-point Likert scale** |
| **(Banerjee, Middel and Chattopadhyay, 2022)** | Height, weight, gender, age, ethnicity, clothing, physiological status, duration of stay in the study area, exposure to fan/AC, beverage intake | **Thermal Sensation** ASHRAE 7-point **Overall Sensation** 7-point scale **Perception of individual climatic parameters** 7-point scale **Thermal preference** 5-point scale **Preference of individual climatic parameters** 5- point scale | |
| **(Deevi and Chundeli, 2020)** | Gender, residence time in the city, types of work (Activity) | **Thermal Sensation** ASHRAE 7-point **Overall comfort** three-point scale **Thermal preference** 3-point McIntyre scale | |
| **(Das, Das and Mandal, 2020)** | Gender, age, height, weight, last half hour activity and environment, exposure to AC/Fan, duration of stay in that location | **Perception of temperature and humidity** ASHRAE 7-point **Perception of wind and solar radiation** four-point ordinal scale | |
| **(Das and Das, 2020)** | NS | **Actual Thermal Sensation** four-point scale | |
| **(Banerjee, Middel and Chattopadhyay, 2020)** | Occupation, clothing, Activity | **Thermal Sensation** ASHRAE 7-point scale **Overall sensation** 7-point scale **Perception of individual climatic parameters** 7-point scale | Question about ways to improve overall thermal comfort and actions to |

| | | | | |
|---|---|---|---|---|
| | | **Thermal preference**<br>5-point scale<br>**Preference of individual climatic parameters**<br>5- point scale | reduce discomfort in the summer | |
| **(Ziaul and Pal, 2019)** | NS | **Thermal Sensation**<br>ASHRAE 7-point | | |
| **(Manavvi and Rajasekar, 2020)** | Age, Gender, height, and current clothing, purpose of visit, frequency of visit, time spent, residence time in the city, and activity level | **Thermal Sensation**<br>ASHRAE 7-point<br>**Perception of individual climatic parameters**<br>5- point scale<br>**Thermal acceptability**<br>2-point acceptability scale<br>**Thermal preference**<br>3-point McIntyre scale | Question regarding the impact of design characteristi cs and related external stimuli on a **5-point Likert scale** | 25 |
| **5(Ali and Patnaik, 2018)** | Gender, age, clothing, activity, education, occupation, and income | **Actual Thermal Sensation**<br>four-point scale<br>**Overall comfort**<br>4 -point scale<br>**Preference of individual climatic parameters**<br>5- point scale | | |

## Sample Sizes and Target Populations

Sample size determination is based on some factors like size of population, confidence level, type of study, sampling techniques, availability of time. In the reviewed studies, sample sizes varies from 55 respondents (Kumar and Sharma, 2022a)to 2523 respondents (Manavvi and Rajasekar, 2022). The majority of the research used basic random sampling, and sample sizes are frequently chosen based on literature support. Transverse sampling and other methods, such as online calculators, are also available to determine sample size. Ali and Patnaik, (2018) employed a random sample method from several different locations. However, in a study Banerjee, Middel and Chattopadhyay, used literature support for sample size determination. No of respondents are less in some studies because of the COVID situation as reported by Kumar and Sharma, 2022c.

In the reviewed studies, there are different outdoor space users considered which includes mainly public space users in squares (Manavvi and Rajasekar, 2020, 2023), parks (Kumar and Sharma, 2022a) , waterfronts (Ali and Patnaik, 2018), open markets (Manavvi and Rajasekar, 2021) followed by entrepreneurial neighborhoods (Banerjee, Middel and Chattopadhyay, 2020, 2022). All the respondents in the reviewed studies are Indian nationality. Table 7, shows the gender ratios of the reviewed studies. Two studies reported influence of gender in outdoor thermal comfort perception. Ali and Patnaik, reported no significant difference between gender and thermal comfort perception. However, Manavvi and Rajasekar, (2020, 2021) reported that gender is statistically significant but influence on thermal comfort perception is weak, this is in contrast to Ali and Patnaik. According to Manavvi and Rajasekar, female respondents are having higher thermal acceptability than male respondents in Indian context. As it is mentioned by Manavvi and Rajasekar, thermal acceptability varies due to chosen outdoor settings for the study.

**Table 7**: Summary of data collection in Indian studies
Source: Authors

| City & Climate | Survey Method | Sample size | Target population | Reference |
|---|---|---|---|---|
| **New Delhi, BSh** | Questionnaire and measurement | 409<br>Female - 191<br>Male- 218 | Users of urban places in Delhi | (Manavvi and Rajasekar, 2023) |
| **Safidon, BSh** | Questionnaire and measurement | 100<br>Female - 0<br>Male - 100 | people were training/exercising | (Kumar and Sharma, 2022c) |
| **Chandigarh, Cwa** | Questionnaire and measurement | 2523<br>Female - 1009<br>Male - 1514 | Visitors | (S and Rajasekar, 2022) |
| **Safidon, BSh** | Questionnaire and measurement | 55<br>Female - 19<br>Male - 36 | Visitors | (Kumar and Sharma, 2022a) |
| **Roorkee, Cfa** | Questionnaire and measurement | 73<br>Female - 32<br>Male - 41 | Pedestrian | (Mohammad *et al.*, 2021) |
| **Sonepat, BSh** | Questionnaire and measurement | 185<br>Female - 68<br>Male - 117 | University students | (Kumar and Sharma, 2021) |
| **New Delhi, BSh** | Questionnaire and measurement | 392<br>Female - 185<br>Male - 207 | Visitors | (Manavvi and Rajasekar, 2021) |
| **Mumbai, Aw** | Questionnaire and measurement | 366<br>Female - NS<br>Male - NS | People working in entrepreneurial neighborhoods | (Banerjee, Middel and Chattopadhyay, 2022) |
| **Vijayawada, Aw** | Questionnaire and measurement | 94<br>Female - 52<br>Male -42 | Pedestrians and street vendors | (Deevi and Chundeli, 2020) |
| **Shantiniketan, Aw** | Questionnaire and measurement | 200<br>Female - NS<br>Male - NS | Local people | (Das and Das, 2020) |
| **Shantiniketan, Aw** | Questionnaire and measurement | 200<br>Female - 93<br>Male -107 | Local people | (Das, Das and Mandal, 2020) |
| **Kolkata, Aw** | Questionnaire and measurement | 318<br>Female - NS<br>Male - NS | People working in entrepreneurial neighborhoods | (Banerjee, Middel and Chattopadhyay, 2020) |
| **English Bazar, Aw** | Questionnaire and measurement | 250<br>Female - NS<br>Male - NS | NS | (Ziaul and Pal, 2019) |
| **New Delhi, BSh** | Questionnaire and measurement | 353<br>Female - 130<br>Male - 223 | Visitors | (Manavvi and Rajasekar, 2020) |
| **Bhopal, Aw** | Questionnaire, Observation and measurement | 240<br>Female -<br>Male - | visitors and vendors | (Ali and Patnaik, 2018) |

## Microclimatic Measurements

Most of the studies in India used some instruments for collecting on site microclimatic data (Table 8). The instrument details are mentioned in the articles, except for (Das and Das, 2020; Khaire, Madrigal and caLanzarote, 2023). Most of these studies have compiled data on several common variables, including air temperature (Ta), relative humidity (RH), and wind speed (Va). Banerjee, Middel and Chattopadhyay have measured some other parameters like globe temperature by globe thermometer, Extech Heat stress WBGT meter (HT30) is used in another study in Haryana (Kumar and Sharma, 2022c). Generally, these instruments are mounted a height range of around 1.1m to 2m. Although most of the studies have placed the instruments at 1.1 m. According to ISO 7726 (1998) 0.6 to 1.1m represents the center of gravity of the human body (Johansson *et al.*, 2014). However, canyon level studies have placed the dataloggers at a height of 2.5 to 3m in (Salal Rajan and Amirtham, 2021). In a canyon level study in Kolkata, De and Mukherjee used two weather station, one a height of 10m and the other at a height of 2m. At the 10m height, wind speed and wind direction were recorded and the other weather station at 2m height recorded other microclimatic parameters. To evaluate UHI intensity in Chennai, Rajan and Amirtham, fixed data loggers on the top of the car. 4 vehicles moved at a speed of a speed of 30km/hr across the city for collecting data. Radiation shield was also used in HOBO U23 data loggers for this study.

Three studies of Rajan and Amirtham, (2021), Rahul, Mukherjee and Sood (2020) and Kotharkar, Bagade and Agrawal (2019) reported that the measurement probes for measuring air temperature and relative humidity are placed inside a radiation shield while rest of the studies did not mention the use of radiation shield. However, it is preferable to use any kind of shield to protect the measuring probes from direct solar radiation. Four studies mentioned that the instruments were set and used according to IS07726 and fourteen studies have mentioned the range, resolution and accuracy of the instruments. For measuring wind speed in canyon level, it is advisable to place the device at a higher position. A black globe thermometer of 40 mm diameter is used to record globe temperature in a study in Bhopal (Ali and Patnaik, 2018), 120mm black globe (Banerjee, Middel and Chattopadhyay, 2020), this globe temperature is again used to calculate $T_{mrt}$. Other studies have calculated $T_{mrt}$ using RayMan software.

**Table 8:** Summary of Microclimatic data collection method
Source: Authors

| Reference | Instruments used | Instrument placement | Months/Season | Time |
|---|---|---|---|---|
| **(Horrison and Stephi, 2023)** | Hobo U23 data loggers | 3.0 meters above ground and 1.5 meters from any surface of a reflecting wall | June | NS |
| **(Khaire *et al.*, 2023)** | Infrared thermometer (Fluke 59 max) | NS | June | 7 am to 6 pm |
| **(Kumar and Sharma, 2022c)** | Extech Heat stress WBGT meter (HT30), Meterevi Digital anemometer (AVM-01) | 1.1 m | July, August, September | 4 PM to 6:30 PM |
| **(S and Rajasekar, 2022)** | radiometer with pyranometer and pyrogeometer | 1.2 m | Summer and Winter | NS |
| **(Kumar and Sharma, 2022a)** | Extech Heat stress WBGT meter (HT30), Meterevi Digital anemometer (AVM-01) | 1.1 m | Summer | Morning, evening |
| **(Mohammad *et al.*, 2021)** | Air meter (Fluke 975 sensor), Kestrel 5400 | 1.5 m | Summer | 9 a.m. and 12 noon, 5 and 7pm |
| **(Kumar and Sharma, 2021)** | Extech HT30 WBGT meter, Extech HT30 WBGT meter, Meterevi Digital anemometer (AVM-01) | NS | Winter | 9:00 and 17:00 hours |
| **(Manavvi and Rajasekar, 2021)** | thermal comfort logging station. A net radiometer comprising sensors for the pyranometer and the pyrogeometer | 1.2 m | Summer, June | 11:00–18:00 |
| **(Rajan and Amirtham, 2021)** | HOBO U23 data loggers | 1.5 meters away from any reflective wall surfaces and 3.0 meters above ground level | February, May | 00:00 and 04:30 h |

| | | | | |
|---|---|---|---|---|
| **(Banerjee, Middel and Chattopadhyay, 2022)** | Lutron HT3015 Thermo-Hygrometer, Lutron 4206M Anemometer | 1.1 m | Winter (Feb), summer (June-Aug) | 11:00 AM and 5:00 PM |
| **(Salal Rajan and Amirtham, 2021)** | HOBO data loggers (HOBO U23 Temp/RH) | 1 m from the back wall and 3 m from the level of the road | NS | NS |
| **(Deevi and Chundeli, 2020)** | Testo 480 with a hot wire probe of Ø10, Testo 870 thermal imager | 1.1 m | February | 10 am to 5 pm |
| **(Das, Das and Mandal, 2020)** | Infrared Thermometer, Digital Anemometer | 1.1 m | Summer | 10:00, 16:00 |
| **(Rahul, Mukherjee and Sood, 2020)** | HOBO MX2302A sensors | 1.5 m above ground level (ONSET RSA solar radiation shield) | May | NS |
| **(Banerjee, Middel and Chattopadhyay, 2020)** | A Lutron HT3015 Thermo-Hygrometer, Lutron 4206 M Anemometer | 1.1 m | Summer (June) winter (Nov to Feb) | 11:00 AM, 5:00 PM |
| **(Kotharkar, Bagade and Agrawal, 2019)** | HOBO U-23 Pro V2 | 1.5 m - 2 m | Winter and Summer | 9 am to 6 pm, 6 pm to 10 pm, 10 pm to 6 am |
| **(Gajjar and Jai Devi, 2019)** | Tenmars TM-188D, Testo 405i | 1.1 m about 1 m away from any nearby structure | October | 14:00, 16:30 |
| **(Ziaul and Pal, 2019)** | infrared thermometer (Psychrometer No.20180126313) and digital anemometer (HTC instrument AVM-06) | NS | Winter, Summer and Post Monsoon | NS |
| **(Ali and Patnaik, 2018)** | BSIDE BTH01 Temperature Humidity Dew Point Data Logger Dual Channel IP66, omnidirectional vane anemometer (Lutron AM-4222) | NS | March & April | 12:30 pm to 4:00 pm |
| **(Bhaskar and Mukherjee, 2017)** | Novalynx 110-WS-18 portable weather stations, Sika MH3330 Digital Universal Temperature & Humidity Meter | 1.4 m | Summer, May | 14:00pm |
| **(Bhaskar and Mukherjee, 2017)** | (Novalynx 110-WS-18) and thermohygrometers | NS | pre monsoon summer | NS |
| **(Horrison and Amirtham, 2016)** | HOBO Pro V2 data loggers | NS | Winter | 7:00 to 19:00 |
| **(De and Mukherjee, 2016)** | Novalynx 110-WS-18, Sika MH3330 Digital Universal Temperature & Humidity Meter, silicon pyranometer | heights one at 10 m level and other at 2 m level | April, Summer | NS |
| **(Das, 2016)** | Whirling psychrometer, Thermo anemometer | 1.2 m | NS | NS |

**Secondary Data**

Majority of the reviewed studies carried out subjective surveys along with objective measurements by instruments manually or only objective measurements either by instruments manually. However, some studies (Kumar & Sharma, 2022b; Pradeep Kumar et al., 2023; Prasad & Satyanarayana, 2022; Raman, Kumar, Sharma, & Matzarakis, 2021; Raman, Kumar, Sharma, Froehlich, et al., 2021) have collected the standard parameters like air temperature, relative humidity, wind speed and solar radiation from nearby weather stations (Table 9).

**Table 9:** Summary of secondary data collection method
Source: Authors

| Reference | Time range | Parameters collected | Source |
|---|---|---|---|
| **(Prasad and Satyanarayana, 2022)** | 2018, 2019, 2020 (Summer & Winter) | Ta, RH, Va | www.data.telangana.gov.in/ |
| **(Kumar and Sharma, 2022b)** | January 2010 to December 2019 | Ta, RH, Va | World Weather Online |
| **(Raman, Kumar, Sharma and Matzarakis, 2021)** | June 2019 | Ta, RH, Va, cloudiness and Tg | Ogimet,<br>India Meteorological Department (IMD), Pune |
| **(Raman, Kumar, Sharma, Froehlich, *et al.*, 2021)** | June 2019 | Ta, RH, Va, cloudiness and Tg | Ogimet,<br>India Meteorological Department (IMD), Pune |

**Methods of Thermal Comfort Assessment**

Most Indian studies are carried out in the same cities and similar climatic zones. These have used questionnaire surveys along with microclimatic measurements by instruments except two studies by (Raman, Kumar, Sharma and Matzarakis, 2021; Kumar and Sharma, 2022b), where weather data is collected from nearby weather station. PET and UTCI are the two thermal indices used widely to derive neutral PET. The Fig. 7 summarizes neutral PET range, neutral PET for different seasons and average PET in different outdoor settings in various climate zones. However, some studies used UTCI and WGBT (Kumar and Sharma, 2022b, 2022c, 2022a). One study (Prasad and Satyanarayana, 2022) used THI to derive thermal neutral range and another study in Santiniketan (Das, Das and Mandal, 2020) used SET. All the reviewed studies are conducted mostly in summers and few studies (Ziaul and Pal, 2019; Banerjee, Middel and Chattopadhyay, 2020, 2022; Prasad and Satyanarayana, 2022; Manavvi and Rajasekar, 2022) in both summer and winter to determine thermal neutral range. Two studies have investigated in winter season only (Horrison and Amirtham, 2016; Kumar and Sharma, 2021). All the data collected through objective measurement and subjective survey, needs to be analyzed through statistical tools like SPSS software.

Most Indian studies, used linear regression method for analytical purpose. Liner regression analysis is done between mean thermal sensation votes and thermal indices to determine the neutral PET range of that thermal indices. Two studies have used Ordinal logistic regression (Ali and Patnaik, 2018; Banerjee, Middel and Chattopadhyay, 2022) and one study (Manavvi and Rajasekar, 2023) used structural modelling equation (SEM). It is observed in that neutral PET range in urban park (Kumar and Sharma, 2022a) is wider than urban open areas (Kumar and Sharma, 2022b) in Haryana even in the similar climate zone. This shows that the people in urban green areas feels more neutral than in other urban open spaces. New Delhi and Sonepat, being of the same climatic zone, neutral PET is different. Analysis shows that the neutral PET also depends on the site characteristics.

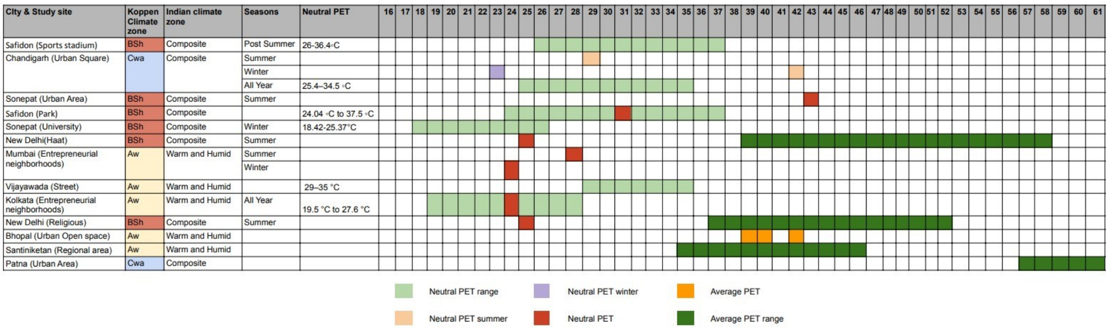


**Fig. 7:** Neutral PET, Neutral PET range for different seasons in different study areas
Source: Authors

## Software Used in Outdoor Thermal Comfort Studies in India

Thermal indices are calculated either by equations or software. Recently, numerical simulation methods are most trending in studying urban thermal environment. This review has focused on different studies that used numerical simulation models to study outdoor thermal comfort. Table 10 shows the frequency of each numerical simulation model used in the reviewed studies. RayMan Pro is the widely used software for calculating PET, UTCI and SET. More than 50% of the reviewed studies used RayMan Pro. Recently BIO-met in Envi-Met software is also used to calculate thermal indices PET, UTCI and SET. Other thermal indices like THI, DI, TA, RSI are calculated using standard equation.

**Table 10:** Software used to calculate Thermal indices
Source: Authors

| Software | No of studies |
|---|---|
| RayMan Pro | 19 |
| ENVI-Met | 8 |
| SkyHelios Pro | 2 |
| UTCI calculator | 1 |

## RayMan Pro

RayMan Pro is a very important software to calculate thermal indices and MRT. Input parameters for this software are geographic location, personal data (Age, gender, height, weight), Clothing, activity and climate parameters (Air temperature, relative humidity and wind velocity) recorded at the site during survey. Cloudiness data can be obtained from India Meteorological Department (IMD) to add in the input data. Thermal indices like PET, UTCI, SET and PMV can be calculated using RayMan Pro software. Obstacle files can be prepared in Obstacle editor of RayMan to model the existing buildings and trees. Due to its user-friendly access and fast simulation time, RayMan Pro software is used widely in India (Kumar and Sharma, 2022a, 2022b, 2022c; Manavvi and Rajasekar, 2022) .

## ENVI-Met

In 1998, Envi-Met was developed by Michael Bruce and Heribert Fleer of the University of Bochum (Yang *et al.*, 2020). Envi-Met is a high-resolution microclimate model to simulate façade, ground, vegetation and microclimatic conditions of an urban area. ENVI-met is used often to study the factors that affect street canyon, outdoor thermal comfort and urban heat island. It is also used to analyze different scenarios. Many studies around the world used Envi-Met in different climate zones. Among the reviewed studies in India, 8 studies have used Envi-Met. However, 4 studies have published the detailed parameterization of the model to predict the accuracy of the model. Table 11, shows a summary of the simulation settings at different locations in India. It is been observed that the simulation date and time changes according to the research objective. Grid size varies from 2m to 3m in x, y and z axis. Domain size depends on availibity of the licensed version of Envi-Met. Meteorological conditions vary according to the location of the place and a clear sky condition is set in all the studies. The simulation output is processed in Biomet software which is incorporated in Envi-Met software to calculate thermal comfort calculation. Envi met is one of the mostly used software to simulate microclimate environment. Fig. 8, shows the general methodology of ENVI-Met to study outdoor thermal comfort.

**Table 11:** Summary of the simulation settings in different locations in India
Source: Authors

| Location | Roorkee (Rahul, Mukherjee and Sood, 2020) | Roorkee (Mohammad *et al.*, 2021) | Chennai (Rajan and Amirtham, 2021) | Chennai (Horrison and Stephi, 2023) | Kolkata(De and Mukherjee, 2016) |
|---|---|---|---|---|---|
| **Climate type** | Cfa | Cfa | Aw | Aw | Aw |
| **Simulated Day** | 02:05:2019 | 11th - 12th June 2020 | 30th May, 2018 | 1st of June 2018 | 24th Nov, 2015 |
| **Simulation time** | 72 h | 26 h | 24hrs | | 24 hours |
| **Spatial resolution (grid size)** | 2 × 2 × 2 | 1.6 x 6.6 x 1 | dx =3, dy = 3, dz = 3 | 2m× 2mx 2m | 2 × 2 × 2 |
| **Domain size** | 200 × 180 × 20 | 60, 60, 30 | X =50, Y =50, Z Z=30 | 30× 30 x 15 | NS |
| **Roughness length** | 0.1 | | 0.01 | NS | 0.1 |
| **Wind speed (m/s)** | 1.4 m/s | 1.325 m/s | 1.5 | NS | 0.01 |
| **Wind direction** | South (180) | 135◦ (south-west) | South easterly | NS | 95° |
| **Air temperature (°C)** | 27.12 °C | Max: 34.44 ◦C Min: 26.11 ◦C | NS | NS | 28.27°C |
| **Relative humidity (%)** | 93.34% | Max: 87% Min: 59% | NS | NS | 70% |
| **Sky condition** | 0 | | NS | NS | 0 |

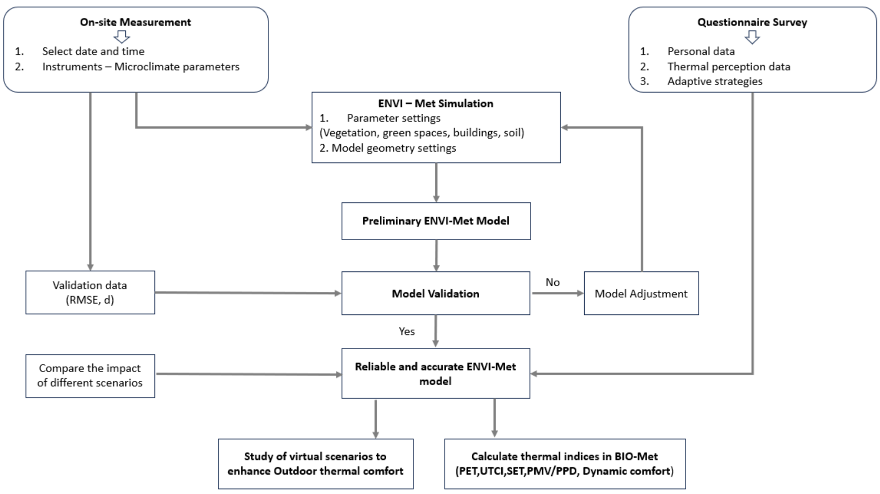


**Fig. 8:** General methodology of ENVI-Met to study outdoor thermal comfort.
Source: Authors

**Study Areas**

Indian studies are mostly carried out in different types of neighborhoods like residential neighborhood in New Delhi (Khaire *et al.*, 2023), entrepreneurial neighbourhoods in Kolkata (Banerjee, Middel and Chattopadhyay, 2020) and in Mumbai (Banerjee, Middel and Chattopadhyay, 2022), Mixed neighborhood in Chennai (Salal Rajan and Amirtham, 2021) followed by Urban areas in New Delhi, Bihar, Sonepat are studied (Raman, Kumar, Sharma, Froehlich, *et al.*, 2021; Kumar and Sharma, 2022b; Prasad and Satyanarayana, 2022; Manavvi and Rajasekar, 2023). As residential and mixed neighborhood areas are important to study for the comfort of the urban people, (Banerjee, Middel and Chattopadhyay, 2020, 2022) focused on the entrepreneurial neighborhoods which is an informal settlement with informal economic activity. Urban open areas and parks are also studied in various cities, Safidon, Chandigarh, Bangaluru, Bhopal (Gopinath, no date; Ali and Patnaik, 2018; Kumar and Sharma, 2022a; Manavvi and Rajasekar, 2022). These urban squares in New Delhi experiences good footfall. Two studies are done in Institutional campuses in the campus of Deenbandhu Chhotu Ram University of Science and Technology, Murthal, Sonepat (Kumar and Sharma, 2021) and in Sathyabama University, Chennai (Amirtham, 2014). Several studies are focused in Streets in urban areas like a commercial street in Vijayawada (Deevi and Chundeli, 2020), and in streets of Rajarhat, Kolkata (Das, 2016; De and Mukherjee, 2016; Bhaskar and Mukherjee, 2017). It is observed that studies can be carried out in various other types of outdoor spaces in Indian context.

**Table 12:** Summary of Study areas examined outdoor thermal comfort in Indian studies
Source: Authors

| Study area | No of studies |
|---|---|
| Neighborhood level | 8 |
| Urban Area | 8 |
| Urban open area | 4 |
| Institutional Campus | 2 |
| Open Market | 1 |
| Street | 6 |
| Sport stadium | 1 |
| Squares | 2 |
| Regional Level | 3 |

**Motivation of Studies**

Studies on outdoor thermal comfort show a rising trend toward improving user comfort in outdoor environments. Studies conducted in India between 2013 and 2023 are shown in Fig. 4, where this rising trend can be seen. Researchers' motivations for conducting studies on outdoor thermal comfort vary. Kumar and Sharma identifies some of the motivations of research studies like for better understanding of thermal comfort conditions, for checking the applicability of the thermal comfort indices, for heat mitigation strategies, for checking the impact of greenery on thermal comfort and for tourism purpose.

Out of all the research that has been evaluated, 53% were conducted with the goal of better understanding the thermal comfort level of outdoor settings. Recently Manavvi and Rajasekar, have studied different urban squares to quantify the influence of different subjective parameters of outdoor thermal comfort. This study suggests that perception of environmental parameters is more important than other attributes. It has been found that there should be active engagement of designers for creating comfortable urban open spaces. S and Rajasekar, highlights that outdoor thermal comfort is specific to context. This study also suggests that the findings of similar kind of researches can help urban planners and designers to enhance the outdoor spaces in a city.

Out of the total studies reviewed, 32% of the studies have carried out the study with the motivation of heat mitigation strategies and also reducing urban heat island. These studies are done to analyze the effect or impact of various heat mitigation strategies to enhance outdoor thermal comfort. Impact of different natural parameters like green cover (Horrison and Stephi, 2023), Ganga canal (Rahul, Mukherjee and Sood, 2020) and water body (Gajjar and Jai Devi, 2019) have been studied. According to Horrison and Stephi, increased green cover has an impact on Tmrt and PET which will further increase the use of the public outdoor spaces in a neighborhood. In another study in Roorkee, it is found that a dynamic water body can lowers the ambient temperature, where maximum cooling impact observed is 140m in open mid-rise LCZ with an amplitude of 2.59 °C and a minimum of 24m in compact low rise LCZ. However, there is a contrasting result to Harrison and Stephi, according to Gajjar and Jai Devi the water body does not have similar effect on all the surrounding areas. Western part of the water body seems to be cooler than the eastern side because of the street orientation and building geometry. Moreover, PET was found high thermal sensation and temperature varies because of street orientation, sky view factor and aspect ratio. The result of these studies assists urban planners to develop more context specific decisions. So, there is a broad scope left for designing the outdoors using these strategies and also making use of the existing natural features.

The applicability of thermal comfort indices for public green spaces in Bengaluru is the subject of one study (Gopinath, no date). This study tries to create a new comfort scale H.O.T.C.I. that may be used in urban green spaces at the local, micro, and macro levels. The applicability of these H.O.T.C.I. must be tested in various climatic zones. Much work can be done to develop and implement these thermal comfort indices for outdoor situations.

Currently, no tourism-related studies are being conducted in India. As stated in the target population, only Indian citizens were selected for all of the samples used in the research in India. None of the research investigates thermal comfort for individuals of other nationalities. It is critical to study visitor perceptions to recommend the ideal time to visit a location and to quantify thermal comfort while designing tourist attractions. Researchers have a lot of opportunities to explore outdoor thermal comfort for tourism purposes.

## Summary

This literature review has identified the spread of OTC studies in India. Studies are mainly focused on different outdoor spaces in urban settings. They are concentrated in same cities like Kolkata, New Delhi & Chennai. The highest % of studies found in West Bengal followed by New Delhi, Haryana, Tamil Nadu. There is an immense opportunity to research OTC in various outdoor locations in the remaining states of India that have not been investigated in the literature.

As observed in Fig. 5, PET and UTCI is widely used thermal indices in India. Out of the 35 reviewed studies, 37% researches are done in Aw (Warm and humid) and 34% studies are done in Bsh (hot and dry). As this climatic condition are not comfortable throughout the year, studies are done more in Aw and Bsh climatic zone. However, there are ample scope to quantify OTC in other climatic zones. OTC studies are not available in several major cities and climatic zones in India like Bengaluru, Hyderabad. Past Indian studies are focused on capital cities in each state and territory. However less researches are done in regional level including rural areas, which may have different comfort level can be studied further. Indian studies have examined OTC of local people present in the site. Further studies should also focus on visitors from different state, climatic zone, cultural background and gender, these might affect the thermal perception.

Local climatic zone (LCZ) approaches have been used by certain studies to quantify the influence of urban morphology on outdoor thermal comfort (M. Das et al., 2020; M. Das & Das, 2020; Kotharkar et al., 2019; Rahul et al., 2020). Various researchers are exploring the applicability of LCZ scheme. Kotharkar's 2019 research helps in understanding outdoor thermal comfort in crucial LCZs in Nagpur, and it also recommends that LCZ classification could be employed in the preparation of Heat Action Plans (HAP) as an efficient approach for adaptation and management. Manob Das and Arijit Das, shows how comfort level varies over LCZs due to variation in geometry and morphology of the outdoor areas.

Data collection methods usually are of two types used in Indian studies. Questionnaire survey and microclimatic data collection. These microclimatic data can be collected either from secondary sources or by measuring the climatic parameters on site by instruments. Studies in India have evaluated outdoor thermal comfort using quantitative methods, but few studies have focused on qualitative methods. Further research should use qualitative methodologies, such as direct observation, to evaluate outdoor thermal comfort, which can influence people's thermal perception.

Other qualitative assessment approaches include direct observation, cognitive microclimate mapping, photographic comparison, and thermal walks. Because it is difficult to quantify subjective experience using quantitative methods, integrating quantitative and qualitative methodologies can provide a more comprehensive knowledge of users' perceptions of thermal comfort in outdoor situations.

## Conclusions

This research provides a comprehensive assessment of outdoor thermal comfort studies in India. Climate change, fast urbanization, population expansion in urban areas, particularly in capital cities, and heat waves, are some of the biggest natural disasters. They are all causes to increase outdoor thermal comfort research.

Although it has been noted that outdoor thermal comfort studies are few in India, there has been a steady rise in OTC research starting in 2019.

Following conclusions are made.

1. Most of the studies are conducted in warm, humid regions (Aw), and subsequently in dry, hot environments (Bsh).
2. They are focused on understanding thermal comfort conditions in different contexts using thermal indices like PET, UTCI.
3. 50% of the reviewed studies have used both subjective survey and objective measurement.
4. Observation research has been conducted in a study on the apparel worn by the user and their activity level. Personal data, thermal perceptions, and thermal adaptation are typically included in questionnaire surveys.
5. The questionnaire formats can vary depending on the study's aim of the research. Mostly ASHARE 7-point scale is adopted to determine thermal sensation of the users. Recently 9- point thermal sensation scale is also used in some studies. Commonly recorded climatic variables are Ta, RH, Va, Tmrt, solar radiation. Neutral PET/UTCI ranges are calculated using mainly linear regression and correlation analysis.
6. ENVI-met can be used to evaluate thermal comfort and it can create virtual microclimate outdoor spaces which can be done before preparation of layout plan to implement heat mitigation strategies.

Thus, outdoor thermal comfort studies are essential for mitigating extreme climatic conditions caused by urban heat islands and global warming. The findings of outdoor thermal comfort studies can be used by policymakers, urban designers and planners, landscape architects, and other stakeholders to create thermally suitable outdoor environments. Outdoor thermal comfort studies have grown in popularity over the last decade, and there remains ample need for more research.

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