Effect of Vertical Urban Surfaces on Human Thermal Comfort in an Outdoor Environment

A Thesis

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by
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The project report entitled "Effect of Vertical Urban Surfaces on Human Thermal Comfort in an Outdoor Environment" submitted by Mr. Jayesh Dashrath Khaire (Roll No. PK4808624) may be accepted for being evaluated.

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Abstract

Traditionally the outdoor open spaces were used by inhabitants; the social life was largely dependent on the user spending time in outdoor spaces. These spaces including streets, markets, shopping precincts, community centers, plazas, and playgrounds play a vital role in the social life of communities. Due to thermal comfort issues, the use of these spaces is declining. It is necessary to keep these spaces active by improving the thermal comfort level.

The focus on a single morphological entity of an urban area and its effect on thermal comfort level is lacking in earlier studies. Out of the various components of the built environment, the vertical surface is one of the components which occupies the maximum area. The role of vertical surfaces in thermal radiation remains unresolved, unobserved, unexplored, and unapplied at the urban scale studies. This study aims to develop an effective response for human thermal comfort level in an outdoor urban space affected by the geometrical configuration of vertical surfaces.

The study begins with an in-depth review of Indian studies which are focused on outdoor thermal comfort. After grasping the necessary knowledge in the field and understanding the gaps present in thermal comfort studies in India, the sites and the respective climatic zones were given attention. This study is focused on two different commercial open spaces in the composite climate of Delhi and four different residential neighborhoods in Jaisalmer and discussed the effect of vertical surfaces on human thermal comfort in an outdoor environment. Software simulations with Envi-met were performed to achieve various climatic indices. These indices were analyzed with physical parameters defined by the height-to-width ratio, sky view factor, and the orientation of vertical surfaces. Field measurements were conducted to validate the results obtained from Envi-met simulation outputs. Alongside this, a questionnaire survey was conducted to understand the subjective thermal comfort level. Results were analyzed for the summer season since winter is not dominant and lasts only for a short duration of the year.

The study shows that the vertical surfaces and their geometry have high effects on outdoor thermal comfort. Complex urban geometries can result in varying thermal comfort levels. Within small proximity, the variation in thermal comfort level can be observed due to the change in the vertical surface geometries around the open spaces. The effect of solar access, shade, and wind velocity is seen in the thermal comfort level. The effect of geometrical parameters is evident in the thermal sensation votes of the user. A higher height-to-width ratio can help improve the thermal sensation level, whereas the effect of the sky view factor is less prominent.

Mean radiant temperature variation is much more prominent than ambient temperature and physiological equivalent temperature. Vertical surfaces in the south, west and south-west direction to the space are beneficial in maintaining the thermal comfort of that location whereas the existence of a vertical surface on the north side of the open space may not benefit. Although a higher height-to-width ratio will give better thermal comfort it is not always true. combining it with appropriate surface orientation is the key to achieving maximum comfort level for

any space. The locations enclosed from the northeast and southwest directions and locations enclosed from the northwest and southeast are having lesser values of temperatures. For this reason, the open spaces and streets can be designed considering these directions.

Shade from the vertical surfaces is the guiding factor for the users to use the space for a certain duration of time per day. Maximum the duration of the shade the user spending time in the space will be higher. Vertical surfaces can so be provided that the space will get the maximum shade during the harsher hours of the day. South and west directions provide the shade for maximum duration. The height-to-width ratio along with the orientation of vertical surfaces can determine the hours of solar access to that open space. This study found a strong positive correlation between hours of solar access and mean radiant temperature. Locations having solar access of fewer than four hours performed better than the rest of the locations.

The open spaces must be well-ventilated. The higher wind speed can reduce the physiologically equivalent temperature significantly. For this reason, the open spaces can be designed in such a way that the wind channeling effect can be created by orienting the open space aligned or oblique to the prevailing wind direction. The duration of the thermal discomfort within a day can be reduced with the right configuration of the vertical surfaces. If the thermal values start increasing late in the morning hours and start decreasing early in the afternoon hours, the user spending time in the outdoor space will be higher.

Height-to-width ratio, sky view factor, and orientation are the typical parameters used in the studies to define the physical composition of urban open spaces. The study suggests looking for parameters beyond these parameters to achieve accuracy in the analysis. The study also suggests that the upcoming studies should consider indoor-façade-outdoor interaction rather than studying the outdoor environment in isolation. The results and conclusions achieved in this study can not be applied to the existing vertical surfaces in urban areas and neighborhoods, and they can only be implemented before the construction activity takes place. This study is the first attempt in the hot and dry region of India, which will help guide other researchers in thermal comfort studies for other cities with similar climates.

Through this study, it is expected that outdoor spaces once again will get importance and can be used as effectively as they used to be. Also, they can be used as effectively as indoor spaces. Functions that deserve the location outdoors can go back to outdoors from indoors as a result there will be less need to construct buildings to achieve those outdoor functions.

This study will give guidelines for architects, landscape architects, planners, and engineers to design thermally comfortable outdoor open spaces. It will also create a serious approach while considering the broad-scale issues such as the urban heat island effect. The outdoor spaces will not be considered as the leftover spaces once the building is constructed, whereas right from the conceptualization the designers will think about the outdoor space while designing the buildings and indoor functions. The study will also act as a base for future research since this research opens up several directions which need attention. I feel research in this field is of great scope in the future as the earth's temperature is increasing due to global warming. It is an architect's responsibility to design spaces in such a way that user experience is not affected while maintaining the thermal comfort level.

Resumen castellano

Tradicionalmente, los espacios abiertos al aire libre han sido utilizados por los habitantes como lugares clave para la vida social, donde la gente pasa su tiempo libre. Sin embargo, debido a problemas de confort térmico, se ha reducido su uso. Es necesario mantener estos espacios activos mejorando el nivel de confort térmico. Hasta ahora, los estudios anteriores han carecido de un enfoque morfológico integral de las áreas urbanas y su impacto en el confort térmico. Entre los diversos componentes del entorno construido, las superficies verticales ocupan una gran parte del área, y el papel de estas superficies en la radiación térmica ha sido descuidado en los estudios a escala urbana. Este estudio tiene como objetivo desarrollar una respuesta efectiva para el confort térmico humano en espacios urbanos al aire libre, considerando la configuración geométrica de las superficies verticales. El estudio comienza con una revisión exhaustiva de estudios indios previos que se centran en el confort térmico en exteriores. Después de adquirir los conocimientos necesarios en el campo y comprender las lagunas existentes en los estudios de confort térmico en India, se presta atención a los sitios y las respectivas zonas climáticas. El estudio se centra en dos espacios abiertos comerciales en el clima compuesto de Delhi y cuatro barrios residenciales diferentes en Jaisalmery, analizando el efecto de las superficies verticales en el confort térmico humano al aire libre. Se llevaron a cabo simulaciones utilizando el software Envi-met para obtener varios índices climáticos, que se analizaron junto con parámetros físicos definidos por la relación altura-ancho, el factor de visión del cielo y la orientación de las superficies verticales. Se realizaron mediciones de campo para validar los resultados obtenidos de las simulaciones de Envi-met, y también se realizó una encuesta para comprender el nivel subjetivo de confort térmico. Los resultados se analizaron para la temporada de verano, ya que el invierno no es dominante y tiene una duración corta en el año. El estudio revela que las superficies verticales y su geometría tienen un efecto significativo en el confort térmico exterior. Las geometrías urbanas complejas pueden generar diferentes niveles de confort térmico en proximidad cercana, observándose variaciones en el nivel de confort térmico debido a los cambios en las geometrías de las superficies verticales alrededor de los espacios abiertos. El acceso solar, la sombra y la velocidad del viento también influyen en el confort térmico, siendo evidente el efecto de los parámetros geométricos en las sensaciones térmicas de los usuarios. Una mayor relación altura-ancho puede ayudar a mejorar el nivel de sensación térmica, aunque la influencia del factor de visión del cielo es menos prominente. Este estudio proporcionará pautas para arquitectos, arquitectos paisajistas, planificadores e ingenieros para diseñar espacios abiertos al aire libre cómodos desde el punto de vista térmico. Además, se abordará seriamente problemas a gran escala como el efecto de isla de calor urbano. Los espacios exteriores ya no se considerarán como espacios adicionales una vez que se construyan los edificios, y desde la etapa conceptual, los diseñadores considerarán el espacio exterior al diseñar los edificios y las funciones interiores. Este estudio también sentará las bases para futuras investigaciones, ya que abre varias direcciones que requieren atención. Considero que la investigación en este campo tiene un alcance amplio en el futuro, dado que la temperatura de la Tierra está aumen-

tando debido al calentamiento global. Es responsabilidad de los arquitectos diseñar espacios de manera que la experiencia del usuario no se vea afectada mientras se mantiene el nivel de confort térmico.

Resumen valenciano

Tradicionalment, els habitants han utilitzat espais a l'aire lliure com a llocs clau per a la vida social, on la gent passa el seu temps lliure. Tanmateix, a causa dels problemes de confort tèrmic, el seu ús s'ha reduït. Cal mantenir aquests espais actius, millorant el nivell de confort tèrmic. Fins ara, els estudis anteriors no han tingut un enfocament morfològic integral de les zones urbanes i el seu impacte en el confort tèrmic. Entre els diversos components de l'entorn construït, les superfícies verticals ocupen una gran part de la zona, i el paper d'aquestes superfícies en la radiació tèrmica s'ha descuidat en estudis a escala urbana. Aquest estudi pretén desenvolupar una resposta efectiva per al confort tèrmic humà en espais a l'aire lliure urbà, tenint en compte la configuració geomètrica de superfícies verticals. L'estudi comença amb una revisió exhaustiva dels estudis indis anteriors que se centren en el confort tèrmic a l'aire lliure. Després d'adquirir els coneixements necessaris en el camp i comprendre les llacunes en els estudis de confort tèrmic a l'Índia, es presta atenció als llocs i a les zones climàtiques respectives. L'estudi se centra en dos espais oberts comercials en el clima compost de Delhi i quatre barris residencials diferents a Jaisalmery, analitzant l'efecte de les superfícies verticals sobre el confort tèrmic humà a l'aire lliure. Es van realitzar simulacions mitjançant el programari Envi-met per obtenir diversos índexs climàtics, que es van analitzar juntament amb paràmetres físics definits per la relació amplada d'alçada, el factor de visió del cel i l'orientació de les superfícies verticals. Es van realitzar mesures de camp per validar els resultats obtinguts de les simulacions Envi-met, i també es va realitzar una enquesta per comprendre el nivell subjectiu de confort tèrmic. Els resultats es van analitzar per a la temporada d'estiu, ja que l'hivern no és dominant i té una durada curta a l'any. L'estudi revela que les superfícies verticals i la seva geometria tenen un efecte significatiu en el confort tèrmic exterior. Les geometries urbanes complexes poden generar diferents nivells de confort tèrmic a prop, s'observen variacions en el nivell de confort tèrmic a causa dels canvis en les geometries de les superfícies verticals al voltant dels espais oberts. L'accés solar, l'ombra i la velocitat del vent també influeixen en el confort tèrmic, l'efecte dels paràmetres geomètrics sobre les sensacions tèrmiques dels usuaris és evident. Una proporció d'amplada d'alçada més alta pot ajudar a millorar el nivell de sensació tèrmica, tot i que la influència del factor de visió del cel és menys destacada. Aquest estudi proporcionarà directrius perquè arquitectes, arquitectes paisatgístics, planificadors i enginyers dissenyin espais a l'aire lliure termalament còmodes. A més, es tractaran seriosament problemes a gran escala com l'efecte insular de calor urbana. Els espais exteriors ja no es consideraran espais addicionals un cop construïts edificis i des de l'etapa conceptual, Els dissenyadors tindran en compte l'espai exterior a l'hora de dissenyar edificis i funcions interiors. Aquest estudi també posarà les bases per a futures investigacions, ja que obre diverses direccions que requereixen atenció. Crec que la investigació en aquest camp té un abast ampli en el futur, ja que la temperatura de la Terra augmenta a causa de l'escalfament global. És responsabilitat dels arquitectes dissenyar espais perquè l'experiència de l'usuari no es vegi afectada mantenint el nivell de confort tèrmic.

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Introduction

1.1 Background

Human being has always appreciated nature and has shown an inclination of being in a natural surrounding i.e. in an outdoor environment. Outdoor open spaces give psychological relief to people and help them to relax. These spaces including streets, markets, shopping precincts, community centers, plazas, and playgrounds play a vital role in the social life of communities. These are the places where people can display their culture and identities, their diversity and differences. They also create opportunities for children and young people to meet, interact, and hang out. All of it has an important benefit in forming a sense of community. These spaces are significant for urban revitalization. These are for people to enjoy nature and provide a gathering space for social events. Also, to improve the quality of the urban environment, and arouse people's sense of identity and belonging to all.

Outdoor open spaces are the key infrastructure for an urbanized area. These spaces provide environmental, social, and economic benefits to cities and their residents Kim and Wentz (2011). They form an important role in the physical and psychological well-being of the users WHO (2016). Traditional Indian outdoor spaces were able to cater to the needs of the residents by providing different types of spaces such as temple courtyards, commercial spaces for shopping, religious spaces, cycling, and pedestrians Gangwar (2018). Due to rapid urbanization, it is necessary to give attention to these spaces.

Traditionally in India, immediate open spaces to buildings were important for various functions such as food preparation, farm processing, sleeping, eating, resting, washing clothes and utensils, etc. These spaces should not act as a separating element for two buildings, instead should act as a binding element. Urban space has physical, ecological, environmental, psychological, social, symbolic, and aesthetic value. They play a pivotal role at a time of declining natural resources, increasing pollution, etc.

Outdoor spaces are used differently by different age groups. Children may find the open space ideal for playing, young people will find it good for gatherings, parties, chitchat, etc., while old people will find it ideal for relaxing in the natural environment. For different times of the day outdoor spaces are used differently due to the certain orientation of adjacent building surfaces, shadow pattern created by them, and most importantly thermal parameters affected by these surfaces. The building is always oriented by the cardinal directions: north, south, east, and west; or north-east, north-west, south-east, and south-west. Outdoor spaces are located as per the direction of the building surfaces facing. For instance, the surface facing east will receive direct sunlight only in the morning hours after that space will be in the shade so that the outdoor functions can be accommodated which can be active in the afternoon hours. Outdoor spaces adjacent to the west side surface will be in shade only during morning hours. The functions like outdoor yoga, exercise, meditation, prayers, etc. can take place on the west side open space in the morning.

The open space provides natural light and ventilation to the living areas and indirectly affect the health of the community and the individual as well. These spaces allow interaction of the housewives in afternoons, and children to find a place to play and thus it allows people to come together informally. The definition of open space has evolved with time, covering all types of opportunities to suit the various needs of human beings. In the ancient period, the sizes of the villages were small, and the surrounding open countryside was quite abundant.

As a quick background of the historical scenario, in the ancient civilization of Greece and Rome, several open spaces were having traditional activities such as a marketplace, gymnasium for athletes, and sacred burial groves. In Islamic cities, open space was an integral part of the city structure. Open space as the courtyard was frequently used in madrasas, mosques, and buildings of secular nature. During the Renaissance, architects began to systematically study the shaping of urban space. Parts of old cities were rebuilt to create elegant squares, long street vistas, and symmetrical building arrangements. In the baroque city, the grand scale was sought in urban public space: long avenues, radial street networks, monumental squares, geometric parks, and gardens.

In present times, the concept of open space in urban areas is not only limited to urban parks and preserves. Public spaces such as streets, school yards, outdoor sports complexes, and public squares are all important open spaces. Recreation is a human need and these activities vary with age, sex, aptitude, etc., this need can be spontaneously fulfilled depending upon adequacy and quality of open space. Open space is associated with pleasure, recreation, human interaction, and communal celebrations.

1.2 Problem statement, gaps and topic justification

The majority of studies carried out on thermal comfort relate to indoor thermal comfort. Climatic parameters for outdoor comfort are determined by radiation, air velocity, precipitation, humidity level, etc. cannot be controlled easily, Whereas, for indoor areas, the comfort level can be achieved by enclosures, ventilators, air conditioning mechanisms, materials, etc. This difference is huge when weather condition changes throughout the year as well as throughout the day.

Man has tried and still trying, to avoid the effects of climate since pre-historic times by various means. Rapid urbanization is causing unplanned land use and land cover changes. Unplanned and unforeseen development is resulting in micro-climatic changes which are evident in urban areas. Such changes give rise to challenges associated with the built environment, public health, thermal comfort, etc. In India, according to the Indian meteorological department, nine out of twelve years were amongst the twelve hottest years since 1901. Such temperature rise led to an increase in the need for space cooling.

The major problem associated with thermal comfort is the declined use of outdoor space which results in a decline in cultural activities, social Interaction etc. The built environment can encourage or discourage social interaction. Children are not playing outside which affects their growth (mental as well as physical), affects learning Knowledge, feelings sharing, Lack of social meetings, community gatherings, etc. If outdoor space is not utilized, there will be further load on indoor spaces, leading to construction and a further increase in vertical surfaces. To explain this fact simple skeptical example is taken.

In case-1 (Figure 1.1a), there is an indoor function and an outdoor function, in case-2 (Figure 1.1b), due to thermal discomfort the function which usually happens outdoors is now part of indoors which initiates the construction of building surfaces, floor, and roof. If we consider only the vertical surfaces to compare case 1 and case 2, we can see a significant increase in the surface area of the vertical surfaces in case 2. This is what happens throughout the world. Due to thermal discomfort outdoor functions are achieved indoors, which increases the vertical surfaces which in turn increases the thermal impact on the adjacent outdoor spaces.

Delhi is the second most populous city in the world and it is projected to become the most

(a) Case 1 (b) Case 2

Figure 1.1: Schematic representation of the highlighted issue

populous city in the world by 2030 (United Nations Department of Economic and Social Affairs, 2018). Most of the areas in the city did not match the criteria of WHO and UN for per capita availability of public open spaces Shahfahad et al. (2019). The designated open spaces for outdoor activities are declining Shahfahad et al. (2019). Due to declining open spaces in the city, it becomes important to use the immediate outdoor open spaces in buildings.

Increasing urbanization also has an impact on the micro-climate of the city (Mallick and Rahman, 2012) because of which user preference for outdoor space use is declining. It is necessary to keep these spaces active by improving the thermal comfort level. With the extreme climate of the city with the ambient temperature ranging between 3°C to 43°C (Indian Meteorological Department, 2010; Sharma et al., 2019), it becomes a challenge to design outdoor spaces with required thermal comfort levels.

Urban civilizations developed early in hot and dry regions are characterized by intensive solar radiation in the summer. The old cities in such regions are often planned in a cluster configuration Bourbia and Awbi (2004). Shady zones are planned to achieve the required thermal comfort (Moos and Duhamel, 1996). Jaisalmer is located in the northwest part of India in the state of Rajasthan. The city is located at the heart of the 'Thar' desert. The old settlement of the city offers an effective solution against the extreme climate (Krishan, 1996). The natural cooling of outdoor open spaces in the city is achieved at three levels. First, at the urban scale, the buildings are shaded by each other due to different wall heights, and secondly with the projections to the building façades in the form of traditional 'jharokhas' and 'chajjas' that increase the shade of the façade. Thirdly, the intricate carving on the façades reduces the heat gain (Krishan, 1996; Gupta, 1985). The city is characterized by narrow streets, designed in such a way that the direct sunlight penetrating the open space is minimal. On the other hand, modern development in the city is apparently done without taking appropriate measures to reduce the thermal impact of solar radiation. Traditionally the outdoor open spaces were used by inhabitants; the social life was largely dependent on the user spending time in outdoor spaces. The old city of Jaisalmer could be seen with users spending maximum time in outdoor shaded spaces whereas, in the later developments in the city, the user spending time outdoors is rare since the measures taken to reduce solar radiation are ineffective.

Research and solutions are focused mainly on the pollution, greenhouse gases, and burning of fossil fuels for urban climate change, whereas the whole surface area of a building contributes to heat emission in higher quantities. The role of vertical surfaces in thermal radiation remains unresolved, unobserved, unexplored, and unapplied at the urban scale. The focus on a single morphological entity of an urban area and its effect on thermal comfort level is missing in earlier studies.

Due to the complexity of an urban area, it is important to understand the effect of an individual entity of the built environment on thermal comfort level. Out of the various components of the built environment, the vertical surface is one of the components which occupies the maximum area. This study hypothesized that the overall geometry of the vertical surfaces has effects on the thermal comfort level of the adjacent outdoor open spaces. With the flexibility of using building materials and architectural styles, thermal comfort levels can be improved in outdoor open spaces.

1.3 Research aim

This study aims to develop an effective response for human thermal comfort level in an outdoor urban space affected by the geometrical configuration of vertical surfaces.

1.4 Research questions

To achieve the research aim, this study seeks the answers to the following research questions.

- What is the current status of outdoor thermal comfort studies in India? What is the status of existing knowledge and the gaps present?
- What are the thermal parameters, and how they are affected due to the built environment around them?
- Which are the thermal comfort indices, that can help define the thermal comfort level?
- How can the interaction with the user help them understand their thermal comfort level?
- How effective can be the simulation software for the simulation of outdoor thermal comfort studies?
- What are the various methods for analyzing the thermal comfort level from the available data?
- What are the various parameters related to vertical surfaces that can affect outdoor thermal parameters?

1.5 Research objectives

To achieve the aim of the study and to answer the research questions, the following objectives have to be completed.

- **Objective 1**: To perform a critical review of thermal comfort studies that are conducted in the Indian context.
- **Objective 2**: To study various subjective and objective parameters of thermal sensation.
- **Objective 3**: To study and analyze various indices that define the outdoor thermal comfort level.

- **Objective 4**: To conduct the on-site survey campaign to understand the subjective thermal comfort level.
- **Objective 5**: To make use of the simulation software to achieve the necessary depth in the study.
- **Objective 6**: To make use of various methods of data analysis for qualitative and quantitative evaluation of the thermal comfort level.
- **Objective 7**: To study various physical/ geometrical parameters of the built environment that affect the thermal parameters.

1.6 Scope and limitations

- The study is mainly focused on the immediate open spaces of the buildings such as public squares, plazas, pathways, etc. within urban areas.
- Qualitative and quantitative methods are used in the study.
- The study primarily focuses on the geometrical configuration of vertical surfaces.
- Since the summer season is dominated by the focused climatic zones, The months of extreme temperature are studied.
- Since the key focus is on vertical surfaces, the sites are chosen in such a way that the urban areas are having negligible vegetation.
- It was also made sure that the urban areas are not showing diversity in terms of surface materials. So that the variation caused by materials can be minimalized/negated.

1.7 Probable outcome

Outdoor spaces once again will get importance and can be used as effectively as they used to be. Also, they can be used as effectively as indoor spaces. Functions that deserve the location outdoors can go back to outdoors from indoors as a result there will be less need to construct buildings to achieve those outdoor functions. This study will give guidelines for architects, landscape architects, planners, and engineers to design thermally comfortable outdoor open spaces. It will show designers how to work with nature to create climatically sensitive spaces for human activities. It will also create a serious approach while considering the broad-scale issues such as the urban heat island effect. The outdoor spaces will not be considered as the leftover spaces once the building is constructed, whereas right from the conceptualization the designers will think about the outdoor space while designing the buildings and indoor functions.

It will also act as a base for future research since this research opens up several directions which need attention. I feel research in this field is of great scope in the future as the earth's temperature is increasing due to global warming. It is an architect's responsibility to design spaces in such a way that user experience is not affected while maintaining the thermal comfort level.

1.8 Thesis structure

Chapter 1: Introduction : Gives insight into the proposed area of research, the aim and objectives of the research, and the scope and limitations of the study.

Chapter 2: Literature review : The chapter first gives an overview of the outdoor thermal comfort studies worldwide followed by an in-depth review of studies conducted in the Indian context.

Chapter 3: Materials and methods : The chapter shows the flow of the study, the site selection, the monitoring locations, and the morphological configuration of those locations.

Chapter 4: Field study : The chapter briefs about the field survey campaign, which broadly involves two major activities; on-site micro-meteorological measurements and a questionnaire survey.

Chapter 5: Numerical simulations and validation : The chapter explains the numerical simulations used in this study that includes the purpose, development of the model, climatic input, and the general simulation settings. the chapter also discusses the validation results.

Chapter 6: Results and discussion : The chapter presents analysis, discusses, and compares the subjective thermal comfort data collected from the studied sites during the field surveys which contains analysis and discussions on thermal sensation votes, thermal comfort votes, thermal preference votes, and comparisons between the results. The chapter also discusses the results of simulations and analyses them in terms of various parameters.

Chapter 7: Conclusion : Presents the key findings through conclusions, highlights the limitations in the study, and shows the future directions. The chapter is followed by appendices and references.

2

Literature review

Studying literature is important for the proposed research in a way it gives the base to the study from various angles. These angles broadly include urban geometry, urban materials, and user response to the thermal comfort level. For the study, literature from tropical regions is preferred. There are studies carried out around the world on the topic of outdoor thermal comfort. The scopes of these studies vary based on the scale of the geographic area, climate scales such as micro-scale, mesoscale, and macro-scale climate, etc. Heldens et al. (2012,?); Wong and Nichol (2013); Taleb and Abu-Hijleh (2013); Emmanuel and Fernando (2007) performed the climatic study at a macro-scale whereas, studies Sharmin et al. (2012); Deevi and Chundeli (2020); Baghaeipoor and Nasrollahi (2019) are conducted at micro scale such as street. Studies also compared two or more neighborhoods (Villadiego and Velay-Dabat, 2014; Axarli and Chatzidimitriou, 2012). The studies were mostly carried out during the daytime since the human parameters can be evaluated when the people are observed using the space (Rupp et al., 2015). The studies targeted various climatic zones. These studies either focused on a single climatic zone or multiple climatic zones for cross-climatic analysis (Krishan, 1996; Natanian et al., 2020). Due to the diversity of the topic, in the first step of the literature study, the overview of worldwide studies is given followed by an in-depth review of Indian studies.

2.1 Overview of outdoor thermal comfort studies worldwide

There is a lack of attention to the cities under the composite climate zone. Ali and Patnaik (2017) evaluated the outdoor thermal comfort level for a composite climate of Bhopal, Madhya Pradesh, India. Most of the previous studies are undertaken in the warm and humid climates of the Indian subcontinent. These studies have highlighted the built environment as a cause of thermal discomfort. Amirtham et al. (2014) found the influence of the built geometry on the outdoor thermal comfort in Chennai, India, and identified that the sky view factor (SVF) and orientation have an impact on daytime comfort level with North-South oriented open spaces were more comfortable than East-West oriented open spaces. Another study Deevi and Chundeli (2020) investigated the factors influencing a street canyon's outdoor thermal comfort in Vijayawada, Andhra Pradesh, India. The study showed that SVF and mean radiant temperature (T_{mrt}) are major influencing factors determining thermal comfort. North-South-oriented open spaces performed better due to the shade from buildings whereas East-West-oriented open spaces perform poorly even with high height-to-width (H/W) ratios.

The effect of incident solar radiation in outdoor open spaces on thermal comfort levels for hot and dry regions was discussed in several studies. Nasrollahi et al. (2021) investigated the thermal comfort of Ahvaz, Iran, and identified that the air temperature (T_a) and mean radiant temperature (T_{mrt}) are lower in the canyons closer to north-south (N-S) orientation, T_{mrt} and physiological equivalent temperature (PET) values are lower on the west-faced sidewalks in the morning and the east-faced sidewalks in the afternoon. It was also identified that there is a strong correlation between the sky view factor (SVF) and PET, as well as SVF and T_{mrt}. Bourbia and Awbi (2004) studied two locations one having old traditional vernacular architecture and the other with modern contemporary architecture for EL-Oued City, Algeria. The study suggested that a more open and exposed nature of urban canyons can increase the daytime T_a within the canyon, because of which the SVF should be controlled. also, the thermal behavior of open spaces can be controlled by the correct orientation of buildings for shading. Another study (Ali-Toudert and Mayer, 2006) did the biometeorological assessment for PET in Algeria and achieved similar results. Achour-Younsi and Kharrat (2016) studied three different urban forms with high, medium, and low density in Tunis, Tunisia, and concluded that the higher the height-to-width (H/W) ratio, the better the thermal comfort level. N-S-oriented streets perform better in thermal comfort than east-west (E-W) oriented streets. Alobaydi et al. (2016) investigated the thermal performance of three different urban configurations having compact, attached, and detached forms and street geometries in the city of Baghdad, Iraq. It was examined that the larger H/W ratios tend to have low values of T_a and T_{mrt} due to the deep compact street canyons which help to minimize the accessibility of solar radiation. It was concluded in the study that the compact urban form represents the climate-sensitive approach.

There are several studies done for tropical climates focusing on the morphological aspects of urban areas. The study by Kakon et al. (2010) emphasized pedestrian comfort conditions in a planned residential area in the city of Dhaka, Bangladesh, and compared the condition of thermal comfort in an existing urban canyon and the same canyon with increased building height. It was found that the T_a decreased to some extent in the canyon with increased building height. Another study done for Dhaka by Sharmin et al. (2012) attempted to examine the role of the physical configuration of urban canyons in controlling the micro-climate. Results have shown that the temperature at the studied canyon was lesser than the temperature of the city at that moment, whereas the greater H/W ratio negatively affected the wind flow resulting in negative ventilation cooling. Perera and Weerasekara (2014) quantified and compared the thermal comfort implications of critical canyon geometry in warm humid Colombo. The enhanced shading potential of the North-South oriented streets over the East-West oriented streets has a positive effect in reducing the thermal stress. It was found that the more the canyon surfaces are exposed to the sky more the negative impact of the incoming solar radiation. All these studies showed that the orientation of open spaces toward North-South directions performed better.

To achieve a wider perspective, studies are also done for different regions having similar aspects. A field study done by Vuckovic et al. (2016) at various locations in Vienna, Austria, showed that the micro-climatic conditions can vary considerably depending on the site features such as urban density and morphology. Horrison and Amirtham (2016) analyzed the impact of SVF, and H/W ratio on thermal parameters to show the relationship between urban character and micro-climate modifications. The study by Haseh et al. (2018) was done in the hot and arid climate of Iran to achieve the optimal form of a courtyard. Building orientation, H/W ratios, and surface albedo were studied to arrive at the right configurations. Courtyards with enclosures on the east, south, and west showed a better environment than the rest of the courtyard options, it was also recommended to have larger height walls since a courtyard with a shorter height wall could not achieve a comfortable environment.

The study by D.S. Ranasinghe, a student from the University of Moratuwa in his master's thesis studied the urban geometry of the neighborhood of Pettah, Sri Lanka. The aim of the study is to analyze the role of urban geometry on outdoor thermal comfort. The study hypothesised the effect of shading and shaded spaces on the thermal comfort level of the people using those urban spaces. Also, the manipulation of urban masses and the increased height-to-width ratio of the built mass increases the level of thermal comfort, the orientation and the ratio of building height to the width of the street considered can be consciously modified in order to achieve thermally comfortable urban space. For the study, the densely urbanized area was selected with the issues of thermal discomfort for its users when using outdoor spaces. The author has analyzed various street orientations. According to him, the east-west orientation of the street is very difficult to create a shadow umbrella, even for the higher height-width ratio. This orientation should be avoided. Being very close to the equator the sun-path is such that the east-to-west street orientation is always exposed to direct sunlight. At this orientation, External shading devices could be used as overhangs/ projections to buildings, to create required shade to open spaces. But, building regulations may restrict it. Because of the sun path, the effect of shading in the North-South orientation is more direct and effective. An even lower height-width ratio is enough to provide a substantial shade. The two sides of the street receive sun at different times of the day. Therefore, different activities could be introduced at different times. The streets will be alive throughout the day. Height to width ratio should be increased. It will enhance the thermal comfort level of the streets. But the buildings should be located parallel to the streets.

In the second study by Kakon et al. (2010), made the assessment of thermal comfort with respect to building height in a high-density city in Tropics. According to the authors, among many design parameters, the building height is an important parameter that affects thermal comfort in the city considerably. This study investigated the effect of building height on outdoor thermal during the daytime in summer in Dhaka with an emphasis on pedestrian comfort conditions in a planned residential area in the city. Thermal comfort was assessed in terms of temperature humidity index (THI) which uses air temperature and relative humidity. Measurements were carried out on a typical summer day. In this study, the existing buildings lower than 10 stories are extended by a maximum of 4 stories to attain heights of 10 stories. The ground coverage, design, and materials of the buildings are considered to be unchanged. After increasing the building height, the average aspect ratio of this canyon is increased from 0.47-0.86. The study has compared the condition of the thermal climate in an existing urban canyon and in the same canyon with increased building height. It is found that the air temperature decreased to some extent in the canyon with increased building height. As a result THI also reduces in the canyon with increased building height. Moreover, it is revealed that during some hours of the day mean radiant temperature and the surface temperature dropped largely in the canyon with increased building height than the existing canyon. It is also observed that the wind speed is increased in the canyon.

One more study done for Dhaka by Sharmin et al. (2012), American international university, Bangladesh attempts to examine the role of a physical configuration of urban canyons in controlling the micro-climate. According to them, building height, the distance between buildings, and street widths are important design features that need to be considered at the design stage of urban outdoor spaces. The study addresses the hypothesis that it is actually possible to achieve a comfortable urban micro-climate through a careful urban arrangement. It has evaluated the thermal comfort factors for the existing urban canyon with high-rise structures and a high height-to-width ratio. The aim of this study was to explore the role of urban planning and urban design in creating a favorable urban micro-climate so that the experts are aware of its consequences at the early design stage. Integration of climatic considerations into city planning and design can thus contribute to sustainable urban development as well as mitigation of the adverse impacts of climate change. According to the authors, building designers are mostly concerned about achieving a comfortable environment indoors. But in tropical countries like Dhaka outdoor environment is equally important. The street-level wind flow is negatively affected by the greater H/W ratio, which results in reduced ventilation cooling. Throughout the study period, a larger amount of outdoor-type people were less satisfied with the thermal environment in comparison to the indoor type. This is because most of the outdoor type people were engaged in heavy physical work. On the other hand majority of the indoor type, people were exposed to discomfort for a shorter period of time.

Bourbia and Awbi (2004) in their paper 'Building cluster and shading in an urban canyon for hot dry climate' attempts to find the interaction between urban canyon geometry and incident solar radiation. In this study, the effect of building height, building surface treatment, and the effect of street width on the shading of the street surface and ground for different orientations have been examined and evaluated. Two sites were selected the traditional site and the contemporary site, both have a similar amount of vegetation to negate the difference caused by vegetation. Old City has a dense network of narrow twisting alleys, varying in width and direction facilitating shaded movement between neighborhoods. New Town is characterized by new patterns that are based mainly on the gridiron master plans, with wide roads and large open spaces. Streets with east-west and north-south orientations were selected. Results show that there are fewer air temperature variations compared to the surface temperature which really depends on the street geometry and sky view factor. At the contemporary site, the direct solar radiation in the summer season reaches a considerably large portion of the building's surface area. This greater contribution of direct solar radiation, due to the large sky view factor in the accelerated increase of air temperature inside the canyon. Increase in the surface temperature of the wall facing south and the temperature of the east-West Street is caused primarily by the lack of shading resulting from the difference in height between the north wall and the south wall. This causes an increase in solar absorption by all the exposed surfaces. This study is relevant for the proposed research since it talks about vertical surface spacing is an important consideration while planning or setting the norm for a particular zone of an urban area.

Shamsuddeen Abdullahi (2016) in their research 'Facade greening -A way to attain sustainable built environment' outlined different types of green facades and their benefits to the built environment. Paper aimed at discussing how facade greening positively affect the built environment through the moderation of air quality, mitigate urban heat stress through transpiration cooling and shading. Author has studied Effect of green facades on urban heat island. Microclimate of a particular area can be affected by facades and the streets around it due to their impermeable nature. This causes discomfort and increases in the amount of energy required for cooling. In this case, the use of greenery on concrete roofs and facades whereby the heat will be consumed through the process of evapotranspiration can be a possible solution. The use of greenery on building façade as shades to solar radiation is obvious, with the advantage that the traditional concrete or brick facades which radiate the heat in and around the building, while greenery does not. This depends crucially on the density of the foliage. The use of vegetation on building facades in form of living walls, green facades, and vertical gardens offers an outstanding number of public and private benefits such as: aesthetic, social, ecological, and environmental and it fits in the principle of ecological engineering.

Dessi (2011) in her paper titled 'Urban materials for comfortable open spaces' showed how the urban space thermal performances change when only one or two walls are considered and if differences occur when the analyzed area is near or far from the wall, as well as when building height changes. A first part considered open space as reference case and evaluates how the thermal performance change according to the changing context I.e. from open space to the corner of the square. Second part points out the differences among the materials due to the physical properties, like albedo, thermal capacity, and density. During a sunny day the surface temperature increases as the albedo decreases, in other words dark colors corresponds to higher temperature and vice versa. Clear and smooth materials like the marble have surface temperature are similar to the air temperature thus they behave as they are in shadow. So one of the clear strategy to reduce UHI consists of using clear materials because they don't heat and reflect solar radiation. The solar radiation reflected from a clear surface like the marble can be easily redirect to a space user. In the heat balance we have the surface temperature with the whole radiation including the reflected one. This study highlights one of the important point that the user spacing from the vertical surface and its material is an important factor. Various users within same premises can have different opinion about the thermal comfort they achieve, reason can be their distance from the vertical surface.

Purpose of the next study is to get an understanding of how people use outdoor public spaces in different climatic conditions. Hocine boumaraf and Abdelmalek Tacherift studied the impact of the micro-climate on space use and the user behavior. For the study, video observations for behavior data, climatic measurement, and interviews with the users. Authors were being able to examine whether the micro-climatic conditions affect people's activities, and more specifically, whether the micro climatic characteristics of a given area favor or hinder the development of particular activities. It was also identified the impact of personal factors like age, gender frequency, and the square knowledge degree on the space perception and sensibility to the micro climatic variations.

Thermal comfort is a subjective response to the thermal condition of the specific space. Tzu ping Lin Department of Leisure Planning, National Formosa University, Taiwan in his paper titled 'Thermal perception, adaptation, and attendance in Public Square in hot and humid regions' analyzed an individual's thermal perception and adaptation for Hot and humid region.

Table 2.1: Studies selected for the review

Study no.	Study	Title
01	(Manavvi and Rajasekar, 2022)	Evaluating outdoor thermal comfort in urban open spaces in a humid subtropical climate: Chandigarh, India.
02	(Manavvi and Rajasekar, 2021)	Evaluating outdoor thermal comfort in “Haats” – The open-air markets in a humid subtropical region.
03	(Kumar and Sharma, 2021a)	Assessing outdoor thermal comfort conditions at an urban park during summer in the hot semi-arid region of India.
04	(Kumar and Sharma, 2021b)	Assessing The Thermal Comfort Conditions In Open Spaces: A Transversal Field Survey On The University Campus In India.
05	(Mohammad et al., 2021)	Evaluating the role of the albedo of material and vegetation scenarios along the urban street canyon for improving pedestrian thermal comfort outdoors.
06	(Rajan and Amirtham, 2021a)	Impact of building regulations on the perceived outdoor thermal comfort in the mixed-use neighborhood of Chennai.
07	(Rajan and Amirtham, 2021b)	Urban heat island intensity and evaluation of outdoor thermal comfort in Chennai, India.
08	(Das and Das, 2020)	Exploring the pattern of outdoor thermal comfort (OTC) in a tropical planning region of eastern India during summer.
09	(Das et al., 2020)	Outdoor thermal comfort in different settings of a tropical planning region: A study on Sriniketan-Santiniketan Planning Area (SSPA), Eastern India.
10	(Banerjee et al., 2020)	Outdoor thermal comfort in various micro-entrepreneurial settings in hot humid tropical Kolkata: Human biometeorological assessment of objective and subjective parameters.
11	(Deevi and Chundeli, 2020)	Quantitative outdoor thermal comfort assessment of street: A case in a warm and humid climate of India.
12	(Manavvi and Rajasekar, 2019)	Semantics of outdoor thermal comfort in religious squares of composite climate: New Delhi, India.
13	(Ziaul and Pal, 2019)	Assessing outdoor thermal comfort of English Bazar Municipality and its surrounding, West Bengal, India.
14	(Ali and Patnaik, 2017)	Thermal comfort in urban open spaces: Objective assessment and subjective perception study in the tropical city of Bhopal, India.
15	(Bhaskar and Mukherjee, 2017)	Optimizing Street Canyon Orientation for Rajarhat Newtown, Kolkata, India.
16	(Horrison and Amirtham, 2016)	Role of Built Environment on Factors Affecting Outdoor Thermal Comfort - A Case of T. Nagar, Chennai, India.
17	(Amirtham et al., 2015)	Impact of urban morphology on microclimatic conditions and outdoor thermal comfort – A study in a mixed residential neighborhood of Chennai, India.
18	(Amirtham et al., 2014)	Study on the Microclimatic Conditions and Thermal Comfort in an Institutional Campus in Hot Humid Climate.

According to his study, thermal adaptation, which involves physiological, psychological and behavioral factors, also plays an important role in the assessment of thermal environments by users. The study examined user thermal comfort in a public square in Taiwan. Physical measurements were taken and a questionnaire survey was used to assess the thermal comfort of subjects. Analytical results indicate that the thermal comfort range and neutral temperature of subjects were higher than those of people in the temperature region.

Currently, there are no studies which conducted the review for Indian context. For this reason, it is not clear the status of the studies performed already, the gaps available and what kind of studies required in the future. For this reason the critical review is performed by the author of this thesis. 18 Indian studies were finally selected for the review.

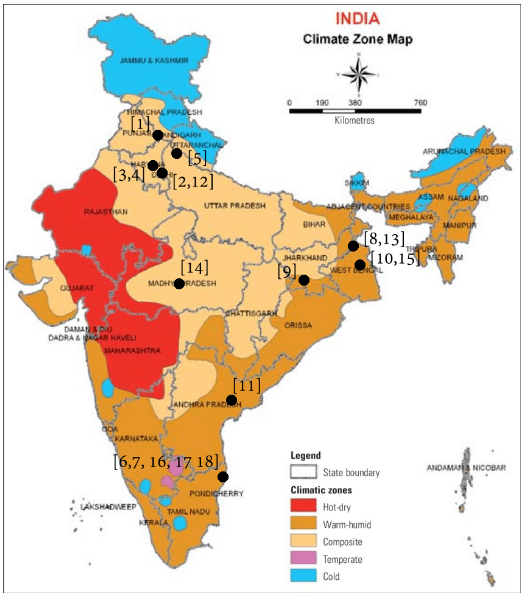


Figure 2.1: Past studies conducted in India with respect to climatic zones of India

2.2 Aim of the review

The current status of outdoor thermal comfort in India and its comparative scenario are not available. Because of which, it is difficult to decide which climatic region, site, population needs to be studied and requires urgent attention. 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 in a comparative manner. Following this, the shortcomings and gaps are identified.

2.3 Review methodology

The following search procedure and selection criteria were followed to select appropriate studies for the review.

In the first step major databases were searched. The keywords used were finalized in order to get the most appropriate results. The Keywords used were "thermal comfort", "thermal per-

Table 2.2: Summary of the studies

Study	Year	Published in Journal	City (State)	Climatic region	Season studied
(Manavvi and Rajasekar, 2022)	2022	Building and Environment	Chandigarh (UT)	Composite	Summer and winter
(Manavvi and Rajasekar, 2021)	2021	Building and Environment	New Delhi (UT)	Composite	Summer
(Kumar and Sharma, 2021a)	2021	Materials today: proceedings	Sofidon (Haryana)	Composite	summer
(Kumar and Sharma, 2021b)	2021	International journal of built environment and sustainability	Sonepat (Haryana)	Composite	Winter
(Mohammad et al., 2021)	2021	Urban Climate	Roorkee (Uttarakhand)	Composite	Summer
(Rajan and Amirtham, 2021a)	2021	Frontiers of Architectural Research	Chennai (Tamil Nadu)	Warm-humid	Summer
(Rajan and Amirtham, 2021b)	2021	Environment, Development and Sustainability	Chennai (Tamil Nadu)	Warm-humid	Summer and winter
(Das and Das, 2020)	2020	Urban climate	Sriniketan-Santiniketan (West Bengal)	Warm-humid	Summer
(Das et al., 2020)	2020	Sustainable Cities and Society	Chotanagpur (Jharkhand)	Warm-humid	Summer and winter
(Banerjee et al., 2020)	2020	Science of the Total Environment	Kolkata (West Bengal)	Warm-humid	Summer and winter
(Deevi and Chundeli, 2020)	2020	Urban Climate	Vijayawada (Andhra Pradesh)	Warm-humid	Summer and winter
(Manavvi and Rajasekar, 2019)	2019	International Journal of Biometeorology	New Delhi (UT)	Composite	Summer
(Ziaul and Pal, 2019)	2019	Advances in Space Research	English bazar (West Bengal)	Warm-humid	Summer, winter and post monsoon
(Ali and Patnaik, 2017)	2017	Urban climate	Bhopal (Madhya Pradesh)	Composite	Summer
(Bhaskar and Mukherjee, 2017)	2017	Environmental and Climate Technologies	Kolkata (West Bengal)	Warm-humid	Summer
(Horrison and Amirtham, 2016)	2016	Indian Journal of Science and Technology	Chennai (Tamil Nadu)	Warm-humid	Winter
(Amirtham et al., 2015)	2015	ICUC9 Conference	Chennai (Tamil Nadu)	Warm-humid	Summer
(Amirtham et al., 2014)	2014	30th Plea Conference	Chennai (Tamil Nadu)	Warm-humid	Summer

ception", "urban thermal comfort", "outdoor thermal comfort", and "thermal comfort in India". Out of the major databases, the very first google scholar, Scopus, and Web of Science were searched, followed by other indexes such as Research Gate, Science direct, and PubMed. Publishers' websites such as Taylor and Francis, SAGE Publications, MDPI, Springer, Hindawi, Wiley, and Emerald were also searched. The search resulted in original journal articles, review articles, conference papers, and a Ph.D. thesis.

In the second step filtration process was conducted manually which involved several micro steps. First, all the studies done for the sites outside India were excluded due to the scope of this review paper. Next, the scale of the project was given attention. The studies done at the regional scale such as macro climate studies, climate change studies, and studies on urban heat islands that are focused on much larger regions were excluded. Since the focus of the review is outdoor thermal comfort, the studies which do not focus on outdoor areas and studies that have not considered subjective and objective thermal comfort parameters were also excluded. Studies published before 2012 were excluded.

The third step deals with the final selection of the articles. The abstracts and conclusion sections of the research articles obtained after filtration were carefully read to understand the scope of the articles and to get an overview. Studies focused on the built environment at an architectural, neighbourhood, and urban scales published between the years 2012 and 2022 were considered. 18 articles were finally selected for the review. Tables 2.1 and 2.2 give the overview of those studies.

2.4 Discussion of the results obtained

2.4.1 The focus of the reviewed studies

Koppen climate classification(Koppen, 2011; Kottek et al., 2006) is the climate classification system used throughout the world. India had developed its own climate classification system known as 'climatic zones of India' (Bureau of Indian Standards, 2005) (Figure 2.1). In this whole manuscript climatic zones of India is referred since the study is based in India. Reviewed 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.

Seven studies are conducted at composite climate zone. Some studies (Ali and Patnaik, 2017; Manavvi and Rajasekar, 2022) are focused on physical features of the urban areas such as waterfront, green open spaces and open spaces enclosed by built masses. Manavvi and Rajasekar (2021) is focused only on the marketplaces whereas Manavvi and Rajasekar (2019) is focused on religious squares. Studies conducted by Kumar and Sharma (2021a) and Kumar and Sharma (2021b) are focused on public park and university campus respectively. The study by Mohammad et al. (2021) focused on the albedo of materials and vegetation.

Five studies (Amirtham et al., 2014; Horrison and Amirtham, 2016; Rajan and Amirtham, 2021a,b; Amirtham et al., 2015) are conducted in warm and humid climate of Chennai, five

Table 2.3: Built environment classification with physical parameters

Study	Built environment	Physical/ Geometrical parameters
(Manavvi and Rajasekar, 2022)	Plaza, green and waterfront	SVF, percentage of tree cover
(Manavvi and Rajasekar, 2021)	The open air markets at 2 locations	SVF, frequency of shade
(Kumar and Sharma, 2021a)	City park	*-NS-*
(Kumar and Sharma, 2021b)	University campus of DCRUST	*-NS-*
(Mohammad et al., 2021)	Single linear street	SVF
(Rajan and Amirtham, 2021a)	Various morphologies defined with LCZs	SVF, H/W
(Rajan and Amirtham, 2021b)	Streets and open spaces	SVF
(Das and Das, 2020)	Various morphologies defined with LCZs	*-NS-*
(Das et al., 2020)	Various morphologies defined with LCZs	*-NS-*
(Banerjee et al., 2020)	Various morphologies of varying heights	SVF, H/W
(Deevi and Chundeli, 2020)	Street with varying building heights	SVF, H/W, and orientation
(Manavvi and Rajasekar, 2019)	two religious squares.	SVF
(Ziaul and Pal, 2019)	Morphologies of varying densities	Open mid rise, compact low rise and open low rise
(Ali and Patnaik, 2017)	Parks, lakefronts, open spaces	Tree canopy density
(Bhaskar and Mukherjee, 2017)	Street orientations	Seven alternative orientations with 15° increment
(Horrison and Amirtham, 2016)	Streets and open spaces within the neighborhood	H/W, SVF, built density, and orientation
(Amirtham et al., 2015)	Various morphologies	H/W, SVF, built density
(Amirtham et al., 2014)	University campus of Satyabhama University	SVF, H/W, green cover, and orientation

studies (Das and Das, 2020; Das et al., 2020; Banerjee et al., 2020; Ziaul and Pal, 2019; Bhaskar and Mukherjee, 2017) are conducted in warm and humid climate of West Bengal, and one study (Deevi and Chundeli, 2020) was conducted in warm and humid Vijaywada.

2.4.2 Study of built environment

Table 2.3 shows the built environments focused on by the reviewed studies. Built environment is primarily distinguished by physical factors such as land-use, morphology of built forms etc. Manavvi and Rajasekar (2022) and Ali and Patnaik (2017) evaluated the outdoor thermal comfort level in three different urban settings: Green space, waterfront, and plaza. Canopy cover of vegetation is used by Manavvi and Rajasekar (2022) and Ali and Patnaik (2017). (Manavvi and Rajasekar, 2021, 2019) evaluated thermal comfort by comparing urban squares, few studies (Amirtham et al., 2014; Kumar and Sharma, 2021b) are performed in the educational campuses, whereas some studies (Deevi and Chundeli, 2020; Horrison and Amirtham, 2016; Mohammad et al., 2021; Rajan and Amirtham, 2021b; Bhaskar and Mukherjee, 2017) are focused on urban streets. Geometrical parameters such as height to width ratio (H/W), sky view factor (SVF) and orientations are also commonly used by hte studies. Bhaskar and Mukherjee (2017) explored various alternative orientation to get hte optimised thermal comfort level. Some studies have classified into local climatic zones (LCZ) which is proposed by Stewart and Oke (2012). Out of reviewed studies Rajan and Amirtham (2021a); Das and Das (2020); Das et al. (2020) used

Table 2.4: Micro-meteorological measurements, software used, and indices evaluated

Study	Micrometeorological measurements	Software used	Indices evaluated	Validation
(Manavvi and Rajasekar, 2022)	T_a, R_h, V_a, T_g, T_s, K↓, K↑, L↓, L↑	RayMan	T_{mrt}, PET	*-NS-*
(Manavvi and Rajasekar, 2021)	T_a, R_h, V_a, T_g, K↓, K↑, L↓, L↑	RayMan	T_{mrt}, PET	*-NS-*
(Kumar and Sharma, 2021a)	T_a, R_h, V_a, T_g, WBGT	RayMan	UTCI, PET, WBGT	*-NS-*
(Kumar and Sharma, 2021b)	T_a, R_h, V_a	RayMan	PET	*-NS-*
(Mohammad et al., 2021)	T_a, R_h, V_a, T_g, and T_s	RayMan, Envi-met	T_{mrt}, PET	R^2= 0.80 to 0.93
(Rajan and Amirtham, 2021a)	T_a, R_h	Envi-met	T_{mrt}, PET	R^2= 0.65 to 0.71
(Rajan and Amirtham, 2021b)	T_a, R_h	Envi-met	T_{mrt}, PET	R^2= 0.51 to 0.91
(Das and Das, 2020)	T_a, R_h, V_a, LST	*-NS-*	UTCI,THI	*-NS-*
(Das et al., 2020)	T_a, R_h, V_a, LST	*-NS-*	PET, SET, DI	*-NS-*
(Banerjee et al., 2020)	T_a, R_h, V_a, T_g,	RayMan	PET	*-NS-*
(Deevi and Chundeli, 2020)	T_a, R_h, V_a	Ecotect, RayMan	PET	*-NS-*
(Manavvi and Rajasekar, 2019)	T_a, R_h, V_a, T_g,	RayMan	PET, UTCI, T_{mrt}	*-NS-*
(Ziaul and Pal, 2019)	T_a, R_h, V_a	RayMan	DI, PET, PMV, T_{mrt}	*-NS-*
(Ali and Patnaik, 2017)	T_a, R_h, V_a, T_g, C*c*	RayMan	PET	*-NS-*
(Bhaskar and Mukherjee, 2017)	T_a, V_a	Envi-met	T_{mrt}, PET	R^2= 0.97, RMSE= 0.411 °C, *d*= 0.995
(Horrison and Amirtham, 2016)	T_a, R_h	RayMan	T_a, R_h	*-NS-*
(Amirtham et al., 2015)	T_a, R_h, V_a, T_g	RayMan	T_{mrt}, PET	*-NS-*
(Amirtham et al., 2014)	T_a, R_h, V_a, T_g	RayMan	PET	*-NS-*

LCZ classification. For the differentiation in the built geometry, material characteristics are also used by the studies (Amirtham et al., 2014; Mohammad et al., 2021).

Some studies (Kumar and Sharma, 2021a,b; Das and Das, 2020; Das et al., 2020) did not used any parameters to differentiate the built environment, these studies used subjective and objective parameters for the evaluation of thermal comfort evaluation.

2.4.3 Micro meteorological measurements

Measurements of micro-meteorological parameters in site is an important step for the outdoor thermal comfort studies. Table 2.4 shows the micro-meteorological measurements taken on site, software used for the evaluation of various indices, and validation outcome of the reviewed studies.

T_a (°C), R_h (%), V_a (m/s), and T_g (°C) are commonly measured indices on site. These indices can be directly used for the analysis or can be used as an input for the development of other indices such as T_{mrt}. Some studies (Manavvi and Rajasekar, 2022, 2021) also measured incoming and outgoing short wave (K↓, K↑) and long wave (L↓ and L↑) radiant flux densities. Kumar and Sharma (2021a) measured WBGT (°C) with a WBGT meter.

When measuring the indices on site, studies have followed certain protocols. These protocols are about the weather conditions, timings and seasons preferred; and the placement of instruments on site. Studies (Deevi and Chundeli, 2020; Kumar and Sharma, 2021a; Das and Das, 2020; Das et al., 2020; Banerjee et al., 2020) installed the mini weather station on 1.1 m hight which follows the prtocols by earlier studies (ASHRAE-55, 2010; Mayer and Hoppe, 1987; Thorsson et al., 2007; Fang et al., 2018; Johansson et al., 2018). studies (Manavvi and Rajasekar, 2022, 2021, 2019) set the instruments on 1.2 m height whereas Mohammad et al. (2021) took 1.5 m height. The study by Rajan and Amirtham (2021b) is the exception which considered 2.5 m height due to the site specific constraints.

2.4.4 Use of software and its validation

Studies used software for simulation and calculations of the indices which can not be measured directly on site with the measuring instruments. RayMan (Matzarakis et al., 1999) and Envi-met (Bruse and Fleer, 1998) are commonly used software. RayMan is used for T_{mrt} and PET calculations whereas Envi-met is used for simulation the outdoor environment. Envi-met gives graphical as well as statistical output for various indices. (Lee et al., 2016) compared Envi-met and RayMan and suggested that Envi-met is more suitable for outdoor thermal comfort studies than RayMan.

Whichever software is used, it is not recommended to analyse the output without validating the model. The validation is usually performed with the on-site measurements. Most of the reviewed studies have used measured T_a and simulated T_a for the validation. Linear regression (R^2), root mean square error (RMSE) and index of agreement (d) methods are usually used for the validation.

2.4.5 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.

To date, various thermal comfort indices have been used. Potchter et al. (2018) 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 (Shooshtarian et al., 2020; Johansson et al., 2014) also found that the PET is the widely used index to evaluate the thermal comfort of users. 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 (Mayer and Hoppe, 1987). It is based on a two-node Munich energy balance model (Höppe, 1993, 1999). The heat balance of PET is given by equation 2.1.

$$M + W + R + C + E_D + E_{Re} + E_{SW} + S = 0 \tag{2.1}$$

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 (Tan et al., 2013). There are various methods to determine the T_{mrt} (Thorsson et al., 2007). Studies Rajan and Amirtham (2021) , Ziaul and Pal (2019), and Perera and Weerasekara (2014) achieved T_{mrt} from the simulation outputs. T_{mrt} is recommended by ISO 7726: 1998 (Geneva: International Organization for Standardization, 1998) and given by equations 2.2, 2.3 and 2.4. These equations are useful when a globe thermometer is used and combined with measurements of T_a and V_a. Equation 2.3 is used by Banerjee et al. (2020) for the calculation using measured Tg with an emissivity of 0.95 and a globe diameter of 120 mm, whereas equation 2.4 is used by Ali and Patnaik (2017) for the calculation using 40mm 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 case of equation 2.2). Equation 2.4 is a simplified equation where a mean convection coefficient and globe emissivity are kept constant. Nowadays, T_{mrt} can be easily calculated with the help of softwares such as RayMan and Envi-met.

$$Tmrt = \left[(Tg+273)^4 + \frac{3.42*10^9 Va^{0.119}}{eD^{0.4}} * (Tg-Ta)\right]^{0.25} - 273.15 \tag{2.2}$$

$$Tmrt = \left[(Tg+273)^4 + \frac{1.1*10^8 Va^{0.6}}{eD^{0.4}} * (Tg-Ta)\right]^{0.25} - 273.15 \tag{2.3}$$

$$Tmrt = Tg + 273 * Va^{0.5} * (Tg-Ta) \tag{2.4}$$

The universal thermal climate index (UTCI) is defined as the air temperature of the reference condition causing the same model response as actual conditions (Błazejczyk et al., 2013). It is based on Fiala's (Fiala et al., 2012) multi-node model. UTCI is very sensitive to changes in temperature, solar radiation, wind, and humidity. It depicts temporal variability of thermal conditions better than other indices (Blazejczyk et al., 2012; Jendritzky et al., 2012). It can be computed using the software developed by Brode et al. (2009). It can also be evaluated with the equation 2.5. As of now, it is not a popular index at the Indian context and its reliability also needs to be tested. Only Kumar and Sharma (2021a); Das and Das (2020); Manavvi and Rajasekar (2019) used UTCI in their studies.

$$UTCI = f(Ta; Tmrt; Va; Rh) \tag{2.5}$$

THI is a measure of the reaction of the human body to a combination of heat and humidity (Thom, 1959; Schlatter, 1987). According to Eludoyin and Adelekan (2013), and Eludoyin (2014) for tropical climates, THI is the most relevant thermal comfort index. It is evaluated with the equation 2.6. Das and Das (2020) used THI along with UTCI for warm and humid climate of West Bengal.

$$THI = 0.8 * Ta + (Rh * Ta)/500 \tag{2.6}$$

DI is a physiological thermal stress indicator that was developed by Thom (1959). It is based on the T_a and R_h and evaluated with equation 2.7. Das et al. (2020) and Ziaul and Pal (2019) used DI.

$$DI = Ta - 0.55(1 - 0.01Rh)(Ta - 14.5) \tag{2.7}$$

SET (Gagge et al., 1971) and OUT-SET (Pickup and de Dear, 2000) use two-node models. OUT-SET is an adapted version of SET to the outdoor environment. SET is defined as the air temperature at which, in a given reference environment, the person has the same skin temperature and wetness as in the real environment. Das et al. (2020) used SET in their study.

WBGT (Yaglou and Minard, 1957) is an outdoor heat stress index in a hot environment (Lin et al., 2013). It is a thermo-physiological index that measures the heat stress of an individual under direct sunlight (Chow et al., 2016). Equation 2.8 (ISO 7933, 1989) shows the index without direct solar radiation whereas equation 2.9 (ISO 7933, 1989) shows the index with direct solar radiation. Kumar and Sharma (2021b) used equation 2.9.

$$WBGT = 0.7Tw + 0.3Tg \tag{2.8}$$

$$WBGT = 0.7Tw + 0.2Tg + 0.1Ta \tag{2.9}$$

Ziaul and Pal (2019) used predicted mean vote (PMV) (Fagner, 1972) 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 outdoor environment by Jendritzky and Nübler (1981), and developed a model called as Klima-Michel Model (KMM). Later-on several other studies adopted PMV to outdoor environments. It overestimates the thermal sensation experienced by Indians, since Indians may have a wider thermal comfort range, especially concerning hotter temperatures (Nutkiewicz et al., 2018). For this reason, though it is widely used in the last ten years all over the world (Grifoni et al., 2013), Indian studies did not rely on this index.

2.4.6 On-site questionnaire survey

Table 2.5 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 (Mohammad et al., 2021), university campus (Amirtham et al., 2014; Kumar and Sharma, 2021b), and city park (Kumar and Sharma, 2021a). The sample size of the studies typically ranged between

Table 2.5: Parameters evaluated from questionnaire

Study	Target population	Sample size	TSV	SSV	WSV	HSV	TC	Acceptability	Preference
(Manavvi and Rajasekar, 2022)	Plaza, green and waterfront	2585	✓	*-NS-*	✓	✓	✓	✓	✓
(Manavvi and Rajasekar, 2021)	Marketplaces	392	✓	✓	✓	✓	*-NS-*	✓	✓
(Kumar and Sharma, 2021a)	City park	55	✓	*-NS-*	*-NS-*	*-NS-*	✓	*-NS-*	*-NS-*
(Kumar and Sharma, 2021b)	University campus	185	✓	✓	✓	✓	✓	✓	✓
(Mohammad et al., 2021)	Street	73	✓	*-NS-*	*-NS-*	*-NS-*	*-NS-*	*-NS-*	✓
(Das and Das, 2020)	23 sites	200	✓	✓	✓	✓	*-NS-*	*-NS-*	*-NS-*
(Das et al., 2020)	23 sites	200	✓	✓	✓	✓	*-NS-*	*-NS-*	*-NS-*
(Banerjee et al., 2020)	Neighbourhoods	318	✓	*-NS-*	✓	*-NS-*	✓	✓	*-NS-*
(Deevi and Chundeli, 2020)	Local street vendor	94	✓	*-NS-*	*-NS-*	*-NS-*	*-NS-*	*-NS-*	*-NS-*
(Manavvi and Rajasekar, 2019)	Religious squares	353	✓	✓	✓	✓	-	✓	✓
(Ziaul and Pal, 2019)	Various densities	250	✓	*-NS-*	*-NS-*	*-NS-*	*-NS-*	*-NS-*	*-NS-*
(Ali and Patnaik, 2017)	Visitors and vendors	240	✓	*-NS-*	*-NS-*	*-NS-*	✓	*-NS-*	*-NS-*
(Amirtham et al., 2015)	Residential neighbourhood	-*NA-*	✓	*-NS-*	*-NS-*	*-NS-*	*-NS-*	*-NS-*	*-NS-*
(Amirtham et al., 2014)	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

200 to 400 users.

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 (2022) adopted the questionnaire from Johansson et al. (2014) which has a higher potential to rescale the thermal indices. The questionnaire utilized by Mohammad et al. (2021) is based on previous research (Nasrollahi et al., 2021; Johansson et al., 2018) and ASHRAE 55 standard (ASHRAE-55, 2010; De Dear and Brager, 2002). Kumar and Sharma (2021b) designed the questionnaire based on ISO 2001 (ISO 2019, 2019).

Current studies generally neglect psychological, socio-economic, and cultural factors (Nazarian and Lee, 2021; Dzyuban et al., 2022), and assume steady-state conditions for outdoor subjects (Aljawabra and Nikolopoulou, 2010). Ali and Patnaik (2017) done the demographic profiling based on the Kuppuswamy scale (Oberoi, 2015). Ali and Patnaik (2017) 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 (2019) who found that gender has a weak influence on thermal perception which agrees well with Shooshtarian and Ridley (2016) but contradicts with Lam et al. (2018). Thermal perception can vary as per age also. Manavvi and Rajasekar (2019) 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 is given by the standards (ASHRAE, 2001, 2004, 2013). Studies (Manavvi and Rajasekar, 2022, 2019) calculated clothing values with reference to (ASHRAE, 2013; Indraganti et al., 2015) whereas, Banerjee et al. (2020) adopted clothing values from the study (Nicol et al., 1999) which suggest the clothing values for traditional Indian subcontinent.

2.4.7 Thermal comfort evaluation parameters and measurement scales

Figure 2.2 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 (Dzyuban et al., 2022). The study (Gagge et al., 1967) first used the descriptive and affective scales. The combination of these three scales explains the thermal comfort level in a better manner (Shahzad et al., 2018).

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 2.5). It is different from the thermal comfort level. Thermal sensation and thermal comfort describe two different attitudes towards micro-climate (Auliciems, 1981; Shooshtarian and Rajagopalan, 2017). The thermal sensation is a conscious feeling generally evaluated on the seven-point scale (ASHRAE-55, 2010; Brager et al., 1993; Shooshtarian, 2019).

As per ASHRAE 55 (ASHRAE-55, 2010), the thermal sensation scale is a seven-point ordinal scale. Zhang and Zhao (2009) and Schweiker et al. (2017) 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 (2022), and Manavvi and Rajasekar (2021) evaluated the thermal sensation on a nine-point ordinal scale for the composite

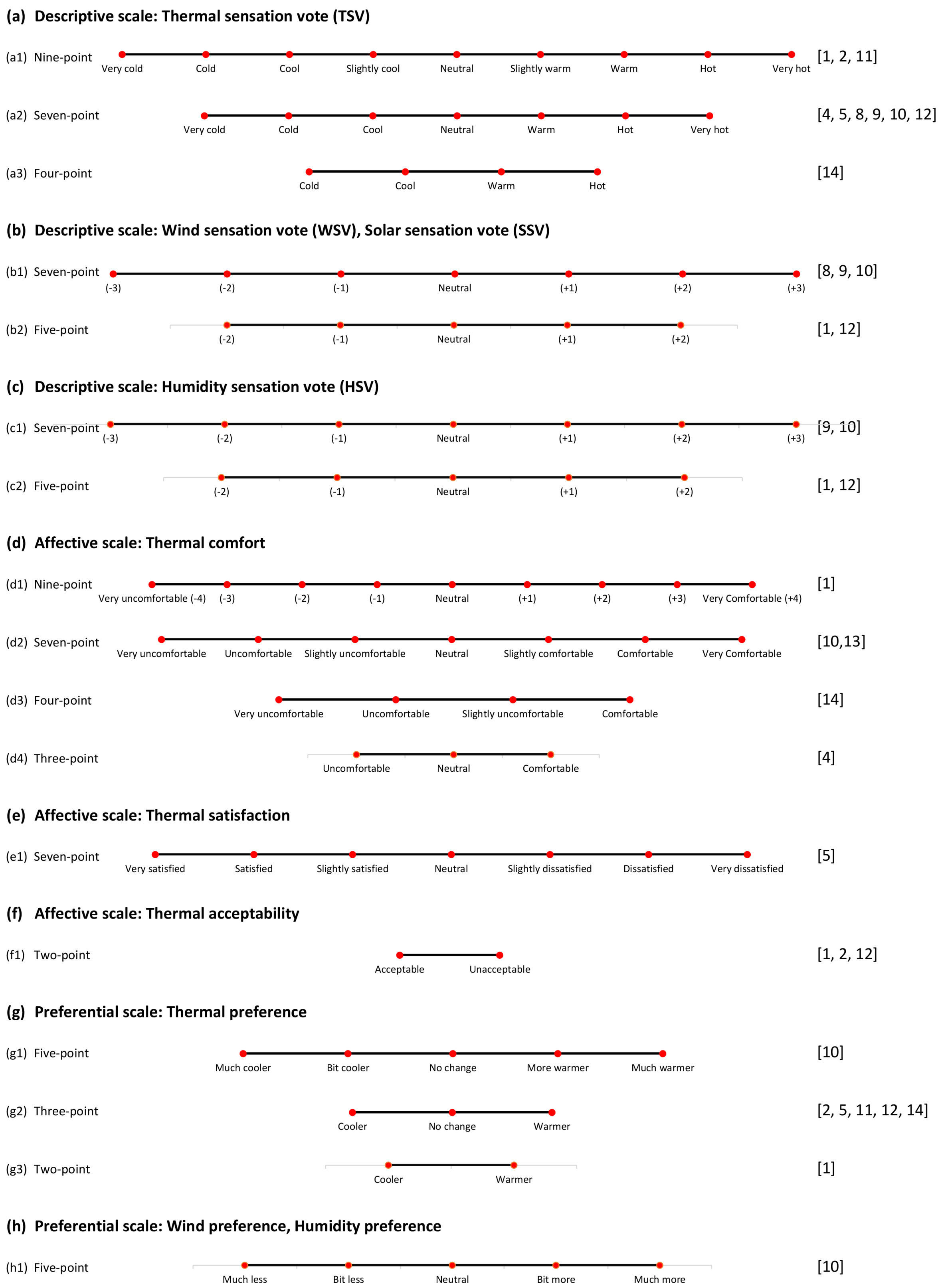


Figure 2.2: Measurement scales used in the studies

climate of New Delhi where extreme climate situation is observed. (Deevi and Chundeli, 2020) followed a seven-point scale, whereas (Ali and Patnaik, 2017) used a four-point scale for the

ASV referred from the international standard (ISO, 1995) (later on revised (ISO 2019, 2019)) to measure thermal sensation level.

HSV, WSV, and SSV were evaluated on a five-point Likert scale by Manavvi and Rajasekar (2022), and Manavvi and Rajasekar (2021), whereas Banerjee et al. (2020) and Das et al. (2020) evaluated HSV on a seven-point scale (dry to very humid). Banerjee et al. (2020) taken SSV on a seven-point scale (very soothing to very harsh).

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 (ASHRAE-55, 2010). Ali and Patnaik (2017) used a four-point thermal comfort scale (ISO, 1995) 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 (de Dear and Schiller Brager, 2001). Mohammad et al. (2021) used seven-point scale (Figure 2.2 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 (Manavvi and Rajasekar, 2022, 2021, 2019) used a two-point scale for thermal acceptability.

Thermal preference is an ideal condition an individual would favour in the thermal environment (Dzyuban et al., 2022; de Dear and Schiller Brager, 2001; Lin, 2009). Studies (Deevi and Chundeli, 2020; Ali and Patnaik, 2017; Manavvi and Rajasekar, 2021; Mohammad et al., 2021; Manavvi and Rajasekar, 2019) used three-point McIntyre scale ((-1) Prefer warmer; (0) No change; (+1) Prefer cooler). Manavvi and Rajasekar (2022) used a two-point scale: want cooler and want warmer whereas a five-point scale is used by Banerjee et al. (2020).

Mohammad et al. (2021), and Ali and Patnaik (2017) used a three-point scale with more humid (+1), same (0), and less humid (-1). (Banerjee et al., 2020) 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.

2.4.8 Acclimatization and adaptation

Acclimatization is one of the determinants of outdoor thermal comfort level (Johansson et al., 2018; Middel et al., 2016; Kruger et al., 2017; Yang et al., 2017; Kantor et al., 2012). Banerjee et al. (2020) highlighted the importance of acclimatization. The study 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.

Nikolopoulou and Steemers (2003) defines three kinds of adaptation: physiological, physical, and psychological. Nikolopoulou (2011) included two more kinds of adaptations: reactive and interactive. Psychological adaptation promotes the presence of people in an urban space (Zabetian and Kheyroddin, 2019). Manavvi and Rajasekar (2019) 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 (2022) also highlighted 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 (2021) 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.

2.4.9 Thermal neutrality

Thermal neutrality is the mean vote on the thermal sensation scale that indicates neutral (ASHRAE-55, 2010). 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 2.6).

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 2.6, 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 (Kantor et al., 2016; Hirashima et al.,

Table 2.6: Thermal neutrality achieved by studies

Study	City	Indices correlated	Values of R^2	Neutral value	Acceptable range
(Manavvi and Rajasekar, 2022)	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
(Manavvi and Rajasekar, 2021)	New Delhi	mTSV vs PET	R^2= 0.63	24.70°C (PET)	*-NS-*
(Manavvi and Rajasekar, 2019)	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-*
(Kumar and Sharma, 2021a)	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
(Kumar and Sharma, 2021b)	Sonepat	mTSV vs PET	R^2= 0.65	21.89°C (PET)	18.42°C to 25.37°C
(Mohammad et al., 2021)	Roorkee	mTSV vs PET	R^2= 0.91	19.91°C (PET)	17.27°C to 22.56°C
(Banerjee et al., 2020)	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

2016). Even increments are permitted in linear regression, whereas uneven increments are permitted in probit regression (Spagnolo and de Dear, 2003). Manavvi and Rajasekar (2022) is the only study from the reviewed studies that used 2-probit regression and compared the results with 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 2.6). 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 (Lin et al., 2017) 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 (2022) 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 (2021) 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 (Ziaul and Pal, 2019) is 21°C-24°C with a comfort range of 18°C-21°C whereas the comfort range defined by Thom (1959) 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 as 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. (2018) is 26°C - 30°C for Taiwan, Matzarakis and Mayer (1996) achieved 18°C - 23°C for Europe whereas, Cohen et al. (2013) 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.

2.4.10 Effect of physical and climatic parameters on thermal comfort

Table 2.7 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 (2020) 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 (Ali and Patnaik, 2017; Manavvi and Rajasekar, 2022; Das et al., 2020; Ziaul and Pal, 2019) observed lower PET in vegetated spaces. The density of the built environment also affects the thermal comfort level. (Bhaskar and Mukherjee, 2017) found that densely built areas reduced the T_a up to 0.7°C. On the contrary, density negatively affected the thermal comfort in the study (Horrison and Amirtham,

Table 2.7: Relationship between physical parameters and thermal comfort indices

Study	Influence	Effect on Index	Method (Relationship)	Key results
(Manavvi and Rajasekar, 2022)	SVF	PET (Summer)	R^2= 0.81 (Strong)	SVF >0.5 is 3.8°C higher than SVF <0.5
(Manavvi and Rajasekar, 2022)	SVF	PET (Winter)	R^2= 0.64 (Strong)	SVF >0.5 is 5.3°C higher than SVF <0.5
(Mohammad et al., 2021)	SVF	PET	R^2= 0.80 (Strong)	Higher relationship is observed after 2pm till 12 am
(Deevi and Chundeli, 2020)	SVF	PET	(Strong)	Up to 3°C difference across the locations
(Manavvi and Rajasekar, 2019)	SVF	PET	R^2= 0.83 (Strong)	Spatial and temporal variation observed
(Manavvi and Rajasekar, 2021)	SVF	PET	R^2= 0.90	Thermal characteristics are predominantly driven by SVF
(Rajan and Amirtham, 2021a)	SVF	PET	R^2= 0.92 (High)	Increase in SVF by 0.2 increases PET by 4.15°C
(Manavvi and Rajasekar, 2021)	SVF	T_{mrt}	R^2= 0.80	Thermal characteristics are predominantly driven by SVF
(Rajan and Amirtham, 2021a)	SVF	T_{mrt}	R^2= 0.83 (High)	Increase in SVF by 0.2 increases T_{mrt} by 1.06°C
(Manavvi and Rajasekar, 2019)	SVF	Tmrt	R^2= 0.76 (Strong)	Spatial and temporal variation observed
(Mohammad et al., 2021)	SVF	TC	-N/A-	SVF is not a precise indicator for thermal comfort conditions.
(Manavvi and Rajasekar, 2019)	SVF	mTSV	R^2= 0.75	An increase of 0.5 in SVF value contributed to an increase of 1.5 in MTSV
(Deevi and Chundeli, 2020)	H/W	PET	-N/A-	H/W is not as effective as SVF to achieve thermal comfort.
(Amirtham et al., 2014)	H/W	T_a, PET	-N/A-	Up to 3.7°C reduction in PET due to higher H/W ratio
(Deevi and Chundeli, 2020)	Orientation	PET	-N/A-	EW oriented streets perform poorly, even with high aspect ratios.
(Amirtham et al., 2014)	Orientation	PET	-N/A-	E-W orientation of the street are 6.6°C higher than N-S oriented streets.
(Bhaskar and Mukherjee, 2017)	Orientation	T_a	-N/A-	N30°E to N60°E perform better during the afternoon when heat stress is higher.
(Bhaskar and Mukherjee, 2017)	Orientation	V_a	-N/A-	Orientation oblique to wind direction improves cross ventilation.
(Amirtham et al., 2015)	Orientation	T_a	-N/A-	Higher temperature at E-W and at the intersection of E-W and N-S street.
(Amirtham et al., 2014)	Orientation	T_a	-N/A-	E-W orientation of the street are 3.7°C higher than N-S oriented streets.
(Ali and Patnaik, 2017)	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
(Ali and Patnaik, 2017)	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
(Amirtham et al., 2014)	Vegetation	PET	-N/A-	Up to 3.28°C reduction in PET
(Manavvi and Rajasekar, 2021)	Albeo	T_s	-N/A-	An increase in albedo of 0.1 can reduce the T_s by 7.9°C
(Manavvi and Rajasekar, 2021)	Albeo	PET	-N/A-	An increase in the albedo of 0.1 can reduce the PET by 4.9°C

2016) even though the SVF is only 0.22. (Das et al., 2020) 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. (2015) 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 (Deevi and Chundeli,

Table 2.8: Relationship between climatic parameters and thermal comfort indices

Study	Influence	Effect on Index	Method (Relationship)	Key results
(Manavvi and Rajasekar, 2022)	T_a	PET	r= 0.81 (summer), 0.74 (winter)	-N/A-
(Manavvi and Rajasekar, 2022)	T_a	mTSV	R^2= 0.95 (Exposed), 0.94 (shaded)	T_a was found to be the most decisive determinant of thermal sensation
(Das and Das, 2020)	T_a	LST	r= 0.98 (Strong)	-N/A-
(Das and Das, 2020)	T_a	UTCI	r= 0.98 (Strong)	-N/A-
(Das and Das, 2020)	T_a	THI	r= 0.96 (Strong)	-N/A-
(Das et al., 2020)	T_a	SET	R^2= 0.96, r= 0.98 (Strong)	-N/A-
(Das et al., 2020)	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.
(Das et al., 2020)	T_a	PET	R^2= 0.99	-N/A-
(Das et al., 2020)	T_a	TSV	R^2= 0.90(Strong)	-N/A-
(Ziaul and Pal, 2019)	T_a	LST	R^2= 0.70 to 0.87	-N/A-
(Manavvi and Rajasekar, 2021)	T_a	TSV	r= 0.43	-N/A-
(Das et al., 2020)	R_h	DI	R^2= -0.70, -0.43	-
(Das et al., 2020)	R_h	T_a	R^2= -0.92 (Strong correlation)	-N/A-
(Das et al., 2020)	V_a	T_a	R^2= -0.72	-N/A-
(Amirtham et al., 2015)	V_a	T_{mrt}, PET	-N/A-	The higher wind speeds during noon reduced the T_{mrt} and PET values significantly.
(Banerjee et al., 2020)	T_{mrt}	PET	R^2= 0.65 to 0.77	-N/A-
(Manavvi and Rajasekar, 2019)	T_{mrt}	PET	R^2= 0.82 (Strong)	-N/A-
(Ali and Patnaik, 2017)	T_g	ASV	(Significant impact)	-N/A-
(Mohammad et al., 2021)	T_s	PET	R^2= 0.45 (High)	The building and tree shading has a considerable effect on T_s

2020; Amirtham et al., 2014, 2015) 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 (Bhaskar and Mukherjee, 2017).

The effect of solar access could be observed in several studies. Manavvi and Rajasekar (2022) observed more significant variation in sun-exposed spaces than shaded spaces. Ali and Patnaik (2017) 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 (2020) found higher THI at high-density built-up areas due to impervious surfaces and high density. similarly, (Ziaul and Pal, 2019) 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. (Manavvi and Rajasekar, 2021) 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 2.8). T_a is the most commonly used parameter. (Manavvi and Rajasekar, 2022) 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. (2021) whereas correlation (r) is accepted for the lowest value of 0.43 by Manavvi and Rajasekar (2021). Since there are no such scales evolved for r and R^2 in the topic of thermal comfort, Table 2.7 and Table 2.8 can be refereed for the strength levels of the relationships between various parameters.

To establish the relationships between two or more parameters various data analysis methods are typically used by researchers. To estimate the thermal neutrality, ordinal probit regression is widely used (Middel et al., 2016; Elnabawi et al., 2016). Ali and Patnaik (2017) used SPSS (SPSS, 2011) to perform various analysis. The study used one-way ANOVA (Stanberry, 2013) to compare perceived thermal comfort and thermal sensation, along with HSD test (Haynes, 2013) to confirm the differences. Ordinal Logistic Regression was carried out to find which of the 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 (Mann and Whitney, 1947) 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. (2020) also used the Kruskal-Wallis test to assess whether a significant difference exists or not between various parameters.

2.5 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. At the same time, it is also importance to undertake the studies in the climatic zones which are already explored since there are other parameters of outdoor thermal comfort that are yet to be given the attention.

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 behaviour. 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, 2012). In this review, studies (Das and Das, 2020; Das et al., 2020) used LCZ classification to differentiate 23 sites. Studies (Perera and Weerasekara, 2014; Liu et al., 2018) 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 yet 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 micro-meteorological 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 the rare cases, heights were significantly changed due to site-specific challenges or the scope of those studies. 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 (Nakayoshi et al., 2015; Chokhachian et al., 2017; Pigliautile and Pisello, 2018) or can be placed on the top of vehicles (Rajkovich and Larsen, 2016; OBrien et al., 2019) 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 (Figure 2.2). 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 (Cortesao et al., 2020) and thermal walk (Vasilikou and Nikolopoulou, 2020). 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 (Johansson et al., 2014; Golasi et al., 2018). Candido et al. (2011) suggested a Brazilian Standard on Thermal Comfort. For Mediterranean climates, the MOCI index (Mediterranean Outdoor Comfort Index) was proposed by Golasi et al. (2016). 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.

2.6 Summary

The section 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 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, on-site questionnaires were commonly collected by some studies. Amongst various parameters, the thermal sensation was the most commonly evaluated parameter. These parameters were evaluated based on various sensation 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 estimated the thermal parameters which were not obtained from on-site micro-meteorological 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.

Following points are inferred from this review which are significant to the whole thesis.

- Although some of the Indian studies are focused on composite climate. The studies mainly deal with the identification of thermal neutrality. The attention towards the effect of built entities on outdoor thermal comfort is lacking. The density of the built morphology at Delhi is much higher than most of the other cities at composite climates. It is thus, necessary to look into the effect of the morphology on human thermal comfort level. The first site area of the thesis thus selected at the composite climate of Delhi. The most important climatic zone which is missing from the current studies is the hot and dry region. In this thesis the second study area selected is Jaisalmer which is part of the hot and dry region.

- Since the focus of the thesis is the effect of vertical surfaces, the physical or geometrical parameters which define the built environment is important. Reviewed studies used H/W, SVF, Orientation, LCZ etc. These parameters also widely used in the studies worldwide.

- On-site micro-meteorological measurements is the common practice. The mini weather station, indices measured and the protocols mentioned in the studies are beneficial references for conducting the on-site study.

- Since Envi-met is an ideal simulation software, it will be used for the simulation of the selected sites to evaluate various parameters and indices.

- PET is commonly used index followed by T_{mrt}. These indices are well explored in the indian context. Due to the reliability of these indices, they are preferred for the study.

- The reviewed studies gave a good insights of the on-site user survey. The sample size, the types of questions, survey season and duration, survey protocols etc. are beneficial for the study.

- The measurement scales which are commonly used and which are in accordance with the standards are followed in the study.

- Due to the focus of the thesis, the topics such as acclimatization, adaptation, neutrality etc. are not followed in the study. The effect of physical and climatic parameters are the relevant topics those are analysed in quiet detail in the thesis study.

3

Materials and Methods

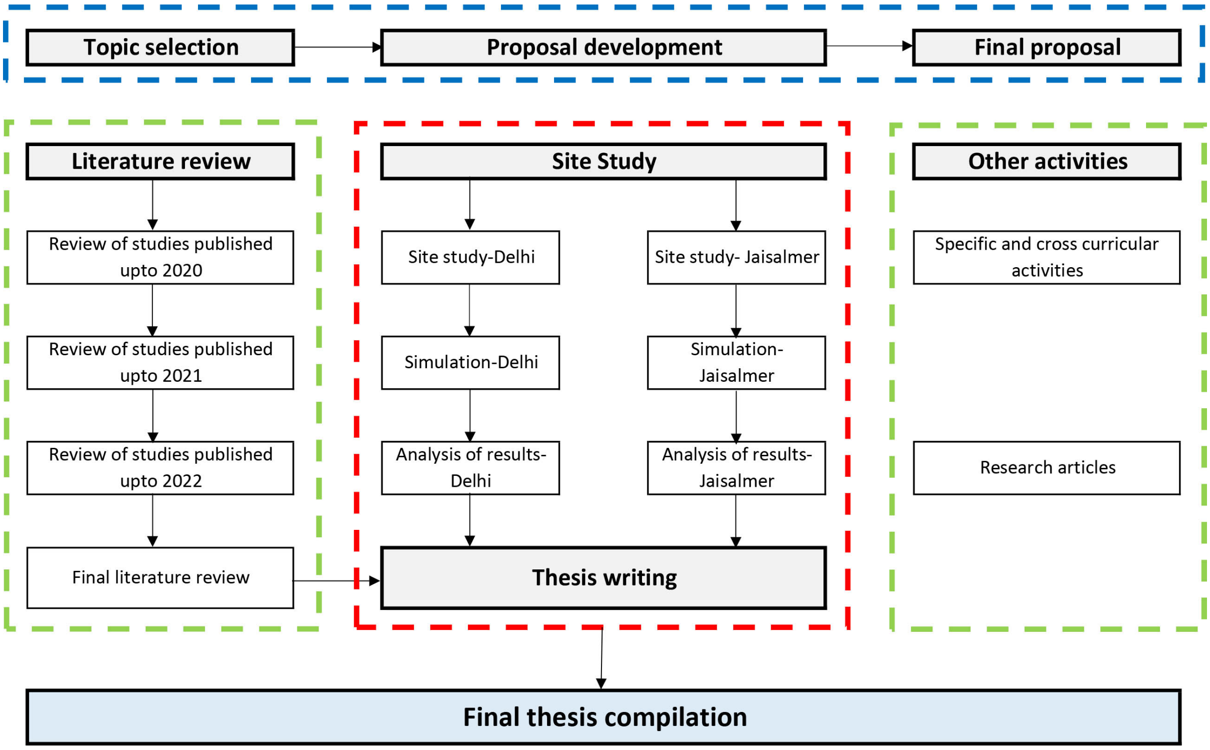


Figure 3.1: Flowchart of the study

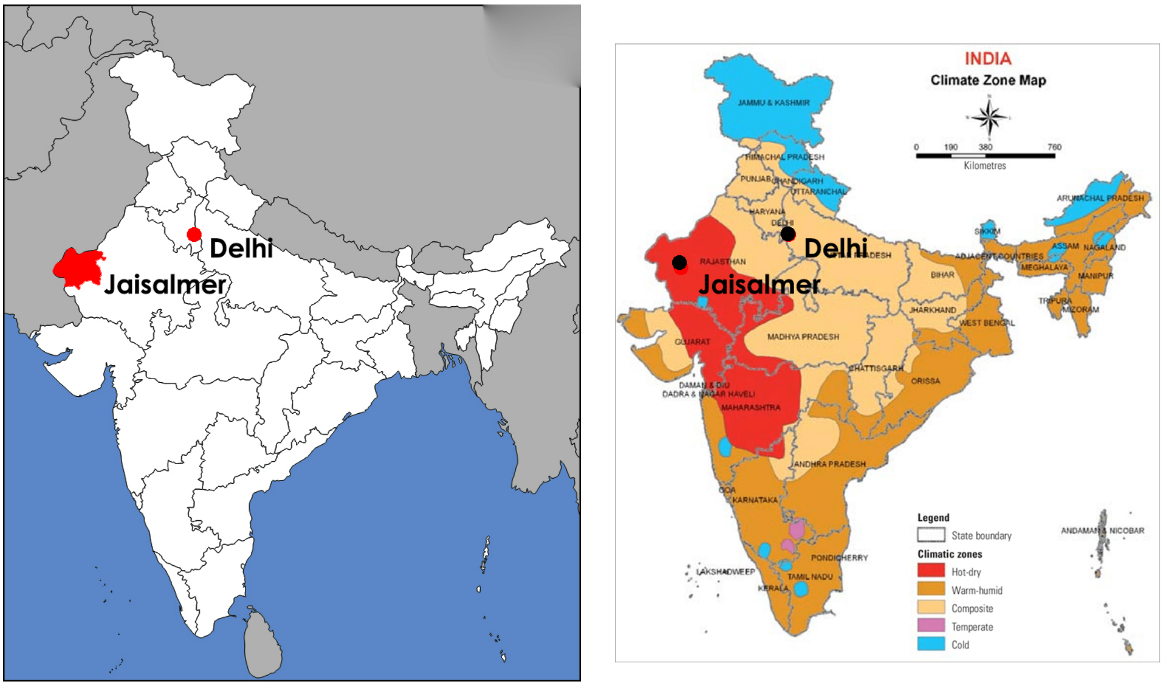
3.1 Flowchart of the study

Figure 3.1 shows the flowchart of the complete study done by the author. The blue highlighted dotted rectangle shows the stages from topic selection up to the final approval of the topic. The dotted rectangles in light green color show the activities which support the development of the core study which is highlighted in the dotted red colored rectangle.

The literature review which shows multiple steps was actually a continuous study that was done alongside the main study. It is because some of the articles which are valuable references were published when the main study was going on.

The main study of the thesis is primarily based on the sites that are present in two different climatic zones in India. The first site study was done during the summer of 2020, and the second site study was done in the summer of 2021. The respective site studies are followed by software simulations and further analysis. There are separate flowcharts (Figure 3.4 and Figure 3.6) which describe the steps involved in the respective site studies.

Along with the main study, the author was also focused on the specific and cross-curricular activities that were useful for the development of the thesis since those are important aspects



(a) Location of the sites in the context of political map of India

(b) Location of the sites in the context of climatic zones of India

Figure 3.2: Locations of the sites selected for the study

that needed to be followed.

The final phase of the thesis is about the thesis writing and the final compilation which was started when all kind of analysis and findings was completed.

3.2 Study areas selection

Finally, selected sites went through several steps before it was finalized for the study. It started with the selection of the climatic zone/ zones. India is climatically divided into five climatic zones as per climatic zones of India. Each climatic zone has its own characteristics and challenges associated with it. The composite climate zone and hot and dry climatic zones are focused on in this study (Figure 3.2)

3.2.1 Site at composite climate zone

Delhi is located in the northern part of India. The city experiences cold to moderate winters for a shorter duration and a long hot summer season which lasts from the third week of April to

(a)

(b)

(c)

Figure 3.3: Location of the site (a) Map of Delhi highlighting the selected sites (source: google maps) (b) Bhikaji Cama Place (source: google earth) (d) Nehru Place (source: google earth)

mid-July, this duration of summer thus becomes a matter of concern. The sites selected (Figure 3.3) for the study are ‘site A: Bhikaji Cama Place’ located at 28° 34’ 06” N 77° 11’ 15” E and ‘site B: Nehru place’ located at 28° 32’ 56” N 77° 15’ 08” E. Out of 15 District Centers, Bhikaji Cama Place, and Nehru place were developed by 1981 (Delhi Development Authority, 2010). Bhikaji Cama Place is a business center, whereas Nehru Place serves as a commercial node for the city, providing major retail and commercial services. These sites have a low residential population but a high concentration of public buildings and offices. It thus becomes a matter of concern in terms of thermal comfort since citizens from nearby neighborhoods are using these open spaces more frequently.

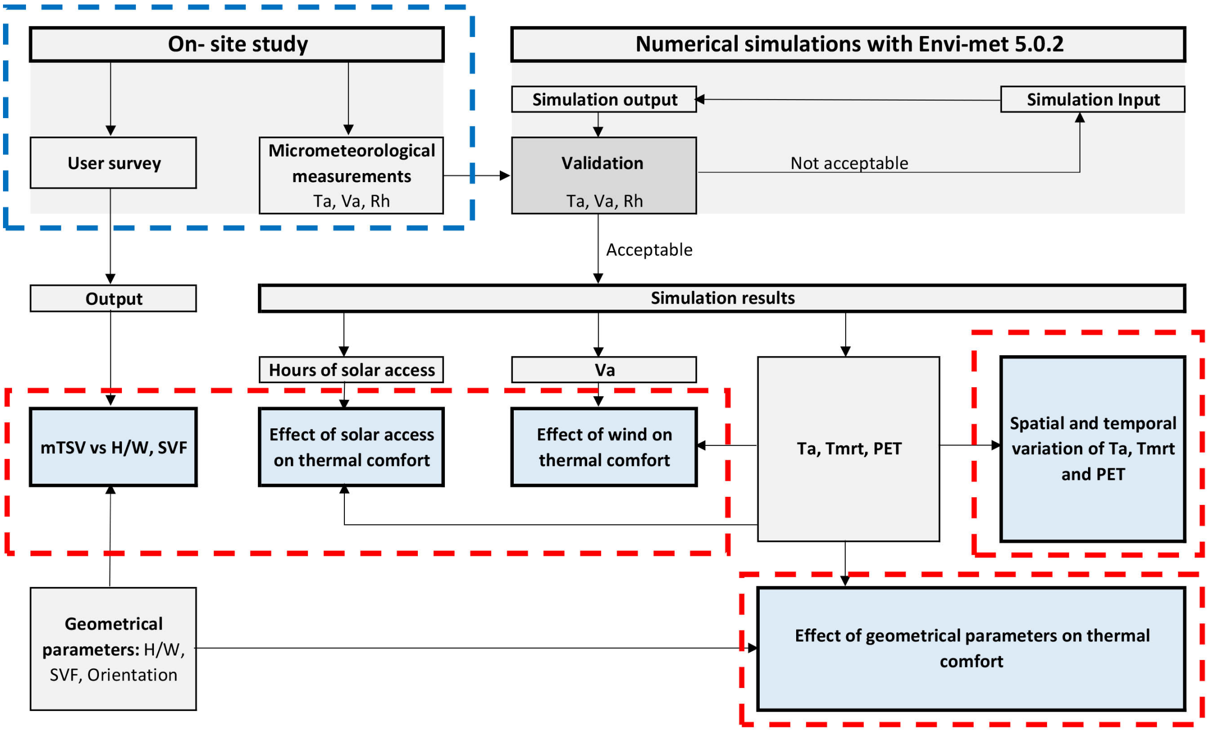


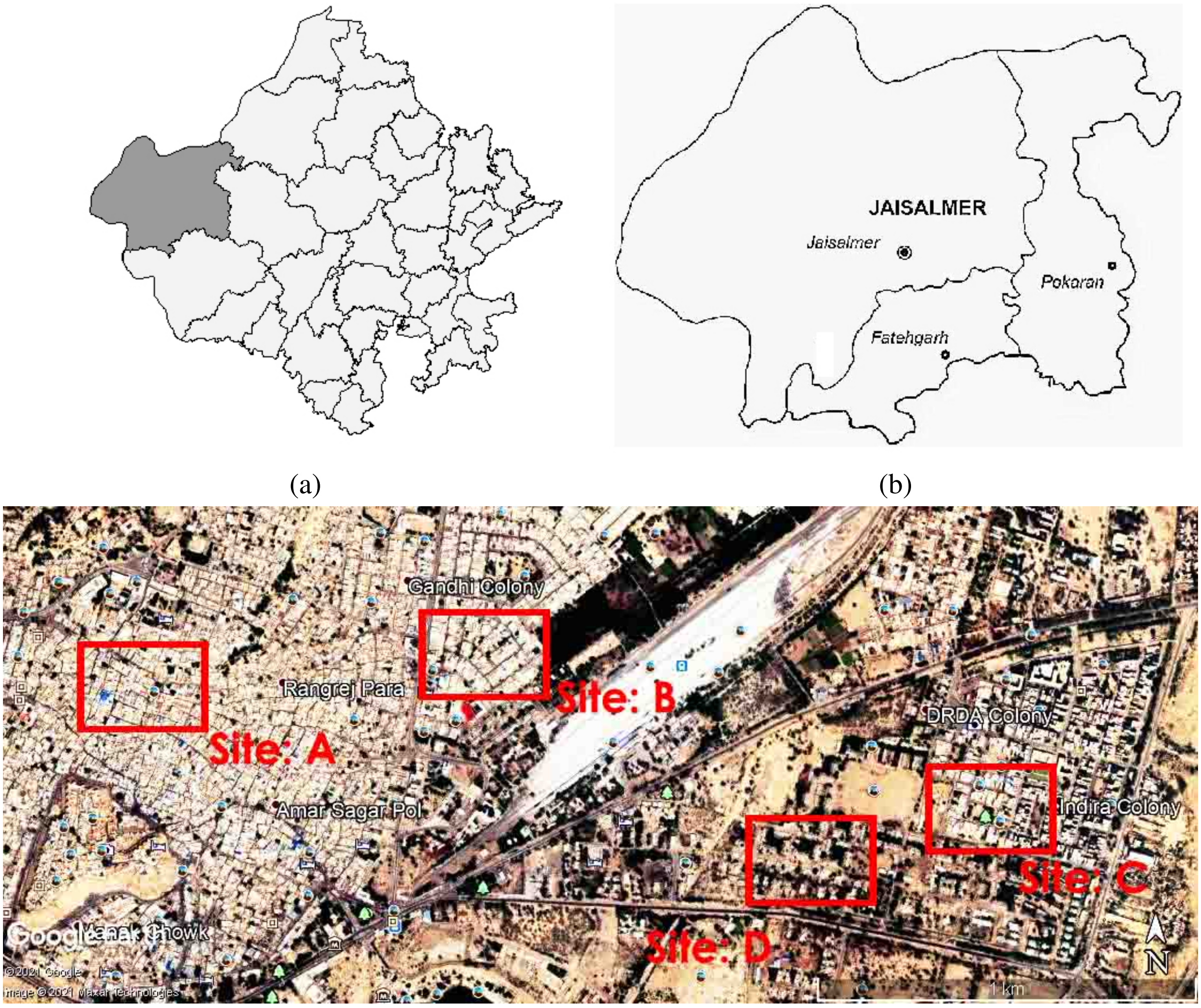
Figure 3.4: Flowchart of the Delhi study

Figure 3.4 shows the flowchart for the study at the composite climate zone. The analysis is based on the data obtained from on-site questionnaire surveys and software simulations whereas micro-meteorological measurements were used for the validation of simulation output.

The first step of the study deals with the existing site study about building morphology and outdoor open space configurations. The built environment is studied to understand the character of the vertical surface, building typologies, orientation, H/W ratios, and SVF. In the second step, field surveys were conducted to identify the thermal comfort level of the user. Responses were taken by filling out survey questionnaire forms which were often translated into the local language 'Hindi' depending upon the user. In the next step, Sun path shadow analysis was done to understand the amount of open space under shade for different times of the day.

3.2.2 Site at hot and dry climate zone

Figure 3.2b shows the climatic regions of India (Bureau of Indian standards, 2016). The selected sites are located in the hot and dry region of Jaisalmer, Rajasthan, India, at the latitude of 26° 54' N, and longitude of 70° 54' E with an elevation of 225 m from the mean sea level.



(a) (b)

(c)

Figure 3.5: Location of the studied site (a) Location of Jaisalmer with reference to other districts of Rajasthan (b) Jaisalmer district highlighting the location of Jaisalmer town (c) Google map of Jaisalmer highlighting the selected sites

The town is located in the ‘Thar’ desert in the northwest part of India. Jaisalmer district ranks 33rd in terms of population and 1st in terms of area covered in the Rajasthan state (Census, 2011) which shows that the district is least preferred to live by the users. The climate data (Indian Meteorological Department, 2010, 2012) for the 30 years average between 1981 and 2010 was taken as input for the various simulations in this study. The summer months of May and June are extremely hot followed by April and July. For June the average high and average low temperatures are 40.9°C and 27.6°C respectively, with the record highest of 49.9°C, except for December, January, and February the average high temperatures for all the months are more than the human thermal comfort range (Bureau of Indian Standards, 2005), It also shows that

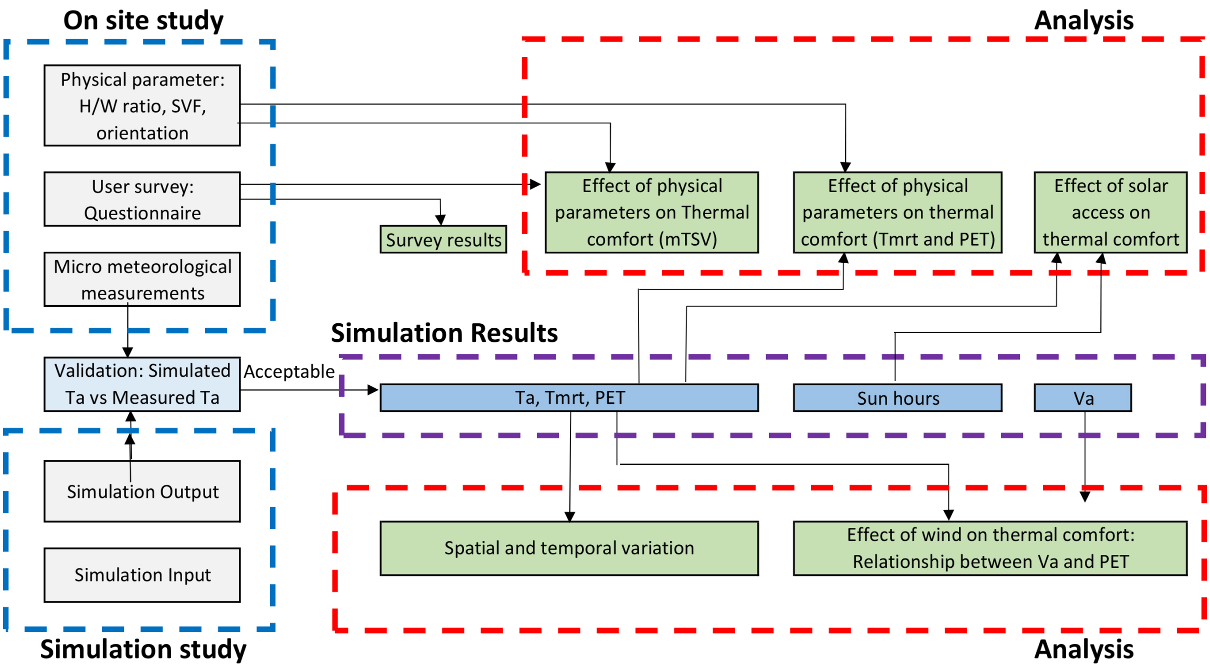


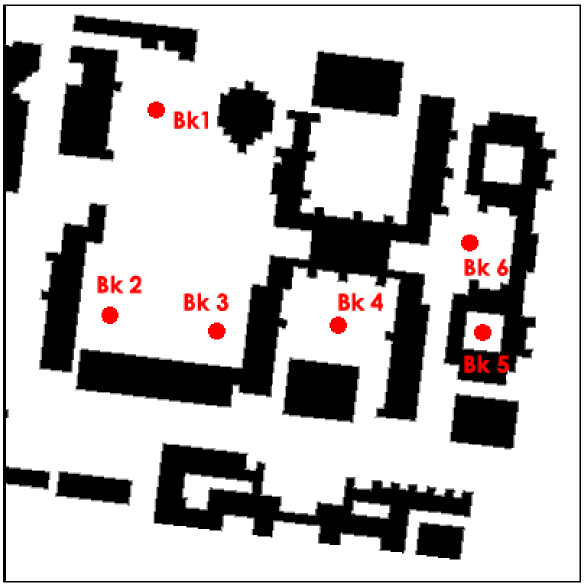
Figure 3.6: Flowchart of the Jaisalmer study

the temperature is not lower than the comfort range for the longer duration of the daytime. The city experienced an average annual rainfall of 201.6 mm. During the hottest month, the average annual rainfall is 21mm with an average relative humidity of 29%.

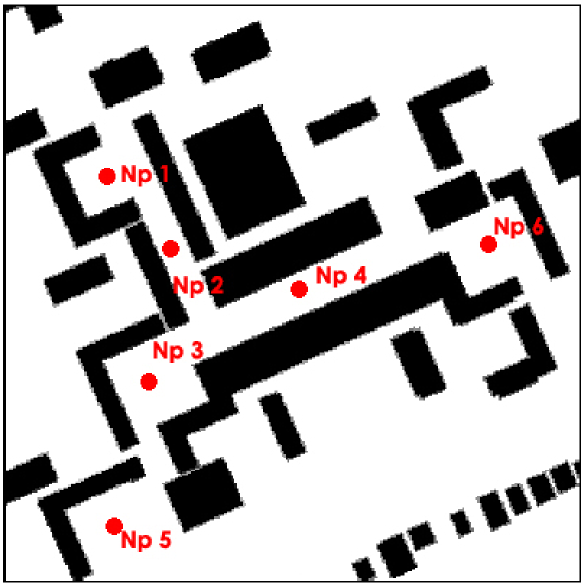
Figure 3.6 shows the steps followed the study at the Hot and dry climate zone. In the first step, the morphological study is done to understand and differentiate the urban forms, spaces, geometry of vertical surfaces, the sky view factors (SVF), and height to width ratios (H/W). Along with the morphological study, an on-site user survey was conducted. In the next step, the software simulations were performed to achieve the required results. The skyhelios model was used to achieve the SVFs, H/W ratios are calculated with geometrical measurements, and Envi-met software is used for the simulations to achieve the results for various parameters like T_a, T_{mrt} and PET.

3.3 Morphological character

The locations (Table 3.1) are selected based on varying morphological characteristics primarily caused by the geometry of vertical surfaces, their orientation, H/W ratio, and SVF. The total vertical surface area to ground coverage ratio is 3.80 at site A and 3.64 at site B. Out of the



(a) Bhikaji Cama Place



(b) Nehru Place

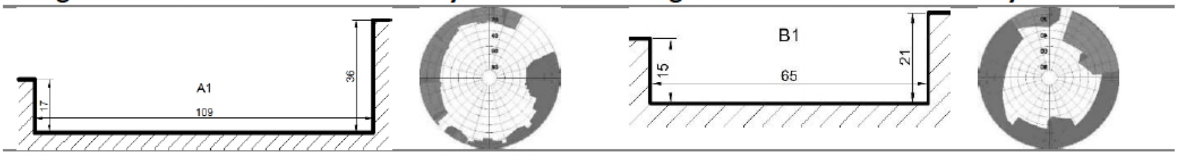
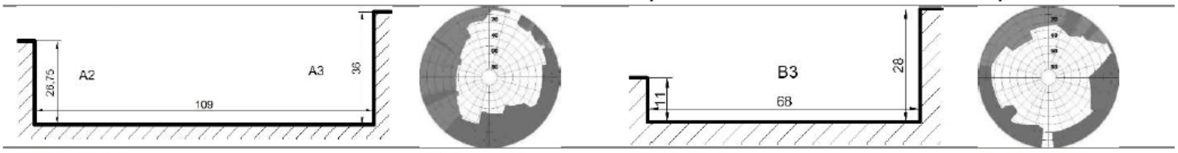
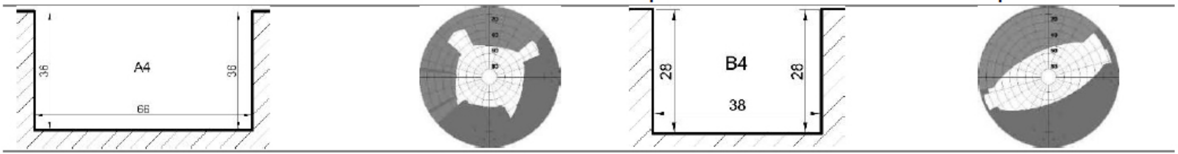
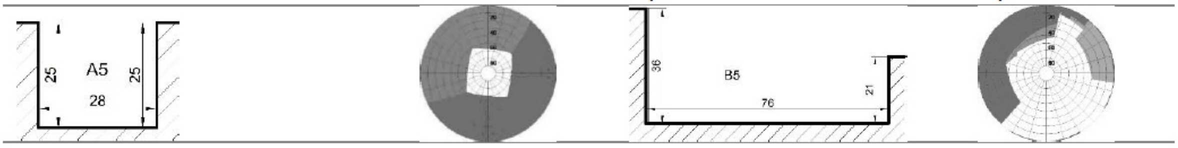
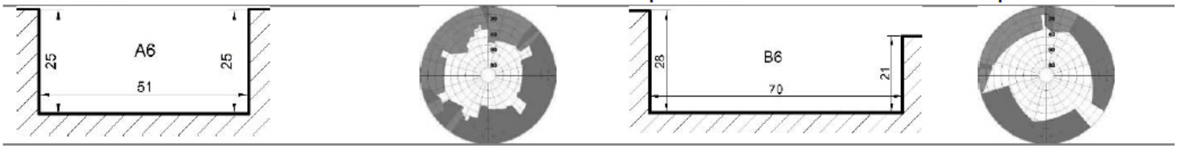
Figure 3.7: Figure-ground plans of selected sites with monitoring locations at Delhi

total vertical surface area at site A, 44.24 % of the area is occupied by N and S while 55.76 % of the area is occupied by E and W. At site B, 43.50 % of the area is occupied by NE and SW while 56.50 % of the area is occupied by SE and NW.

H/W ratio (also known as aspect ratio) is calculated by taking an average of the heights of the vertical surfaces to the width of that open space for which vertical surfaces are acting as an enclosure. Many studies (Nasrollahi et al., 2021; Ali-Toudert and Mayer, 2006; Kakon et al., 2010; Sharmin et al., 2012; Perera and Weerasekara, 2014; Ali-Toudert and Mayer, 2007; Abdollahzadeh and Biloria, 2020) have found that the higher H/W ratio along with the appropriate orientation of the adjacent buildings is an important factor affecting the thermal comfort level.

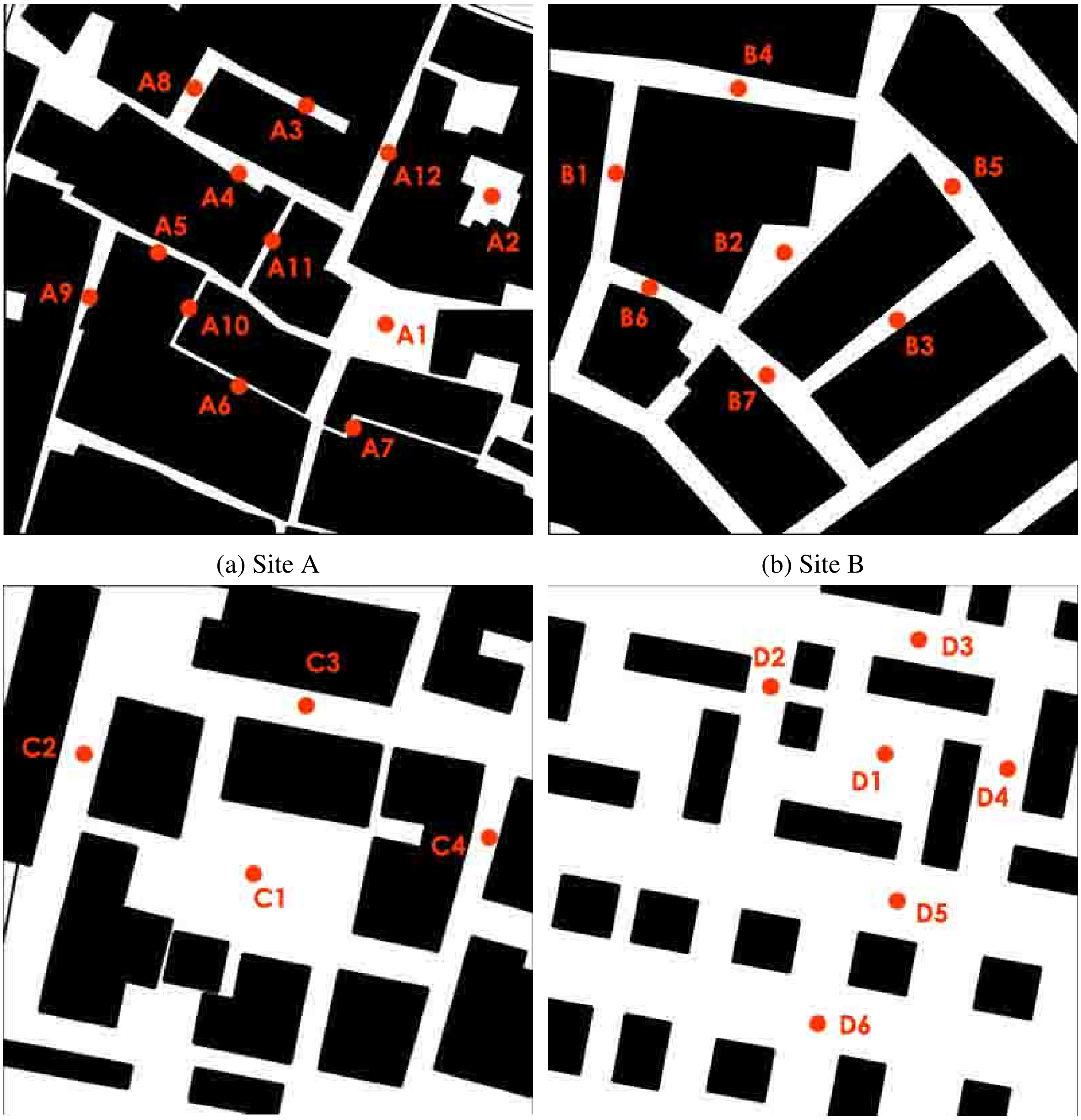
Along with the H/W ratios, the SVF is developed for all the locations with the software program 'Skyhelios' (Matzarakis and Matuschek, 2011; Matzarakis, 2012; Fröhlich and Matzarakis, 2018). SVF indicates the proportion of the sky visible at a scale of 0 to 1. Where, 0 means no sky visible and 1 is completely visible. It gives a better understanding of the built environment around the open space since the built environment on all sides of the open space can be visualized in one picture. The output is useful in having a quantitative understanding of the amount of exposure for vertical surfaces to direct solar radiation. Several studies (Bourbia and Awbi, 2004; Deevi and Chundeli, 2020; Tan et al., 2013; Kruger et al., 2011; Lin et al., 2019;

Table 3.1: Morphological character of each location of Delhi sites

Height to width ratio	Sky view factor	Height to width ratio	Sky view factor
			
Bk1=0.24	Bk1=0.68	Np1=0.28	Np1=0.52
			
Bk2=0.29	Bk2=0.51	Np2=0.91	Np2=0.30
			
Bk3=0.29	Bk3=0.51	Np3=0.29	Np3=0.60
			
Bk4=0.54	Bk4=0.32	Np4=0.74	Np4=0.38
			
Bk5=0.89	Bk5=0.16	Np5=0.38	Np5=0.76
			
Bk6=0.49	Bk6=0.40	Np6=0.35	Np6=0.54

Mahmoud, 2019; Hwang et al., 2011) used SVF for outdoor thermal comfort studies.

Four different sites with varying morphologies are selected (Figure 3.8). All these sites are selected based on the variation of open spaces and the vertical surfaces enclosing them. It was also considered to have a variety of SVFs and orientations for the locations within these sites so that variations of the thermal comfort could be visualized. Table 3.2 shows the values for the various factors which are linked to the geometrical aspects of the vertical surfaces. Each site with a dimension of 32400 sq.m. (180 meters X 180 meters) selected for the study. Site A is located in the old city whereas sites B, C, and D are later developments. All these sites are part of residential neighborhoods. Site A is very dense with a built-to-an-un-built ratio of 3.36



(a) Site A (b) Site B

(c) Site C (d) Site D

Figure 3.8: Figure-ground plans of selected sites with monitoring locations at Jaisalmer

followed by site B and site C having built-to-unbuilt ratios of 2.65 and 0.96 respectively. The lowest density is at Site D which is having built-to-unbuilt ratio of 0.33. Structures at all four sites are ranging from 1 to 3 storied, with most of the heights of the structures being between 8 to 10 meters high. The variation in the densities at these sites can be observed with plan-area density and frontal-area density. Calculations are performed after referring the studies (Wong and Nichol, 2013; Grimmond and Oke, 1999; Chen et al., 2017; Burian et al., 2005). The plan-area density at site A is 0.75, at site B it is 0.74, at site C it is 0.50 and at site D it is 0.25, whereas their frontal-area densities are 0.15, 0.12, 0.10, and 0.06 respectively. Due to

Table 3.2: Morphological character of each location of Jaisalmer sites

Site	Location	H/W Ratio	SVF	Enclosing surfaces	Hours of solar access
Site A	A1	0.37	0.73	NE, NW, SE, SW	9.5
	A2	0.63	0.61	NE, NW, SE, SW	6
	A3	2.22	0.25	NE, SW	3.8
	A4	1.43	0.33	NE, SW	5.7
	A5	3.13	0.19	NE, SW	3.2
	A6	5.00	0.12	NE, SW	2.5
	A7	5.00	0.05	NE, NW, SE, SW	1.2
	A8	1.54	0.36	NW, SE	3.2
	A9	1.85	0.20	NW, SE	2.3
	A10	5.00	0.12	NW, SE	0.8
	A11	3.33	0.17	NW, SE	1.6
	A12	1.82	0.31	NW, SE	2.5
Site B	B1	1.33	0.42	E,W	3
	B2	0.56	0.65	NW, SE	7.6
	B3	1.37	0.41	NW, SE	5.4
	B4	1.00	0.50	N,S	10
	B5	1.03	0.52	NE, SW	5
	B6	1.82	0.33	N,S	7.2
	B7	0.88	0.60	NE, SW	6.2
Site C	C1	0.13	0.96	NE, SW	12.5
	C2	0.55	0.71	E,W	6.2
	C3	0.57	0.73	N,S	11.3
	C4	0.81	0.60	E,W	4.8
Site D	D1	0.24	0.90	N,E,W,S	12
	D2	0.67	0.73	E,W	5.8
	D3	0.56	0.76	N,S	11.8
	D4	0.56	0.74	E,W	6.4
	D5	0.31	0.91	N,S	12
	D6	0.25	0.96	N,E,W,S	12.3

the variation in the width of the open spaces, the variation in the H/W ratio and SVF could be observed. Apart from this variation most of the characteristics for all the studied sites are similar in terms of elevation from sea level, wind direction, surface properties, etc. In terms of streets and open spaces, site A is characterized by very narrow streets with irregular patterns these open spaces are enclosed by vertical surfaces in such a way that the amount of solar access to these spaces is minimal along with the minimum wind speed. Site B, C, and D are characterized by geometrical patterns of forms and open spaces.

4

Field study

4.1 User survey

The on-site user survey was conducted by filling out the questionnaire form (A.1 and A.2). The questionnaire is developed by referring (ASHRAE, 2017, 1992). It was made sure that the conditions during the survey campaign were typical sunny. The survey campaign took two weeks between 15th June 2020 to 27th June 2020. The everyday survey started at 7 am, but very few users were spotted around the sites until 9 am. for this reason surveys conducted between 9 am to 6 pm are considered for further analysis. 208 Valid responses from Bhikaji Cama Place and 324 from Nehru Place were finally selected. The difference in the number of respondents occurred due to the different frequencies of the users at both sites. The sample sizes are in agreement with similar studies (Nasrollahi et al., 2021, 2017).

To take the measurements and fill out the questionnaire form, eight students (four on each site) from the architecture school worked as volunteers, who were given clear instructions about the measurements and user survey. They were also asked to translate and simplify the questions in the local language 'Hindi'. Although there are six locations per site, the proximity of these locations is such that all the locations at Bhikaji Cama Place can be covered within 750 meters of a walk, whereas at Nehru Place all the locations can be covered within 450 meters. Due to this, the volunteers could relocate easily and quickly between the locations to take the measurements and conduct the questionnaire survey.

Most of the respondents from Bhikaji Cama Place visited the locations more often since they belonged to the nearby workplaces. At Nehru Place, the respondents were those who visited the site primarily for the shopping of electronic goods. In all the cases it was made sure that the respondent is not from another city or remote area. At both sites, the maximum users were between the age of 22 to 45 years, and very few users were between 45 to 58 years.

To avoid errors in the survey outputs, responses from various locations from both sites were analyzed by carefully considering similar criteria, for example, the responses received between 2 pm to 4 pm from all locations are analyzed together. Respondents who had visited most of the monitored locations were asked to compare these locations from a thermal comfort point of view. But these criteria were not taken into further analysis since very few users could answer this point.

At Jaisalmer, a questionnaire survey was conducted in the span of two weeks between June 21st, 2021 to July 4th, 2021 at the selected sites of this study. The times chosen for the survey were based on user frequency. Daytimes between 8 am to 6 pm were chosen since the variety of activities could be observed during this duration of the day. Questions were often translated into the local language. For the on-site survey, twelve students from architecture school assisted who were equally distributed among the four sites. Each user took between five to ten minutes to complete the questionnaire. The questionnaire was developed after referring the standards (ASHRAE-55, 2010; ISO7730, 2005). 326 the number of users responded at site A, 144 at site B, 160 at site C, and 78 at site D. Most of the users were using the selected locations as part of their daily routine, some of them were passersby and there were very few users who visited the locations rarely. The clothing type for the surveyed users was almost similar to the local traditional clothing style. Comparative analysis was done from the valid responses received from each site. the means of the thermal sensation votes (mTSV) was correlated with the H/W ratio and SVF to estimate the effect of physical parameters on thermal comfort.

4.2 Climate of the site

India is climatically divided into five zones. Those are hot and dry, warm and humid, composite, temperate, and cold (Bureau of Indian standards, 2016). Delhi is a part of a composite climate zone. It is the most challenging climatic zone when it comes to the urban areas in India since the user living in the composite climates must deal with the extreme climatic conditions.

The weather data of a single year (Indian Meteorological Department, 2020) can be irrelevant to use in this study since there can be a variation in the values if compared to the data of preceding years; for this reason, ‘Climatological tables of observatories in India 2081-2020’ (Indian Meteorological Department, 2010) is referred to get the average values of climate. The same data is used for the Envi-met simulations’ input. The most relevant weather station for the studied sites is ‘Safdarjang’. The climatic values for June are referred to since it is the month of extreme temperatures. The mean daily temperature in the summer month of June is 28°C to 43 °C, which is the highest compared to the other months of the year.

Table 4.1: Summary of measuring instruments

Variable	Equipment	Range	Accuracy
T_a	Testo 608-H2	-10 to 70	+/- 0.5
RH	Testo 608-H2	+2% to +98%	+/- 2%
V_a	Three cup anemometer WS 202	0 to 70 m/s	+/-3 %

Table 4.2: Summary of micro-meteorological measurements at Delhi

Location	Bk1	Bk2	Bk3	Bk4	Bk5	Bk6	Np1	Np2	Np3	Np4	Np5	Np6
$\uparrow T_a$ (°C)	40.7	40.6	40.7	40.1	40	40.1	40.3	40.2	40.1	39.9	39.9	39.9
$\downarrow T_a$ (°C)	30.7	30.7	30.5	30.5	30.5	30.9	31.1	30.5	31.1	30.9	31.2	31.2
μ T_a (°C)	36.5	36.5	36.7	36.2	35.9	36.1	36.5	36.3	36.4	36.4	36.4	36.4
$\uparrow V_a$ (m/s)	1.25	0.7	1	0.5	0.1	0.25	0.6	2	0.9	0.75	0.5	1
$\downarrow V_a$ (m/s)	1.2	0.5	0.8	0.2	0.1	0.1	0.35	1.5	0.7	0.7	0.25	0.85
μ V_a (m/s)	1.1	1	1	0.25	0.1	0.2	0.5	1.9	0.75	0.75	0.3	1
$\uparrow R_h$ (%)	67	67	69.5	68	68	67	67.5	69	68	69	67	68
$\downarrow R_h$ (%)	51.5	51.5	51.5	53	54	53	52.5	52	52	52.5	52.5	52.5
μ R_h (%)	58.2	58.2	59.1	59.1	60	59.1	58.2	58.9	59.2	59.2	58.2	59.1

For most of the days in the year, the wind speed stays below 5 m/s with prevailing wind direction from west to north-west. The humidity in June is between 39% to 56%.

4.3 Micro-meteorological measurements

Alongside the questionnaire survey, the micrometeorological measurements were collected from monitoring locations (Figures 3.5d, 3.5e, 3.5f, 3.5g)

At each site one representative was dedicated to handle the mini weather station to take the micro meteorological measurements. The measurements were taken at the centre of the monitoring locations as shown in the Figure 3.8 at the height of 1.5 m from finished ground level. The height of the measuring instruments and the rest of the protocols are in accordance with the previous studies, as described in the section 2.4.6.

The measurements were taken from 7 am to 6 pm, sequentially at each location for every hour. On each location 5 to 10 minutes were spent to make sure all the locations are covered. The average values at each location for each hour from the span of two weeks campaign were finally taken for the further study.

Table 4.1 shows the summary of equipment used for the measurements. The primary pur-

Table 4.3: Summary of micro-meteorological measurements at Jaisalmer

Site A	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
T_a min (°C)	31.5	31.7	31.7	31.7	31.5	31.3	31	31.5	31.3	31.1	31.3	31.5
T_a max (°C)	41.1	40.7	40.4	40.5	40.7	40.5	40.3	40.7	41	40.5	40.6	40.6
T_a avg (°C)	37.5	37.5	37.4	37.4	37.3	37.1	36.5	37.1	37.2	36.9	37.1	37.3
V_a min (m/s)	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.1	0.1	0.1
V_a max (m/s)	0.8	0.1	0.1	0.3	0.2	0.1	0.1	0.6	0.6	0.1	0.1	0.3
V_a avg (m/s)	0.4	0.1	0.1	0.2	0.1	0.1	0.1	0.4	0.4	0.1	0.1	0.2
R_h min (%)	22.3	22.5	22.5	22.5	22.6	22.8	22.8	22.8	22.8	22.8	22.8	22.8
R_h max (%)	33.4	33.6	33.6	33.6	33.6	33.7	33.7	33.7	33.7	33.7	33.7	33.7
R_h avg (%)	27	27.2	27.2	27.2	27.3	27.4	27.4	27.4	27.4	27.4	27.4	27.4

Site B	B1	B2	B3	B4	B5	B6	B7
T_a min (°C)	31.5	31.7	31.7	31.7	31.8	31.8	31.8
T_a max (°C)	41.1	40.8	41.1	41	40.7	41.3	41.5
T_a avg (°C)	37.5	37.3	37.6	37.5	37.3	38.1	38.1
V_a min (m/s)	1.2	0.6	0.3	0.4	0.1	0.1	0.1
V_a max (m/s)	1.8	0.9	0.4	0.7	0.3	0.2	0.3
V_a avg (m/s)	1.5	0.75	0.35	0.55	0.2	0.1	0.2
R_h min (%)	22.6	22.7	22.7	22.7	22.7	22.7	22.7
R_h max (%)	33.8	33.6	33.6	33.6	33.6	33.6	33.6
R_h avg (%)	27	27.2	27.2	27.2	27.2	27.2	27.2

Site C	C1	C2	C3	C4
T_a min (°C)	31.5	31.7	31.8	31.5
T_a max (°C)	42.1	42	42	42
T_a avg (°C)	37.9	38.1	37.8	38.1
V_a min (m/s)	2.4	4.2	0.9	2.4
V_a max (m/s)	3.1	5.8	1.8	2.7
V_a avg (m/s)	2.7	5.1	1.4	2.5
R_h min (%)	22.5	22.7	22.5	22.7
R_h max (%)	34.5	34.9	35.2	34.9
R_h avg (%)	26.2	26.6	25.9	26.6

Site D	D1	D2	D3	D4	D5	D6
T_a min (°C)	31.5	31.3	31.3	31.2	31.4	31.5
T_a max (°C)	42	42.2	42	42.2	42.3	42.4
T_a avg (°C)	38.22	38.42	38.15	38.44	38.42	38.68
V_a min (m/s)	1.2	4.2	2.4	2.7	1.8	3.6
V_a max (m/s)	1.8	4.8	3.6	3.6	2.4	4.8
V_a avg (m/s)	1.5	4.5	2.9	3.1	2.1	4.3
R_h min (%)	22.3	22.3	22.3	22.3	20.2	20.2
R_h max (%)	34.8	34.8	34.8	34.8	34.7	34.7
R_h avg (%)	26.1	26.1	26.1	26.1	25.2	25.2

pose of the on-site micro-meteorological measurements in the study is to validate the Envi-met simulated outcome and not for using the measurements directly for the analysis. The analysis is performed with the simulated results obtained from the caliberated Envi-met model.

Measurements were taken on clear sunny days, between the 15th to 27th of June 2020 during the daytime between 7 am to 6 pm. The month of the survey was decided based on the yearly temperature trends (Indian Meteorological Department, 2010). Variables T_a and R_h were measured with the equipment thermo-hygrometer 'Testo 608- H2' having a temperature measurement range of -10°C to +70°C with an accuracy of +/- 0.5 °C and humidity measurement length of +2 to +98 with an accuracy of +/-2%. The measurement interval for this sensor is 18s. 'Va' was measured with three cup sensor, and the cup anemometer 'WS102' having a measurement range of 0 to 70 m/s with an accuracy of +/-3%.

All the measurements were taken at the monitoring locations mentioned in Figure 3.1 and at the height of 1.5 m from finished ground level. Table 4.2 and Table 4.3 show the summary of the measurements.

4.4 Thermal comfort indices

Air temperature (T_a) is insufficient to present a wholesome evaluation of thermal comfort conditions. In this study, the biometeorological parameters physiological equivalent temperature (PET) and mean radiant temperature (T_{mrt}) are also focused, which are highly affected by wind velocity, solar radiation, etc. T_{mrt} is an important index since it takes long-wave radiation and short-wave radiation fluxes into account(Kántor and Unger, 2011) that influences human thermal comfort level (Mayer and Hoppe, 1987). The T_{mrt} is also the important meteorological parameter governing the urban thermal comfort (Tan et al., 2013; Ali-Toudert and Mayer, 2007; Mayer and Hoppe, 1987) and it is directly influenced by urban geometry (Thorsson et al., 2014). Along with T_{mrt}, the bioclimatic index PET is also used. According to (Andreas, Matzarakis and Iziomon, 1999), PET is the effective index for the bio-meteorological assessment to evaluate the Urban thermal comfort (Höppe, 1999; Alur and Deb, 2010). Its unit is '°C', the results can also be presented graphically or as bio-climatic maps. PET does not take subjective clothing value into consideration which is one of the advantages of using it in this paper.

5

Numerical simulations and validation

5.1 Numerical simulations

5.1.1 Selection of software

In this study, along with the on-site measurements of various parameters, software simulations are also performed. The micro-climate of an urban area is regulated by many variables and processes. From the field surveys, it is difficult to understand the contribution of only one or two variables to the thermal comfort level due to the complexity of an urban area. For this reason, software simulations are performed in this study to identify the contribution of each variable.

‘Envi-met 5.0.2’ (Bruse and Fleer, 1998) simulations were performed and studied to understand the cause of thermal discomfort and to see if there is any correlation between shading due to vertical surfaces to the T_{mrt} and PET. Also, to understand if the comfort level varies in various open spaces and causes were identified. Only vertical surfaces are simulated with uniform material to analyze the effect of vertical surface geometry. Other entities like vegetation, horizontal surface characteristics, etc. are not considered so that more precise results are achieved.

Several studies (Nasrollahi et al., 2021; Ali-Toudert and Mayer, 2006; Haseh et al., 2018; Bhaskar and Mukherjee, 2017; Ali-Toudert and Mayer, 2007; Kruger et al., 2011; Égerházi et al., 2013; Emmanuel et al., 2007; Othman and Alshboul, 2020; Allegrini et al., 2015; Langer et al., 2014; Taleghani et al., 2015; Berardi and Wang, 2016; Forouzandeh, 2018; Yang et al., 2018) used this software to evaluate the various parameters within the outdoor environment of an urban area.

5.1.2 Model development

Before entering into the simulation mode, the model has to be constructed in the software. It can be constructed at the ’SPACES’ a tool that is part of the Envi-met package. Alternatively, the model can be developed in the software ’sketch up’, and then exported to the Envi-met. Either way, the accuracy of the output doesn’t get affected. In this study, the first sketch-up was used to develop the models for all the sites. The appropriate materials were applied as per the

Table 5.1: Envi-met simulation input for all the sites at Delhi

Model input	
Simulation date	21st June 2020
Simulation duration	24 hours starting at 00:00 am
No. of grid cells	x-grids: 116, y-grids 100 z-grids: 100
Size of grid cells	x-grids: 5m, y-grids 5m z-grids: 5m
Boundary conditions	
T_a	28°C to 43°C
V_a	2.5 m/s
Wind direction	North-west
Cloud cover	Clear sky
R_h	39% to 56%
Material input	
Wall	Brick-wall with sandstone cladding (Site A), Brick-wall with plaster (site B)
Roof	RCC 150mm
Outdoor horizontal surface	Hard-paved
Properties of the materials	As per Envi-met database
Biomet input (default)	
Age	35 years
Weight	75 kg
Height	1.75 m
Clothing value	0.9
Personal metabolism	1.48 met

Table 5.2: Envi-met simulation input for all the sites at Jaisalmer

Model area	**Input**
Simulation date	21st June 2021
Simulation duration	24 hours (00:00 am to 00:00 am)
Site area	32400 sq.m. (180m X 180m)
Number of grid cells (x, y, z)	222,222, 15
Size of grid cells (meters) (x, y, z)	1,1,5
Roughness length	0.1m
Meteorological input	
T_a	24°C to 46°C
V_a (m/s)	5 m/s to 12 m/s
RH (%)	20 to 70
Wind direction	210° from north
Building input	
Wall thickness	300 mm
Surface finish	Jaisalmer limestone (site A), Plaster (other sites)
Physical properties	Envi-met default

site observations. the material characteristics were kept as Envi-met default.

5.1.3 Climatic input

Table 5.1 shows the input data for simulations for Delhi sites. Full forcing mode was used to get the maximum accuracy, which can calculate all-important thermal comfort indicators such as T_a, T_{mrt}, and PET.

Simulations were performed for the date of 21^{st} June which is the longest and the typical hottest day in a year for the studied climatic region. It is the date of the summer solstice which creates minimal shade on the ground and results in higher solar access to the open spaces. It was also made sure that the weather conditions a few days before the simulation date are usual and not cloudy. Since unusual weather conditions may affect the overall results.

5.1.4 Input parameters

Envi-met 5.0.2 database was used for material properties for vertical surfaces. To achieve maximum accuracy, the simulations were performed for the whole 24-hours cycle out of which the duration of the daytime between 7 am to 6 pm was taken for the analysis since a similar duration was considered for on-site measurements and surveys. Other than vertical surfaces, the entities such as vegetation and street furniture were not taken into the simulation input to get more accurate results only from vertical surfaces. The values of the albedo of flooring were modified during the calibration stages. Measurements of building footprints, streets, and open spaces were taken using satellite images and on-site measurements. The results were achieved at 1-hour intervals.

The input of climatic parameters is based on the 30 years average values (Indian Meteorological Department, 2010, 2012) which are more relevant rather than the on-field measurements which could be highly affected by the immediate weather situations. A typical summer day of 21^{st} June which is also the longest day of the year was chosen for the simulation when the average weather conditions are extreme and the altitude of the sun during noon is at its peak. All the climatic inputs for all four sites are constant. Table 5.2 shows the simulation input for Jaisalmer sites.

Skyhelios (Matzarakis, 2012; Matzarakis et al., 2007) is used in this study for the calculation of sky view factors (SVF). The SVF is an expression of the morphological factors for a

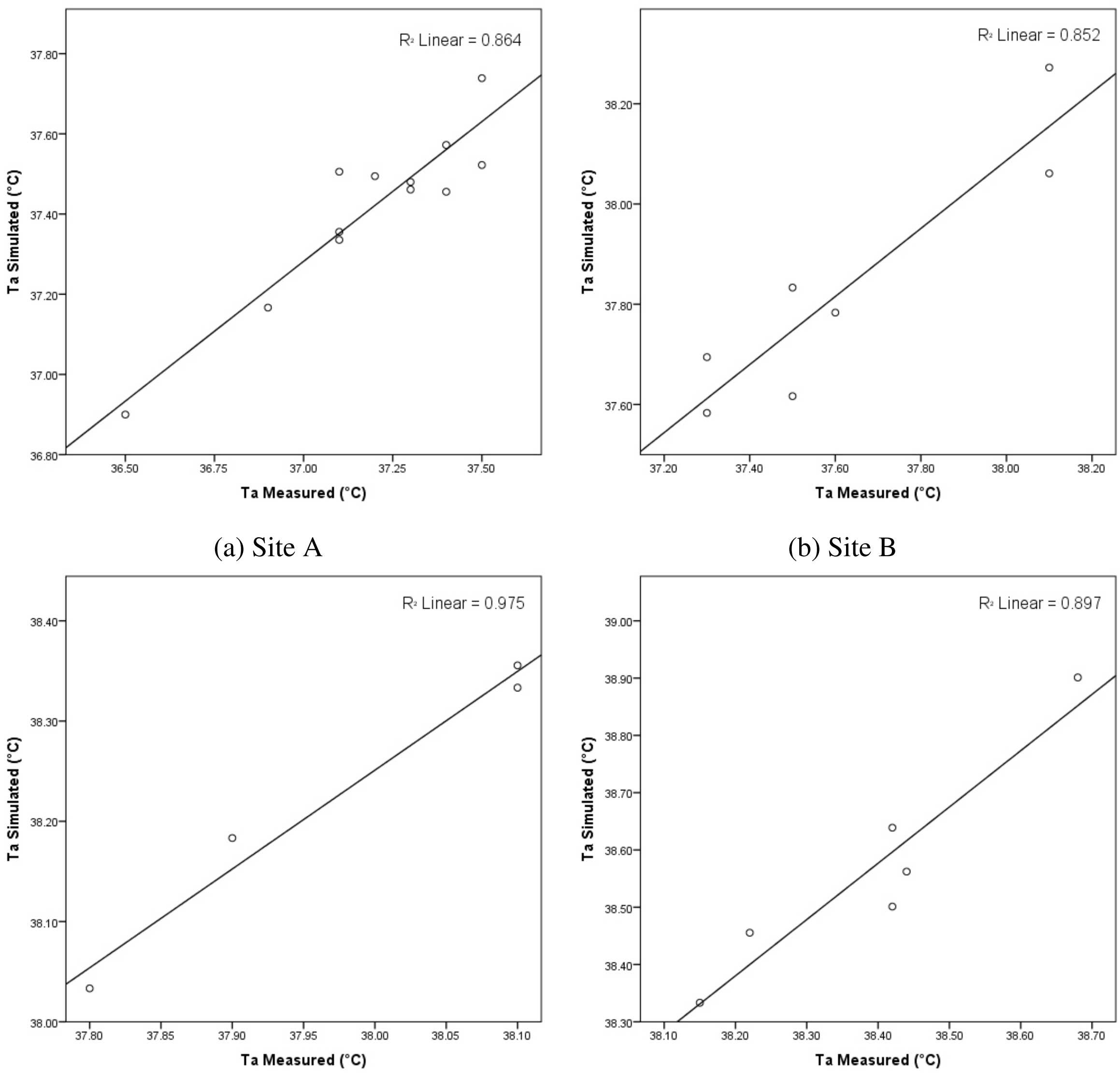
Table 5.3: Validation output for the sites in Delhi

	Bhikaji Cama Place			Nehru Place		
Climatic variable	R^2	RMSE	d	R^2	RMSE	d
T_a	0.90	0.95	0.43	0.91	0.64	0.25
V_a	0.88	0.17	0.97	0.75	0.32	0.86
R_h	0.69	0.77	0.79	0.77	0.54	0.93

Table 5.4: Validation output of other studies

Study	Variable	Validation outcome	Interpretation
(Brozovsky et al., 2021)	T_a	$R^2 = 0.85$	Good, acceptable
	V_a	$R^2 = 0.40$	-
	R_h	$R^2 = 0.80$	-
(Jihad and Tahiri, 2016)	T_a	$R^2 = 0.87$	Acceptable
	T_a	RMSE = 0.35	Acceptable
(Qaid et al., 2016)	T_a	$R^2 = 0.69, 0.83$	-
	T_a	RMSE = 1.49	-
	T_a	d= 0.91, 0.92	-
(Kakon et al., 2010)	T_a	$R^2 = 0.91$	Strong
(Nasrollahi et al., 2021)	T_a	$R^2 = 0.86$	-
	T_a	RMSE = 2.8°C	-
	T_a	d = 0.91	-
(Heris et al., 2020)	T_a	RMSE = 1.29 to 1.61	Acceptable
	T_a	d= 0.96 to 0.98	Acceptable
(Hedquist and Brazel, 2014)	T_a	R^2= 0.71 to 0.99	Acceptable
	T_a	RMSE= 1.46°C to 4.32°C	Acceptable
	T_a	d = 0.68 to .94	Acceptable
(Kong et al., 2016)	T_a	d= 0.95	Acceptable
(Battista et al., 2016)	T_a	RMSE= 1.64	Acceptable
	T_a	d = 0.99	Acceptable
	R_h	RMSE= 8.77	-
	R_h	d = 0.90	-
(Rajan and Amirtham, 2021a)	T_a	$R^2 = 0.65, 0.71, 0.72$	-
(Mohammad et al., 2021)	T_a	$R^2 = 0.91$	Acceptable
	V_a	$R^2 = 0.80$	Acceptable
	R_h	$R^2 = 0.93$	Acceptable

specific site in one single value and therefore allows for an estimation of relevant climatological information (Matzarakis and Matuschek, 2011).



(a) Site A (b) Site B

(c) Site C (d) Site D

Figure 5.1: Validation of Jaisalmer sites

5.2 Validation

It is important to validate the simulated model before its output can be used for further analysis. To achieve an acceptable model, the simulations were performed several times with modifications in the input parameters as necessary. The modifications were done in terms of the number of grid cells, grid sizes, model area, material properties, etc. T_a achieved from simulation output was compared with T_a measured on site.

Several statistical methods were used to calibrate the simulated and measured data. A study by Willmott (1981) suggested that R^2 is insufficient and RMSE and d are alternatives. Envi-met results are validated with metadata analysis by Tsoka et al. (2018) which shows the maximum studies focused on T_a for validation. Statistical methods used in this study are R^2, RMSE, and d. Simulated values of T_a, V_a, and R_h are compared with measured values. Table 5.3 shows the validation output for sites at Delhi and Figure 5.1 shows the validation output for sites at Jaisalmer. As per standards, if the values of R^2 are close to 1, it shows a statistically significant correlation. If RMSE values are close to 0, it indicates the errors are minor and if values of d are close to 1, it indicates the model performed perfectly.

The validation process includes the calibration of the Envi-met model several times until the valid model was achieved. In this study, the calibration broadly took three stages. The outcome of the first stage was not satisfactory. The model grid dimensions along with the built mass surrounding the site were added in the second stage to improve the accuracy of the model. In the third stage, the properties of ground surface materials (albedo) were modified.

For validation, one quick study was performed (Table 5.4) by the author to get the background on the validation that includes the variables validated, methods used, outcome achieves, and the interpretation of the outcome. Based on the validation outcome (Table 5.3) and after comparing with other studies (Table 5.4) it can be said that the simulated model is valid for Delhi and Jaisalmer (Figure 5.1). After the model was validated the simulated output of T_a, T_{mrt} and PET was used for further analysis.

6

Results and discussion

6.1 Results of User survey

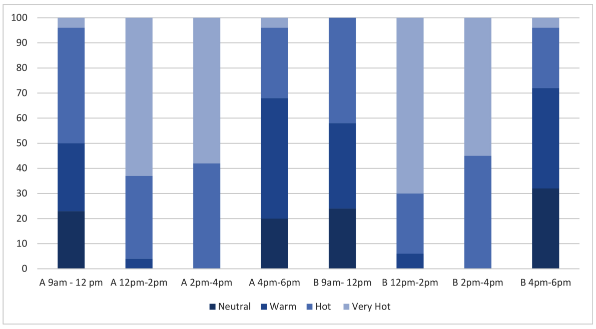
6.1.1 User survey results of Delhi study

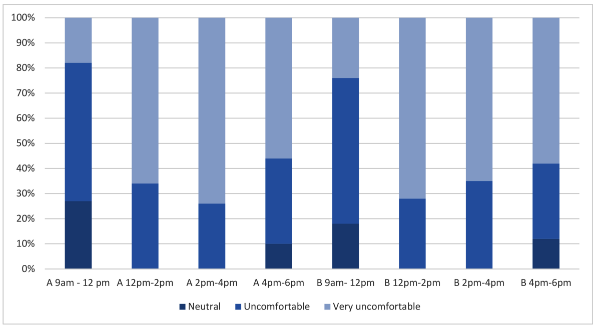
The thermal sensation was taken on the seven-point PMV scale (Fagner, 1972) and for assessing the comfort level, ASHRAE (1992) was referred. Thermal sensation and comfort level are the most important criteria for estimating the subjective thermal comfort level. Many studies (Ali and Patnaik, 2017; Nasrollahi et al., 2021; Mohammad et al., 2021; Banerjee et al., 2020; Shooshtarian and Ridley, 2016; Sharmin et al., 2015; Chen et al., 2015) emphasized on thermal sensation (TSV / mTSV) in their studies. The other questions in the questionnaire are considered supportive.

Figure 6.1a shows the percentage distribution of thermal sensation votes (TSV). 62% of users felt very hot followed by 36% hot between 12 pm to 4 pm and 44% of users felt very hot followed by 26% hot between 4 pm to 6 pm. Figure 6.1b shows the percentage distribution of thermal comfort. 69% of users felt very uncomfortable from 12 pm to 4 pm followed by 31% as uncomfortable. No user voted for neutral or below during this time of the day. 57% of users felt very uncomfortable from 4 pm to 6 pm. Neutral votes of 23% were achieved for morning hours between 9 am to 12 pm. The duration between 12 pm to 4 pm thus becomes the duration of concern when it comes to designing the vertical surfaces.

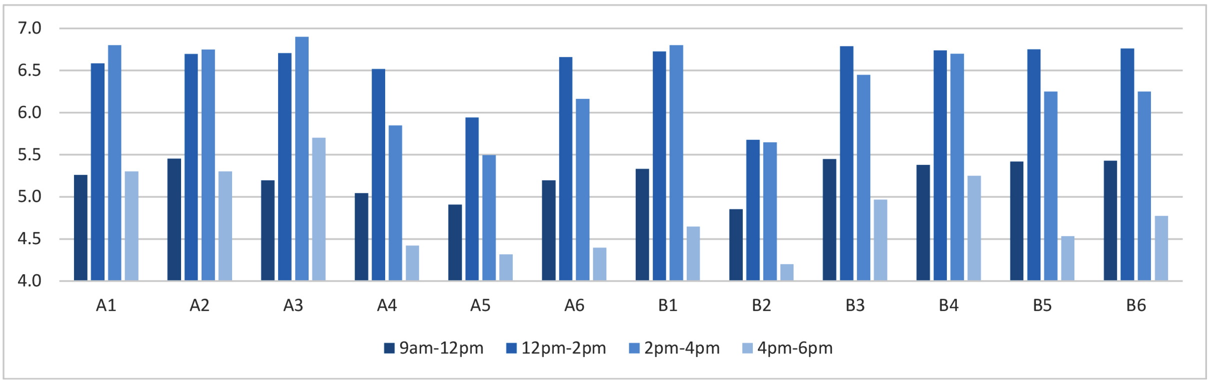
Figure 6.1c shows the mean thermal sensation votes across all the locations. Not a huge difference occurred among the locations. the locations Bk4, Bk5, and Np2 are observed with lower values of mTSV throughout the day. To understand the effect of vertical surfaces on mTSV, the correlation was performed (Figure 6.2). The impact of urban geometry on thermal sensation was also studied by Sharmin et al. (2015). A good negative correlation (R^2=0.62) is observed between mTSV and H/W ratio. whereas a moderate correlation (R^2=0.49) could be seen between mTSV and SVF. At this point, it can be said that the geometry of the vertical surfaces affects the thermal comfort level of the user which is analyzed further in subsequent sections.

86% of users felt the source of the discomfort is primarily solar radiation very few users felt there are other reasons like the lack of wind velocity and excess humidity. Out of the users,





(a) (b)

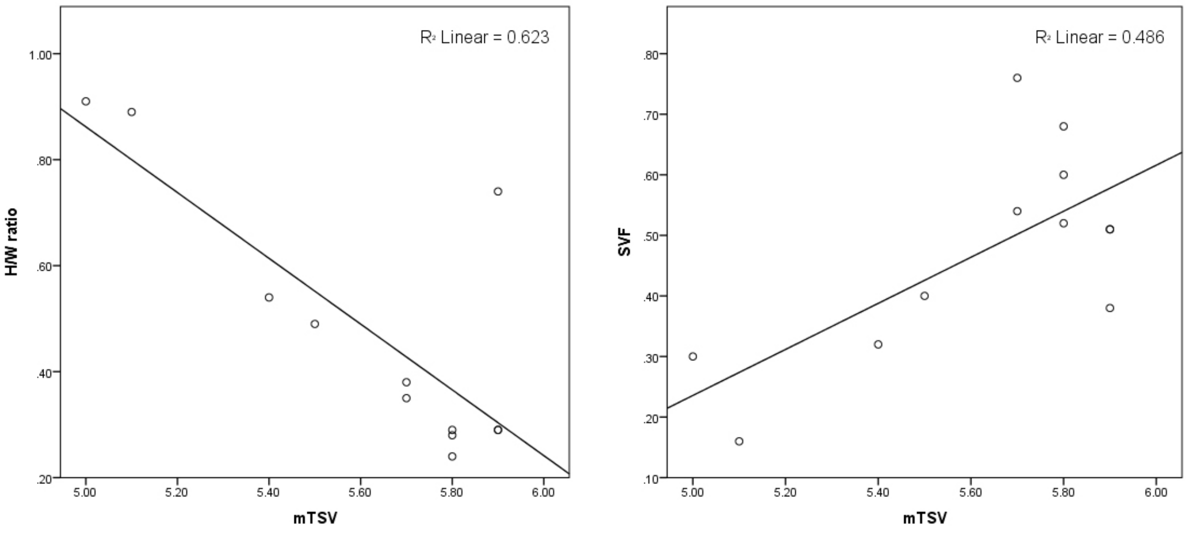


(c)

Figure 6.1: (a) Percentage distribution of thermal sensation vote (TSV) (b) Percentage distribution of thermal comfort level (c) Mean thermal sensation votes (mTSV) across all the locations at Delhi.

who commented on humidity, 78% felt that the humidity should have been lowered to improve the thermal comfort level. Out of the preferred areas to get refuge from the thermal discomfort maximum users (47%) preferred the tree shade whereas 37% users preferred buildings shade since the altitude of the sun and the vertical surface configuration is such that a very less amount of shade can be achieved from vertical surfaces. It is also one of the challenges to achieving the maximum comfort level by designing the vertical surfaces in such a way that maximum shade can be achieved especially during the post-noon session of the day.

From the questionnaire survey, it was observed that no user felt comfortable at any of the surveyed locations between 12 pm and 4 pm. In the noon hour, the preference was given to the areas with tree canopy rather than building shade at both sites since negligible shade was seen during this period whereas in the latter part of the day, users could be seen occupying the spaces having building shade.



(a) (b)

Figure 6.2: Correlation of mean thermal sensation vote (mTSV) with (a) H/W ratio (b) SVF, at Delhi

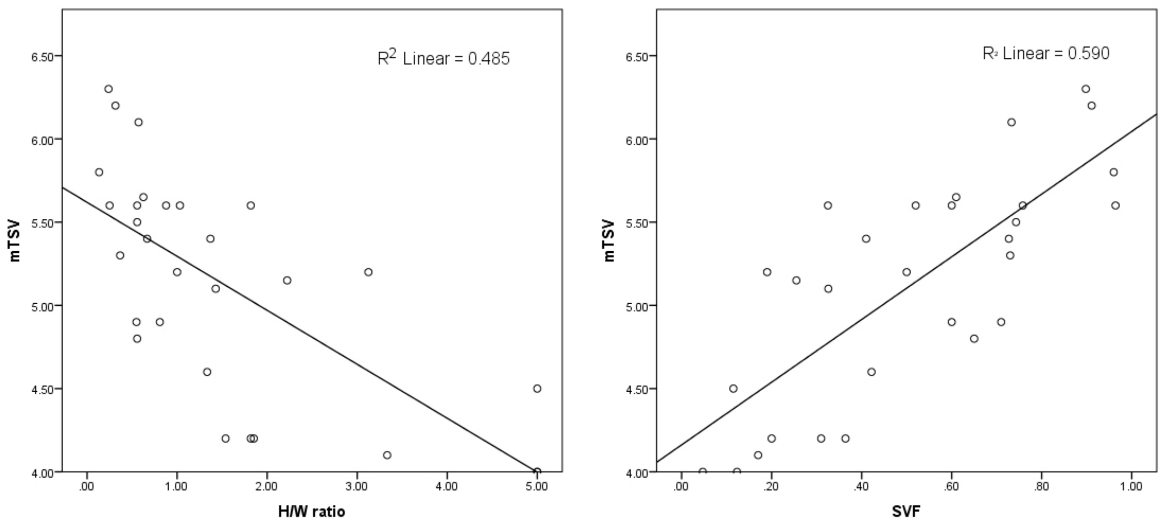
6.1.2 User survey results of Jaisalmer study

Figure 6.3 shows the output of the questionnaire survey in terms of the percentage of votes received for various questions. The results at site A during the survey show that the respondents' comfort range is better than the respondents at other surveyed sites. Thermal sensation (Figure 6.3a) is measured on a seven-point scale adopted from (ASHRAE-55, 2010). The thermal sensation of the user at site A is better than the rest of the sites. 54% users felt neutral at site A whereas 16% and 14% users felt neutral at sites B and C respectively. Only 4% voted for neutral at site D. Maximum users felt warm at all the sites except site A. Amongst the users who voted for hot, site D received the maximum votes (32%). The thermal comfort level (Figure 6.3b) of the users was assessed on a five-point scale. During the survey period, no user felt comfortable among any of the surveyed sites. At site A the votes were received between neutral (62%) and uncomfortable (38%). Site D is voted as the most uncomfortable with 73% voting as uncomfortable and 22% voting as very uncomfortable.

For all the sites, the maximum users were the residents who visited the surveyed locations almost daily (Figure 6.3c). Users spent maximum time at site A, and the least time at site D. It shows the preference given by the users for site A is much higher than the rest of the locations (Figure 6.3d). When asked about the source of discomfort (Figure 6.3e), maximum

Figure 6.3: Questionnaire survey results showing (a) Thermal sensation votes, (b) Thermal comfort level, (c) Frequency of space use, (d) Time spent on the location, (e) Source of discomfort, and (f) Preferred area to get refuge from the thermal discomfort

users felt the source is direct solar radiation, and very few users voted for other reasons like ventilation, lack of humidity, etc. Maximum users from all the sites felt that the building shade would be useful in improving the thermal comfort level, except for site D where users gave preference to other sources like tree shade or covering the head with a hat or umbrella (Figure 6.3f). This opinion was obvious since at site D the built density is much lesser, and trees could be observed on the site, whereas negligible vegetation is observed on the rest of the sites. Figure 6.4 shows the relationship between mean thermal sensation votes (mTSV) and physical parameters of the sites' H/W ratio and SVF. Moderate negative correlation (R^2= 0.48) could



(a) (b)

Figure 6.4: Correlation of mean thermal sensation vote (mTSV) with (a) H/W ratio (b) SVF, at Jaisalmer

be established between mTSV and H/W ratio whereas moderate correlation (R^2= 0.59) found between mTSV and SVF. It shows that a higher H/W ratio or lower SVF is attributed to the lower (towards neutral) votes of human thermal sensation. The survey outcome revealed that site A (traditional site) which is having narrow lanes which are usually shaded performed better in terms of thermal sensation and comfort level.

6.2 Simulation Results

6.2.1 Spatial and temporal variation of T_a, T_{mrt}, and PET at Delhi

In the subtropical climate of India, the comfort range is between 25°C to 30°C, with the optimum temperature at 27.5°C (Bureau of Indian Standards, 2005; Bureau of Indian standards, 2005).

Figure 6.5a and Figure 6.5b illustrates the spatial variation of T_a during the hottest duration of the day (3pm) and Figure 6.6a and Figure 6.6b shows the temporal variation of T_a during the daytime at all the studied locations. It shows that locations Bk1, Bk3, Np3, and Np5 are having a higher T_a than the rest of the locations. The lowest T_a from Bhikaji Cama Place is observed at location Bk5 which is enclosed from all sides and has the lowest SVF of 0.16. During the

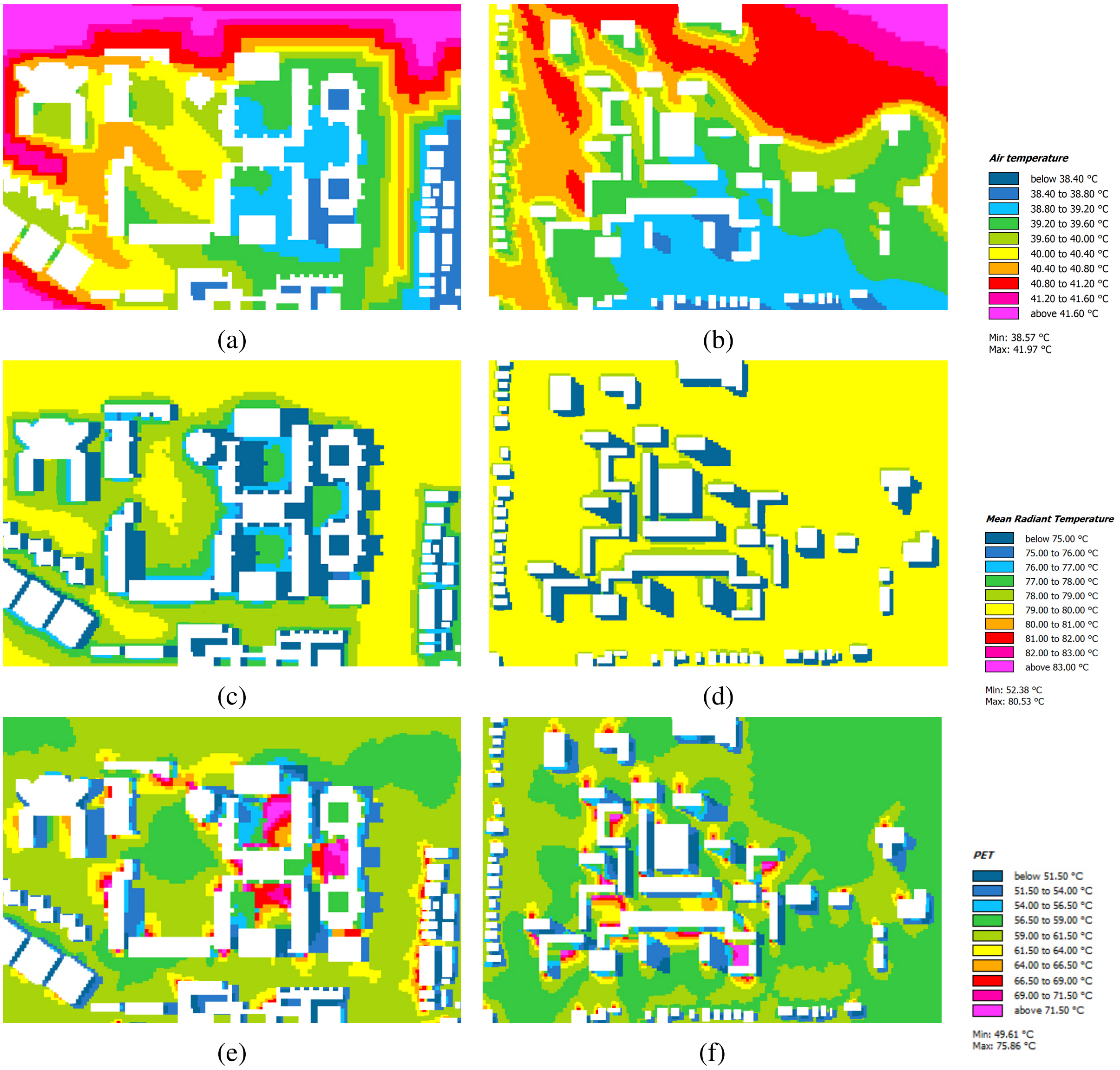


Figure 6.5: Spatial variation of (a) T_a at Bhikaji Cama Place (b) T_a at Nehru Place (c) T_{mrt} at Bhikaji Cama Place (d) T_{mrt} at Nehru Place (e) PET at Bhikaji Cama Place (f) PET at Nehru Place

harshest hour at Bhikaji Cama Place, the average T_a at the shaded area is 39.70 °C and at the non-shaded area is 40.69 °C. Not a huge variation of T_a is observed for locations at Nehru Place. Location Np2 is having lowest T_a (SVF 0.30). During the harshest hour at Nehru Place, the average T_a at the shaded area is 39.90 °C, and the non-shaded area is 39.95°C.

Maximum variation of T_a is observed at the locations of Bhikaji Cama Place than at the locations of Nehru Place. Possible reasons can be the hours of solar access and the variation in the wind flow. It can be observed that the temperature variation is directly linked to the adjacent vertical surfaces. Not only the presence of vertical surfaces but the direction from

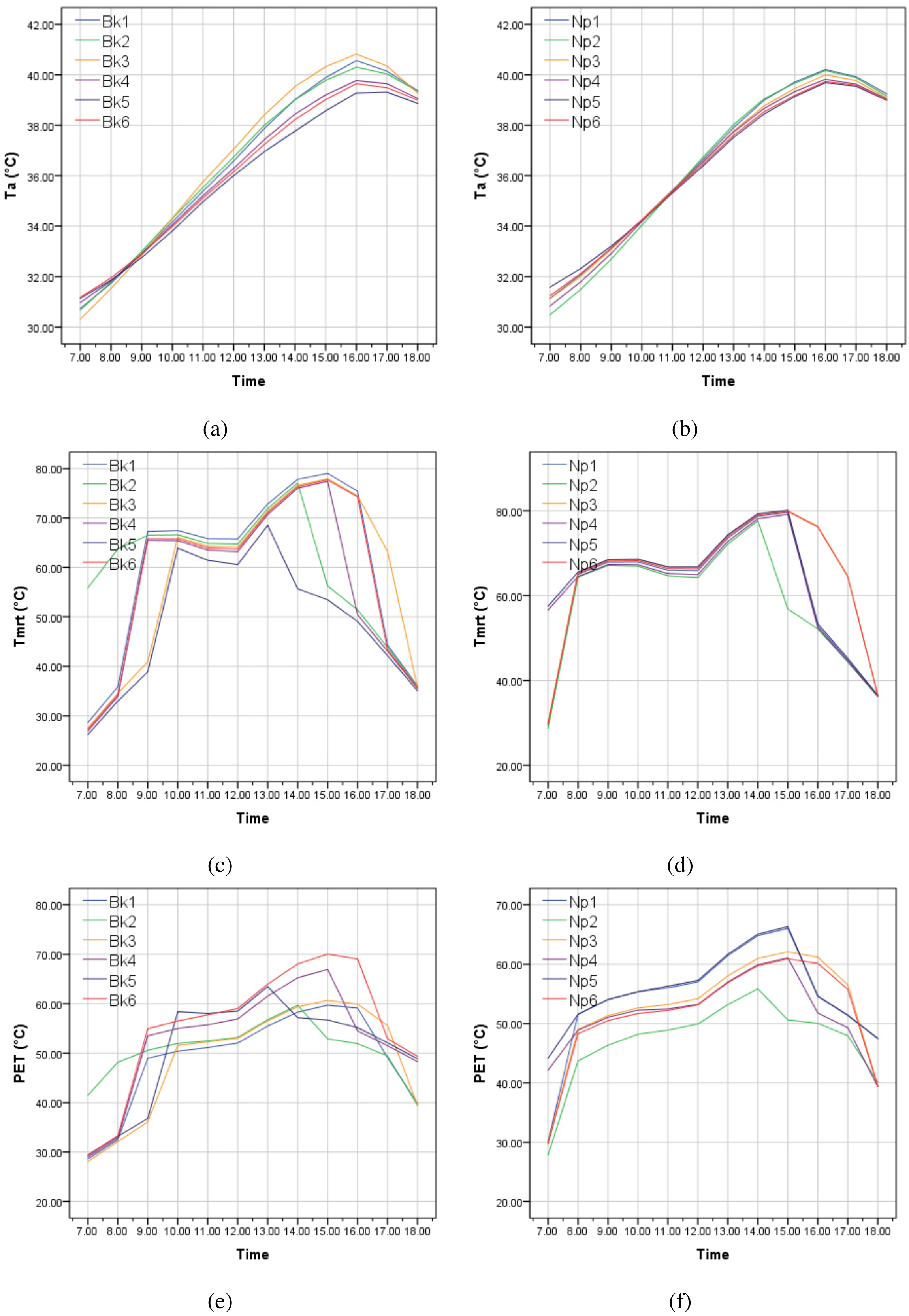


Figure 6.6: Temporal variation of (a) T_a at Bhikaji Cama Place (b) T_a at Nehru Place (c) T_{mrt} at Bhikaji Cama Place (d) T_{mrt} at Nehru Place (e) PET at Bhikaji Cama Place (f) PET at Nehru Place

which they are enclosing the locations is highly affecting the T_a of that open space. Locations with higher H/W ratios and lower SVF show the lower T_a, the result coincides with other studies (Bourbia and Awbi, 2004; Ali-Toudert and Mayer, 2006; Sharmin et al., 2012), who found similar relationships.

Figure 6.6 shows the temporal variation at all the studies locations at Delhi. T_{mrt} increases in the morning till around 11 am, but it lowers slightly in the noon since the reflected radiation from vertical surfaces is very less due to the angle of incident solar radiation with the vertical surfaces being very small, this drop in the T_{mrt} is observed. In the afternoon hours, the T_{mrt} level was observed to be higher with the highest between 3 pm and 4 pm after that T_{mrt} value starts decreasing. Maximum variation among the locations is observed in the latter part of the day.

Location Bk5 is observed with the lowest T_{mrt} with the maximum drop in T_{mrt} level observed after 1 pm. With SVF as low as 0.16, the vertical surfaces around this location rarely get exposed to direct solar radiation. Although the T_{mrt} at Bk5 is the lowest during the noontime, the PET is observed with a higher value. Location Bk2 is observed to be highest in T_{mrt} and PET in the morning hours but the values drop significantly in the afternoon since the location is enclosed from the south and the west directions which helps this location to get shade in the afternoon, also the surfaces are not exposed to the direct solar radiation in the afternoon. On the other hand location, Bk3 is cooler in the morning hours but T_{mrt} and PET are observed to be the highest in the afternoon hours since this location is enclosed in south and east directions, in the afternoon the vertical surface facing west is exposed to the direct solar radiation.

The values of T_{mrt} and PET for all the locations start decreasing at different times of the day. Location Bk5 which has shown the lowest value starts decreasing the T_{mrt} and PET after 1 pm which is the earliest followed by locations Bk2, Bk4, and Bk6 respectively. the temperature at location a3 decreased very late in the afternoon. location Bk1 is the worst affected location where thermal discomfort was observed for the longest duration (9 am to 4 pm) compared to the rest of the locations. In the case of Nehru Place, location Np2 performed better with lower values of temperature and the smallest duration of thermal discomfort. the temperature at Np2 starts increasing late in the morning and starts decreasing earliest in the afternoon compared to the other locations. locations Np3 and Np6 are having almost similar characters and performed worst at Nehru Place. The temperature at these locations starts decreasing very late in the afternoon.

Although the variation in T_a is very small, the drastic difference in T_{mrt} and PET are observed. This is in agreement with the results achieved by Nasrollahi et al. (2021) for the hot season. At Bhikaji Cama Place, the average T_{mrt} for shaded areas is 54.70°C and for non-shaded areas, 78°C and the average PET for shaded areas is 54.90°C and non-shaded areas is 64.33°C. Whereas at Nehru Place, the average T_{mrt} for shaded areas is 56.70°C and for non-shaded areas, 79.78°C and the average PET for shaded areas is 50.60°C and non-shaded areas 62.60°C. These differences indicate the importance of shading during harsher hours of the day. The T_{mrt} and PET can be minimized by increasing the H/W ratio. This also agrees with the study (Johansson et al., 2014) which concluded that the PET can be reduced if the building height in an urban area is increased.

6.2.2 Spatial and temporal variation of T_a, T_{mrt}, and PET at Jaisalmer

Spatial variation of T_a is much lesser than T_{mrt} and PET. Figure 6.7, Figure 6.8 and Figure 6.9 show the spatial variation at all the sites for the harshest hour of the day (3 pm- 4 pm). A variation could be observed as the density of built mass decreases that is the lowest values are observed at site A which increase gradually to site B, site C, and site D respectively. Density is built mass defined by H/W ratios and SVFs. The effect of orientation can also be seen in the variation in temperatures. In the case of T_{mrt} and PET, the values in shaded and un-shaded areas are very distinctive. In the case of PET, the influence of wind flow can also be observed. The spatial variation in T_{mrt} is much higher than T_a and PET. The maximum difference in T_a among all the sites is 1.63°C, in the case of T_{mrt} it is 28.45°C and for PET it is 4.85°C. The results are in agreement with the previous studies (Emmanuel, 2021; Mayer et al., 2008).

Figure 6.10 shows the average temporal variation between all four sites. The variation of T_a is lesser than PET, whereas the variation of T_{mrt} is higher. Although the observed difference is very small within the site, a big difference is observed between all four sites. The T_as increased gradually from site A to site B, site C, and site D; this pattern negatively correlates with the

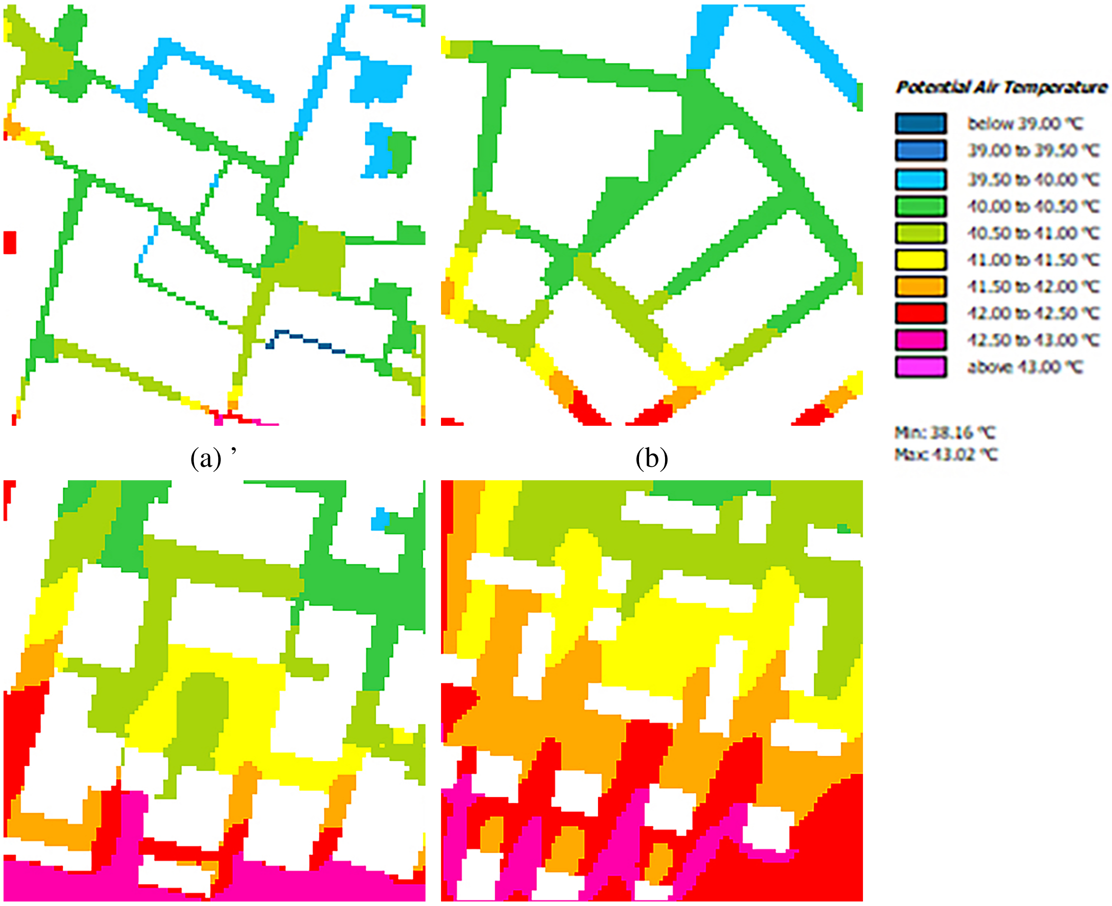


Figure 6.7: Spatial variation of (a) T_a at site A, (b) T_a at site B, (c) T_a at site C, and (d) T_a at site D

densities of these sites which are decreasing gradually. Even at the hottest period of the day, site A showed the lowest T_a with an average of 40.85°C, while average T_a of 41.33°C, 42.10°C, and 42.48°C was achieved for site B, site C, and site D respectively. These variations are attributed to the difference in the H/W ratios. The average difference between site D and site A is 1.15°C, whereas at 4 pm it is observed as the highest at 1.63°C. The average difference of T_{mrt} is 23.42°C and at 3 pm it is the maximum at 28.45°C. In the case of PET, the average difference is 5.78°C, and at 3 pm it is 4.85°C.

The temporal variations of T_a were observed maximum for the time between 3 pm to 5 pm. The maximum difference within site A is 0.75°C, for site B it is 1.0°C, for site C it is 0.6°C, whereas for site D it is 0.8°C. Site D was observed to be having the highest in T_a's and the minimum temperature of 42.2°C at location D3 which is higher than the highest temperature at site A. T_a at location D6 is the highest among all the studied locations from all the sites which

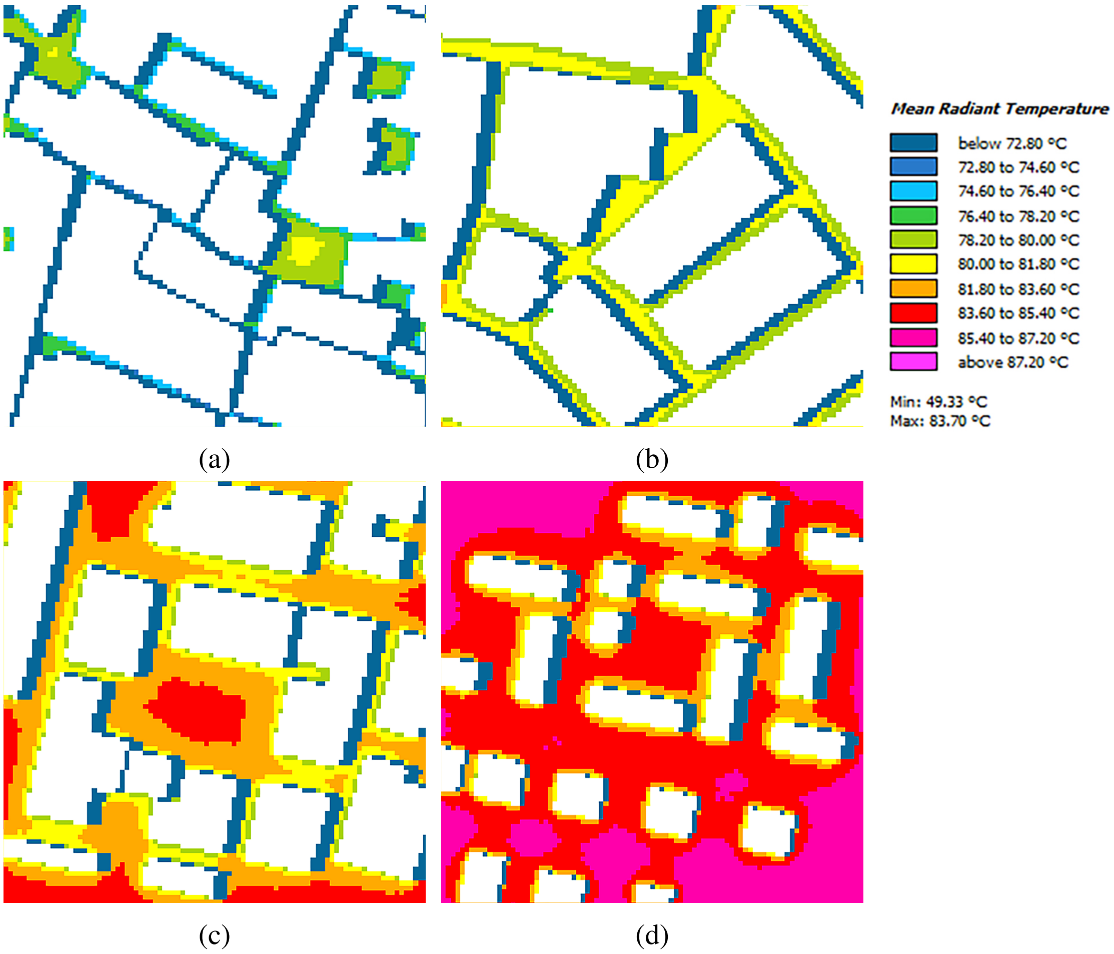


Figure 6.8: Spatial variation of (a) T_{mrt} at site A, (b) T_{mrt} at site B, (c) T_{mrt} at site C, and (d) T_{mrt} at site D

is 43°C.

Figure 6.11 illustrates the hourly variation in the T_{mrt} and PET for locations having vertical surfaces on the east, west, north, and south directions of the open spaces. The highest variation of T_{mrt} and PET are observed in the case of locations enclosed in east and west directions. Not a big variation is observed between 11 am to 1 pm due to the higher altitude of the sun when the outdoor spaces are exposed to direct sunlight and shade cast by the vertical surface is minimal. The difference in temperature increases in the latter part of the day. The highest values are observed at locations D2 and D4 which are having the maximum SVF of 0.73 and 0.74 respectively, whereas location B1 was observed with the lowest temperature due to the smallest SVF of 0.42. The drop in the temperature occurred around 2 pm for location B1, around 3 pm for location C4, and around 4 pm for locations C2, D2, and D4; this difference occurred due to the difference in the time of the shading of these locations which is primarily

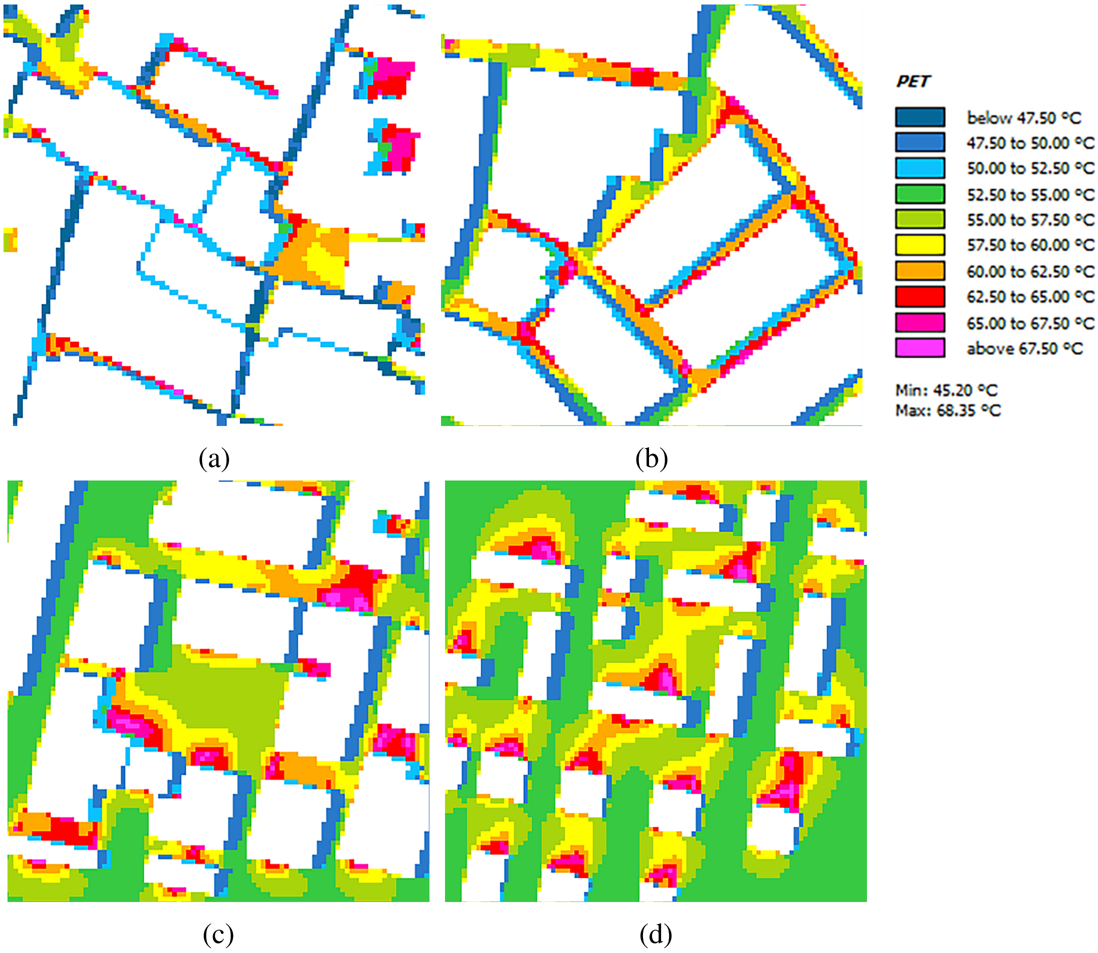


Figure 6.9: Spatial variation of (a) PET at site A, (b) PET at site B, (c) PET at site C, and (d) PET at site D

the outcome of the H/W ratios and SVF.

In the case of locations enclosed from north and south directions, the variation in T_{mrt} is uniform throughout the day at location B6 (lowest in T_{mrt}) and location D5 (highest in T_{mrt}). Because the open spaces are open in east and west directions the duration of the solar access for each location is almost the same. The trend of PET followed the trend of T_{mrt}, except for location B6, where the PET in the morning and the late afternoon is lower than the rest of the locations, this is due to the smaller SVF than the rest of the locations. In the case of locations enclosed from all four directions i.e. North, east, west, and south directions, the variation in the T_{mrt} is very less.

Figure 6.12 shows the variation of T_{mrt} and PET for the directions north-east, north-west and south-east, and south-west. Unlike Figure 6.11, the variation of the T_{mrt} and PET within the sites is much higher. It is due to the uneven distribution of the temperature caused by the

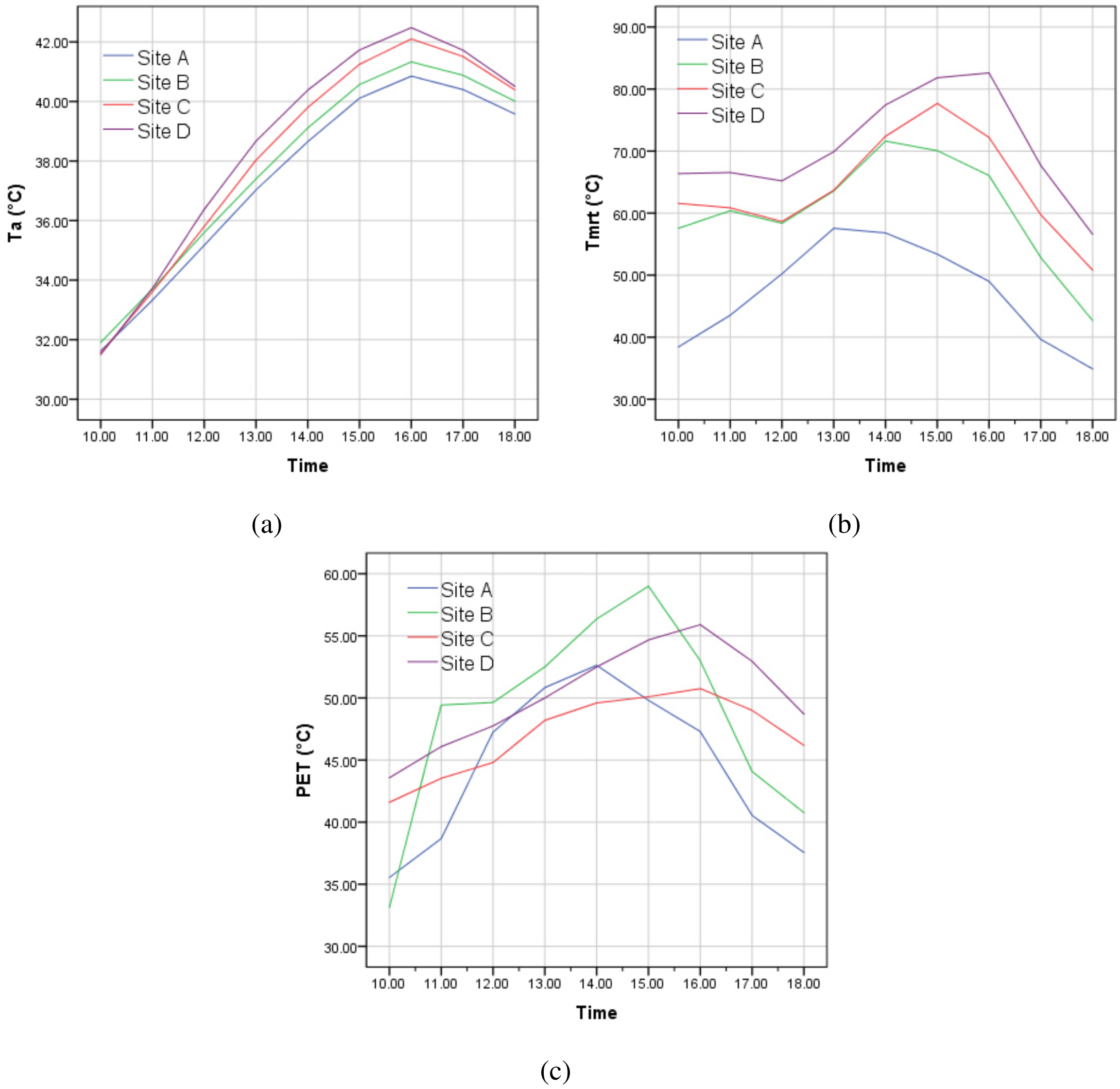
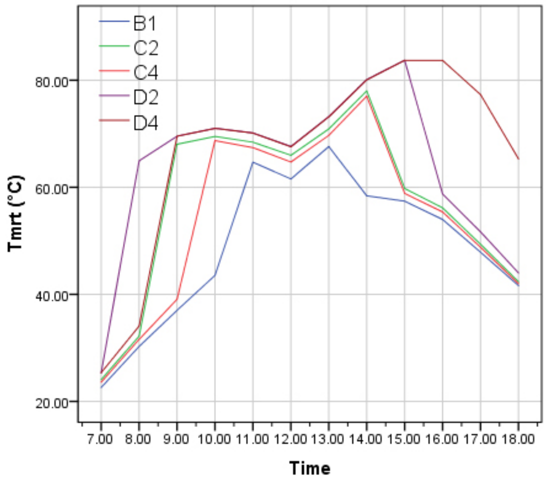
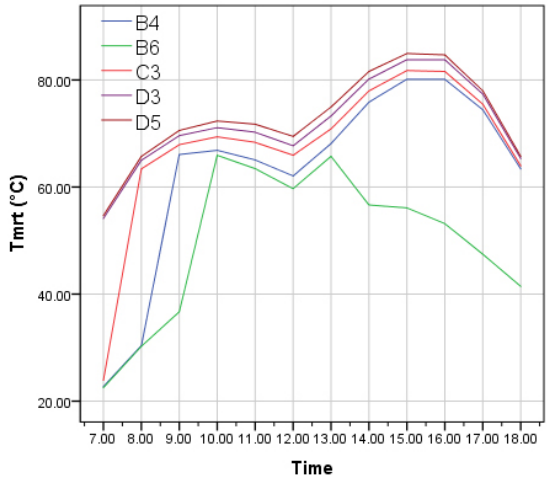


Figure 6.10: Average temporal variation at all the sites for (a) T_a, (b) T_{mrt}, and (c) PET

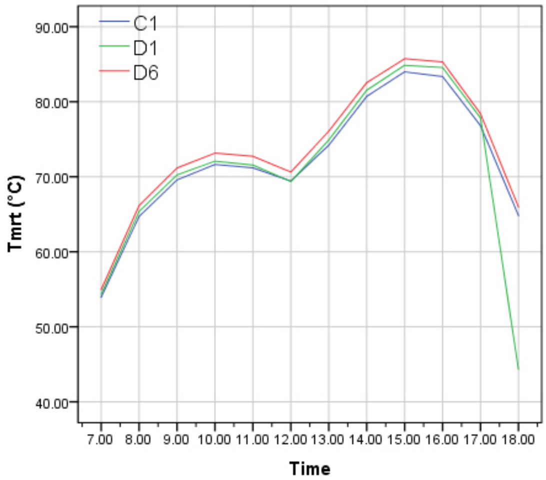
variation in the solar access to the open spaces. The time between 12 pm to 1 pm saw a smaller variation of the temperature between all the locations enclosed by vertical surfaces from SW and NE directions. This variation increased for the rest of the hours of the day. Location A6 starts reducing the temperature at around 1 pm, followed by A5, A3, A4, B5, and B7. Location A6 is a narrow open space having a H/W ratio of 5 and SVF of just 0.12 due to which the location is protected from direct solar exposure resulting in the smallest T_{mrt} and PET values. on the other hand location, B7 is more open to the sky with a H/W ratio of 0.88 and SVF of 0.6, it allows more sunlight to enter the open space. A similar trend was observed for the locations enclosed by SE and NW surfaces. Narrow open spaces at locations A10 and A11 are lowest in the temperatures, followed by A9 and A12. Locations A8 and B3 have more T_{mrt}



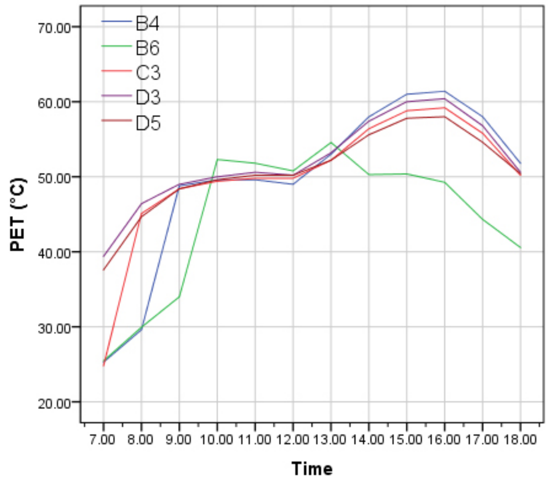
(a) East and west directions



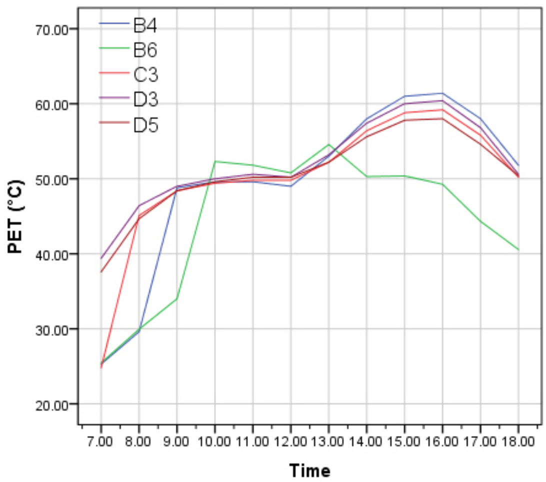
(b) North and south directions



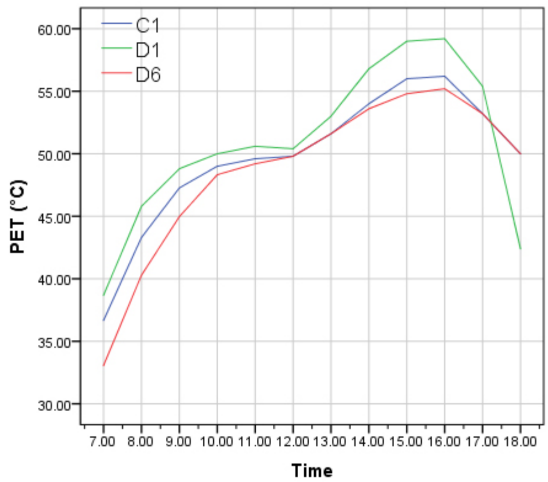
(c) East, west, north and south directions



(d) East and west directions

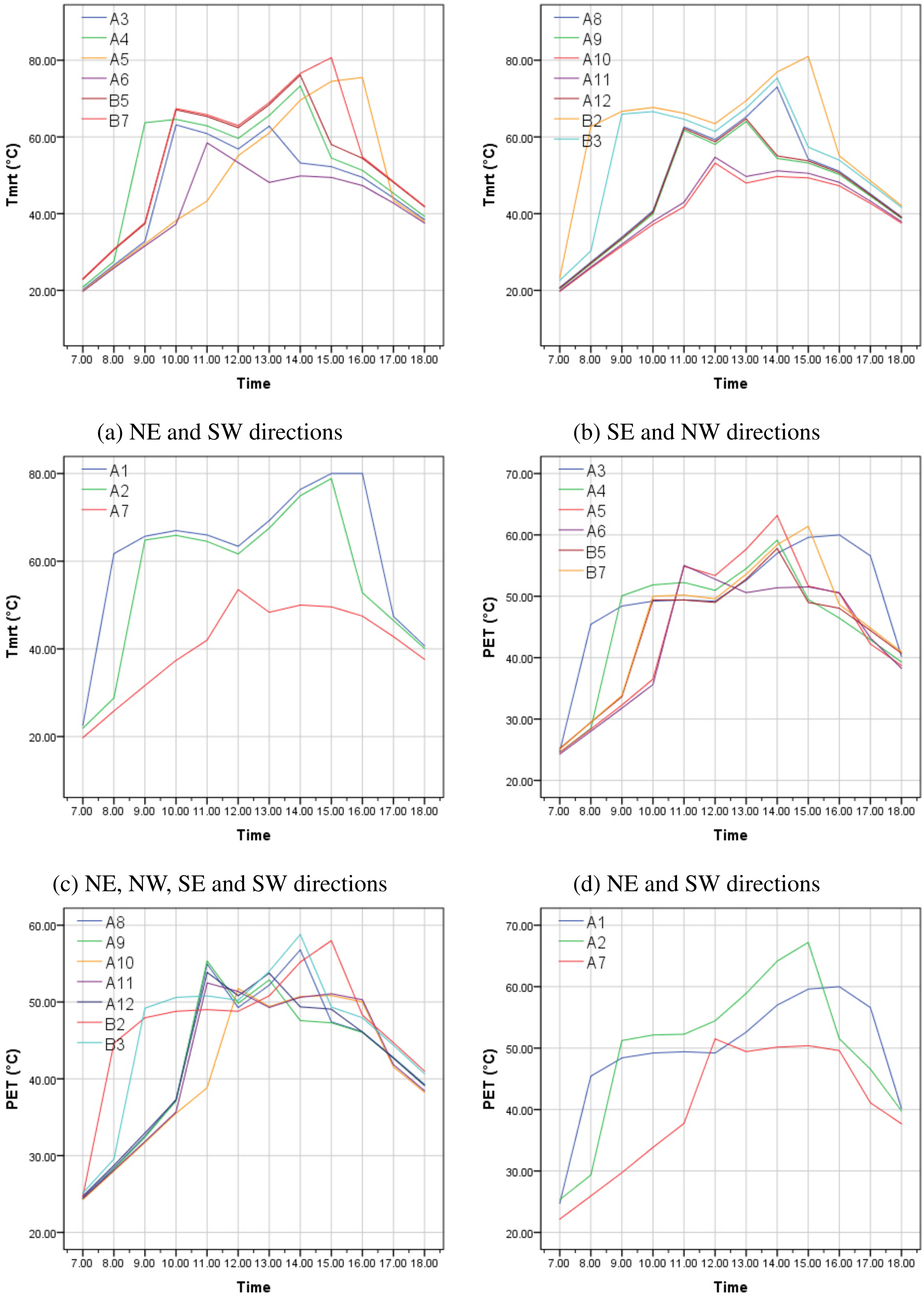


(e) North and south directions



(f) East, west, north and south directions

Figure 6.11: Variation of T_{mrt} and PET for locations enclosed by vertical surfaces on north, east, west, and south directions



(a) NE and SW directions

(b) SE and NW directions

(c) NE, NW, SE and SW directions

(d) NE and SW directions

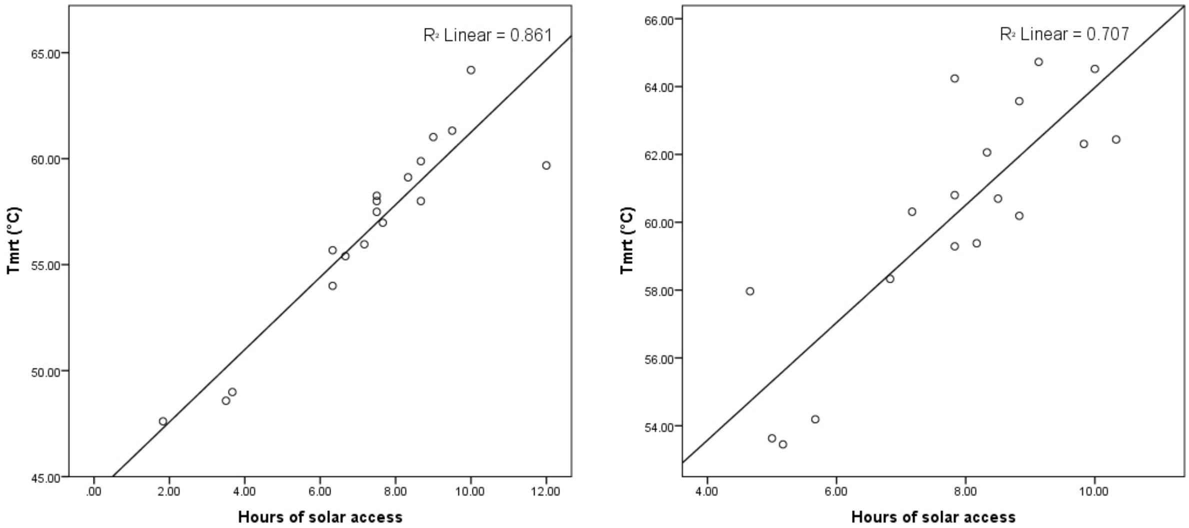
(e) SE and NW directions

(f) NE, NW, SE and SW directions

Figure 6.12: Variation of T_{mrt} and PET for locations enclosed by vertical surfaces on north-east, north-west and south-east, and south-west directions.

and PET which starts decreasing after 2 pm followed by location B2 which was observed to be highest in T_{mrt}. Locations A1 and A2 which are enclosed by all four sides are comparatively larger locations with SVF 0.73 and 0.61 respectively. These locations are having higher T_{mrt} which starts reducing at around 4 pm and PET starts reducing at around 3 pm. Location A7 is the narrowest location amongst all the studied locations with an SVF of 0.05, this location has the lowest T_{mrt} and PET values. When compared to all the locations from all four sites, the locations enclosed from NE and SW directions and locations enclosed from NW and SE are having smaller values of T_{mrt} and PET. it is due to the exposure of these locations to direct sunlight for the very short duration of the day which ultimately reduces the overall heat gain. For the locations enclosed from NE, NW, SE, and SW, the T_{mrt} is very much uniform similar to the the locations enclosed from N, E, S, and W due to the similar reason of the equal distribution of the temperature is observed, except for location A7 which is very narrow. The effect of the SVF and the orientation could be seen since the solar access and wind speed (V_a) etc. are affected by the configuration of the vertical surfaces.

The open spaces having enclosures in east and west directions are more comfortable than open spaces having enclosures in north and south directions. But, this is still not a favourable option, especially for the design of streets since the design of a street for the single orientation is not possible due to the requirements of the circulation of any urban area, the street has to turn towards the perpendicular directions, in that case, street orientation towards E-W direction can not be a suitable option. For this reason, the streets and open spaces oriented towards NE-SW, and NW-SE directions are more suitable since both of these orientations were observed to be better in thermal comfort than the east-west oriented open spaces. this contradicts with the other studies (Nasrollahi et al., 2021; Taleghani et al., 2015; Hamdan and de Oliveira, 2019) done for the tropical climates.



(a) (b)

Figure 6.13: Correlation between solar access and T_{mrt} (a) at Bk (b) at Np

6.3 Effect of physical and climatic parameters on thermal comfort

6.3.1 Effect of solar access on thermal comfort

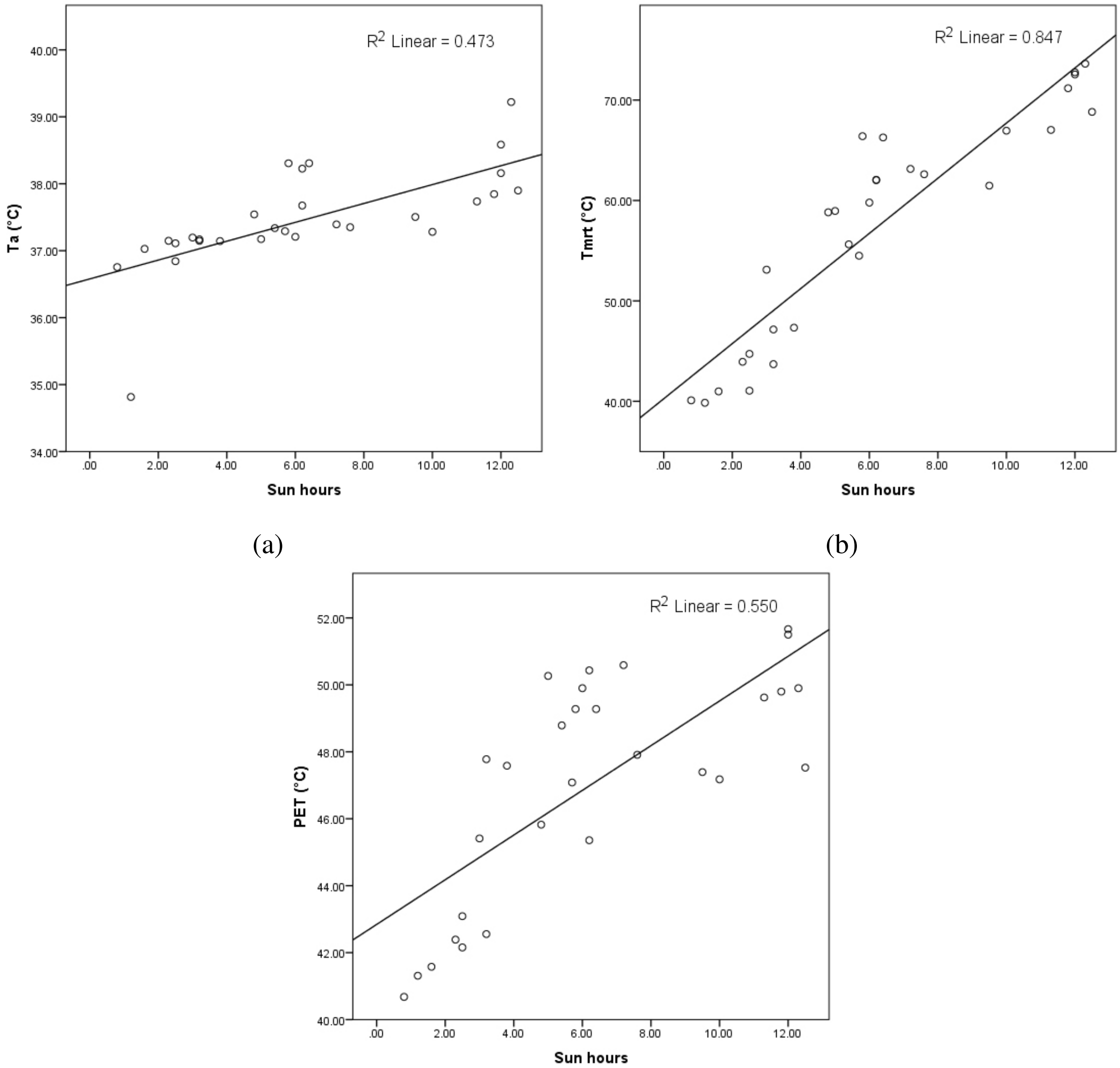
The duration of exposure to direct sunlight highly affects the thermal comfort level of the user (Huang et al., 2015). During thermal discomfort, the very first measure taken by the user is to move towards the shaded area to have a refuge from the direct sunlight (Wang et al., 2017).

At Delhi, variation of solar access and respective T_{mrt} is observed at all the locations. the variation was also observed within the location at different points. Figure 6.13 shows the significant correlation (R^2= 0.86 at Bhikaji Cama Place and R^2= 0.71 at Nehru Place) between hours of solar access to average T_{mrt} values. No significant correlation could be established between hours of solar access and PET.

Among the locations of Bhikaji Cama Place, at the center of Bk1, the highest solar access of 12 hours is observed with a T_{mrt} of 59.68°C. At location Bk5 minimum hours of solar access (1.83) is observed with a T_{mrt} of 47.61°C. In the case of Nehru Place, the highest solar access of 10.33 hours is observed at Np4 with a T_{mrt} of 62.44°C. It is noteworthy to see that the H/W ratio at Np4 is as high as 0.74 still it is the location of the highest solar hours, due to the orientation of this location and the absence of vertical surfaces enclosing the direction of solar access (SW and NE). On the other hand location, Np2 is enclosed from SW and NE with a H/W ratio of 0.91 that allows minimal solar access of 4.66 hours resulting in the lowest average T_{mrt} value of 53.45°C. Within Bhikaji Cama Place the difference of 16.57 °C and at Nehru Place the difference of 11.28 °C is observed for the average T_{mrt} values.

It is usually very difficult to control the amount of solar radiation received by the built environment. As per Gupta (1985) horizontal projections are useful for the reduction of solar access whereas Hamdan and de Oliveira (2019); Latini et al. (2010); Huang et al. (2016) suggested the use of vegetation. From the above analysis, it can be said that the higher H/W ratio with vertical surfaces enclosing the directions of solar access is key to reducing the hours of solar access and T_{mrt} level without the use of horizontal projections and vegetation.

At Jaisalmer, variation in the hours of solar access and shade due to vertical surfaces was observed at various locations. At 10 am, most of the locations from all the sites are partially shaded. There is no concern over shade for this hour of the day because the temperature is much lesser than in the later hours of the day. Between 12 pm to 2 pm, negligible shade is observed, it is interesting to see that for site A, some locations still get shade due to their smaller SVF compared to the rest of the locations from all the sites, during this time the maximum area of locations A7 and A10 are under shade. Maximum shade could be observed at 4 pm for each site, this is an important hour to understand the sun's movement and shade since the highest temperature of the day is observed for this hour (Figure 6.10). At site A, most of the locations are shaded fully except for locations A1 and A2 which are shaded partially, most of the area at location A1 is still unshaded. Locations A3 and A4 are partially shaded and the rest of the locations are fully shaded by this time. Locations A6, A7, A10, and A11 are under shade for almost the whole day. In the case of site B, locations B1 and B3 are maximum shaded B2, B5, and B7 are partially shaded, whereas location B4 is still unshaded which makes this location the most exposed to direct solar radiation. In the case of site C, locations C2 and C4 are partially shaded, a very little portion of location C1 is shaded and location C3 is the most exposed location to direct solar radiation since this location is not shaded throughout the day. In the case of site D, only locations D2 and D4 are partially shaded and the rest of the locations



(a) (b)

(c)

Figure 6.14: Relationship between sun hours and (a) T_a, (b) T_{mrt}, and (b) PET

are exposed the whole day to direct solar radiation.

Figure 6.14 shows the relationship between sun hours and thermal indices (T_a, T_{mrt}, and PET). A moderate correlation could be observed between sun hours and T_a (R^2 = 0.47) as well as PET (R^2 = 0.55). Whereas, a strong correlation could be seen between sun hours and T_{mrt} (R^2= 0.85). The maximum difference in T_a is 2.46°C and for PET, it is 9.22°C. The huge difference of 33.5°C observes between the highest and lowest values of T_{mrt}. Each solar hour increase shows the increase in T_{mrt} by 2.74°C. It shows that the effect of solar access is higher on T_{mrt} than the rest of the indices, which also reveals the importance of shading. It can be said that to reduce the T_{mrt}, the concern should be to achieve a higher H/W ratio and lower SVF. The locations having vertical surfaces on NE-SW and NW-SE are better in thermal comfort level due to the longer duration of shading. This result is in agreement with the previous research (Ali-Toudert and Mayer, 2006).

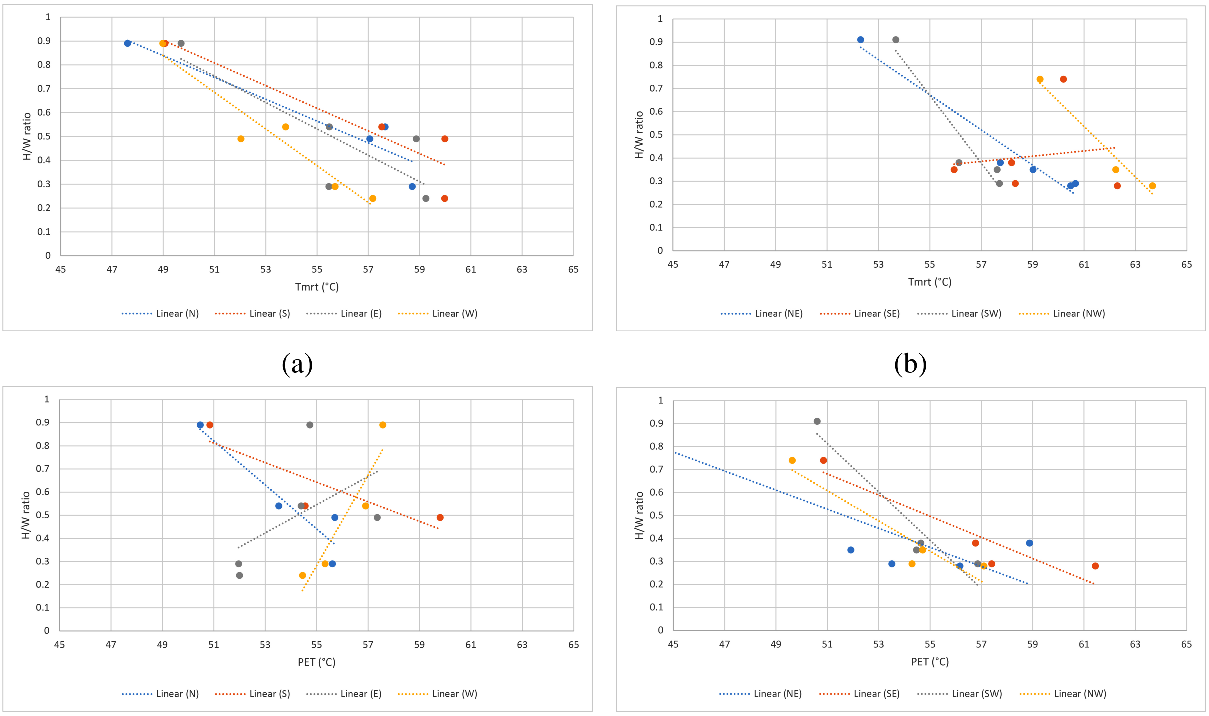
6.3.2 Effect of geometrical parameters on thermal comfort

Parameters determining geometry are the H/W ratio, SVF, and orientation of vertical surfaces. The geometrical parameters are correlated with comfort parameter T_{mrt} and PET (Figure 6.15). The enclosing vertical surface to the location may have a varying effect on thermal comfort parameters. For this reason, the T_{mrt} and PET values up to 10 meters horizontal distance from enclosing vertical surfaces are taken for the analysis. These values are plotted separately (Figure 6.15) as per the orientation of the vertical surface enclosing that space.

Table 6.1 shows the values of R^2. A strong correlation could be found between thermal comfort parameters and the H/W ratio, whereas, a poor to moderate correlation is found with SVF. It contradicts with the previous studies (Deevi and Chundeli, 2020; Nasrollahi et al., 2021; Perera and Weerasekara, 2014; Rajan and Amirtham, 2021; Ali-Toudert and Mayer, 2007; Sharmin et al., 2015; Yahia et al., 2018) which identified a strong correlation of T_{mrt} and PET with SVF.

Figure 6.15a and Figure 6.15b showed a good negative correlation of T_{mrt} with H/W all the orientations of vertical surfaces could be observed creating an impact on thermal comfort level. South facing vertical surface is the highest due to its exposure to direct solar radiation for a longer duration of the day. In the case of south-east facing vertical surfaces, an insignificant correlation was found whereas north-west facing vertical surfaces showed the highest effect on T_{mrt}. Figure 6.15c and Figure 6.15d showed a good negative correlation of PET with H/W. Except for east-facing and west-facing surfaces which showed a positive correlation. It can be observed that the higher H/W ratio significantly reduces T_{mrt} which is more prominent in the case of site A where vertical surfaces are aligned more toward cardinal directions. At a lower H/W ratio, south-facing surfaces showed higher values of T_{mrt}, and PET, west-facing surfaces showed lower values. At the lowest H/W ratio, average south-facing surfaces are 2.81°C higher in T_{mrt} and 5.35°C higher in PET than west-facing surfaces.

It can be inferred that the orientation of vertical surfaces more toward cardinal directions



(a) (b)

(c) (d)

Figure 6.15: Correlation of (a) T_{mrt} and H/W at Bhikaji Cama Place (b) PET and H/W at Nehru Place (c) T_{mrt} and SVF at Bhikaji Cama Place (d) PET and SVF at Nehru Place for all the orientations of vertical surfaces.

	N	S	E	W	NE	SW	NW	SE
T_{mrt} vs H/W	0.89	0.84	0.68	0.91	0.96	0.91	0.97	0.02
PET vs H/W	0.87	0.76	0.28	0.88	0.69	0.90	0.88	0.86
T_{mrt} vs SVF	0.79	0.63	0.65	0.86	0.46	0.88	0.01	0.13
PET vs SVF	0.89	0.03	0.32	0.11	0.83	0.54	0.55	0.16

Table 6.1: R^2 values for the correlations between physical parameters and comfort parameters for the locations with enclosing vertical surface

(east, west, north, and south) is the better option to reduce the negative effect of vertical surfaces on thermal comfort parameters. South-facing vertical surfaces are usually exposed to direct solar radiation for maximum hours of the day which increases the contribution of these surfaces to thermal discomfort. A higher H/W ratio can help increase the shading of south-facing surfaces from adjacent vertical surfaces.

Figure 6.16 show the relationship between physical parameters (H/W ratio and SVF) and thermal comfort indices T_{mrt} and PET. A good negative correlation could be established between H/W and T_{mrt} (R^2= 0.72); and a moderate correlation between H/W and PET (R^2= 0.50). whereas a strong positive correlation could be seen between SVF and T_{mrt} (R^2= 0.87);

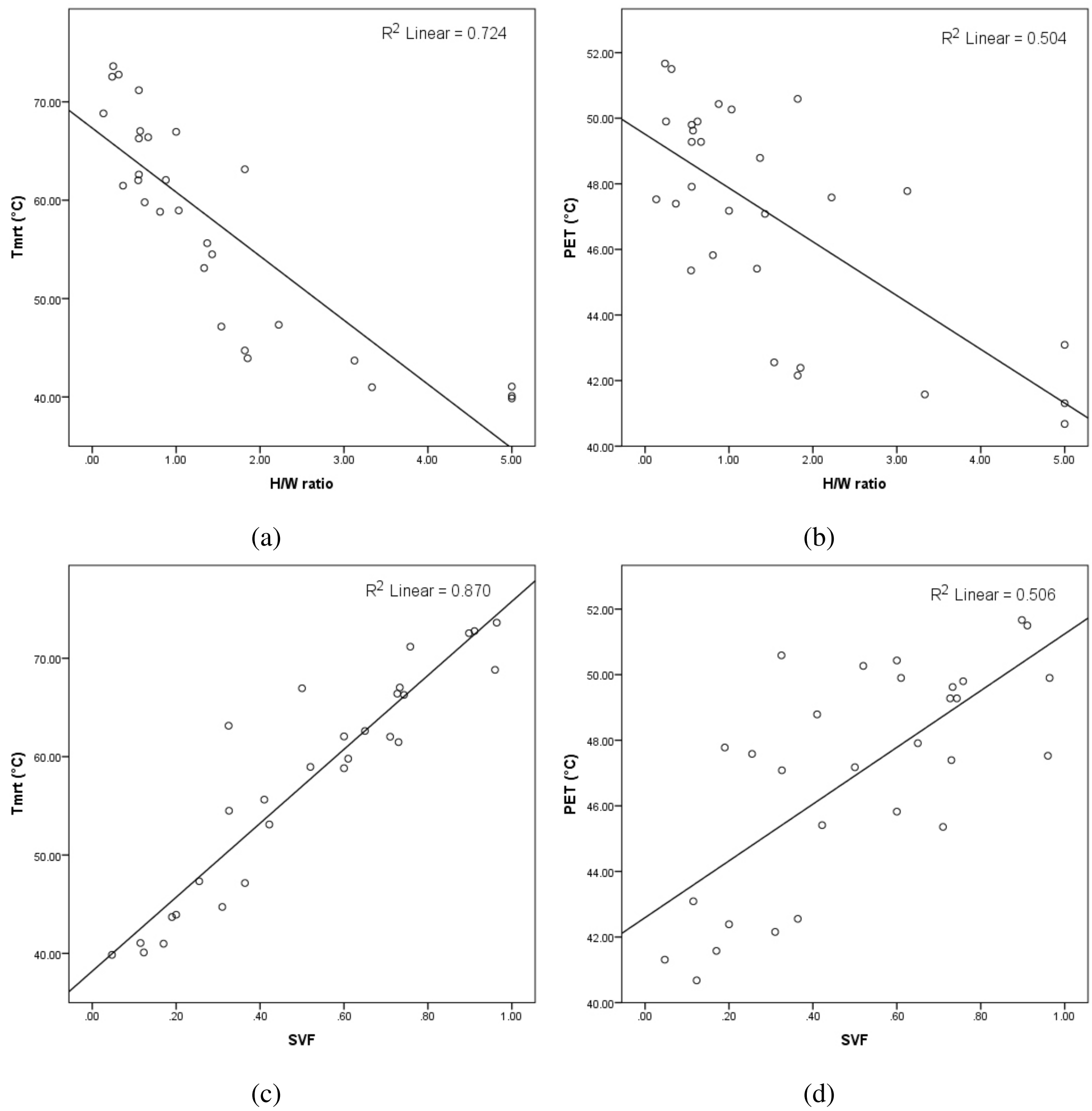
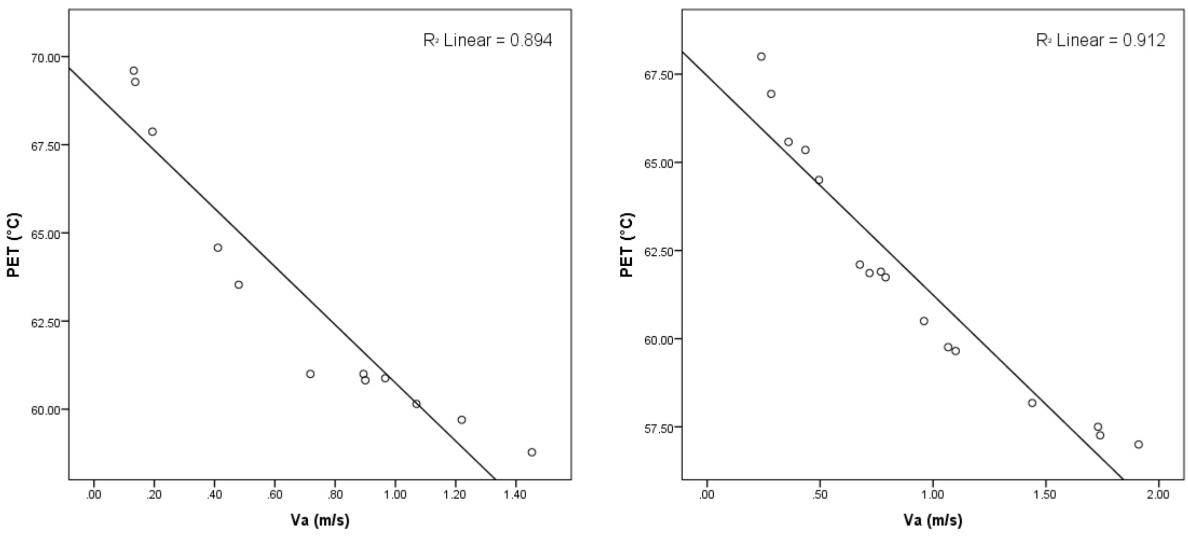


Figure 6.16: Relationship between (a) H/W ratio and T$_{mrt}$, (b) H/W ratio and PET, (c) SVF and T$_{mrt}$, and (d) SVF and PET

and a moderate correlation between SVF and PET (R^2= 0.50). These results imply that more than PET, the T$_{mrt}$ is highly regulated by the physical parameters (H/W ratio and SVF) of the built environment.

6.3.3 Effect of wind on thermal comfort

The analysis is done for the duration between 3 pm and 4 pm when the PET is at its peak. To negate the effect of shade the values were taken only for non-shaded open spaces. Also, where wind speed shows the change, the values were taken at that point. A good negative



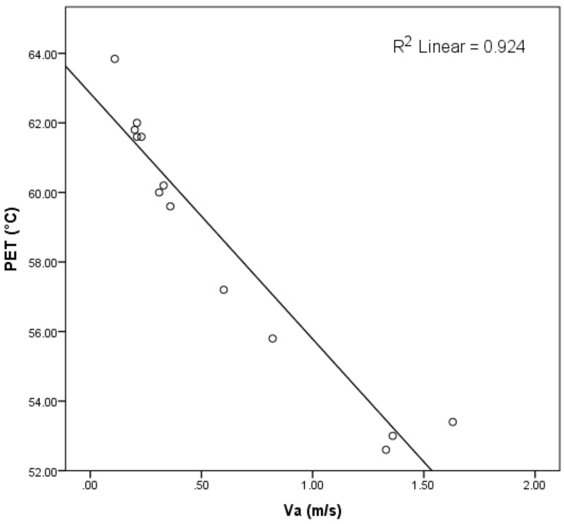
(a) (b)

Figure 6.17: Correlation of PET and V$_a$ at (a) Bhikaji Cama place (b) Nehru place

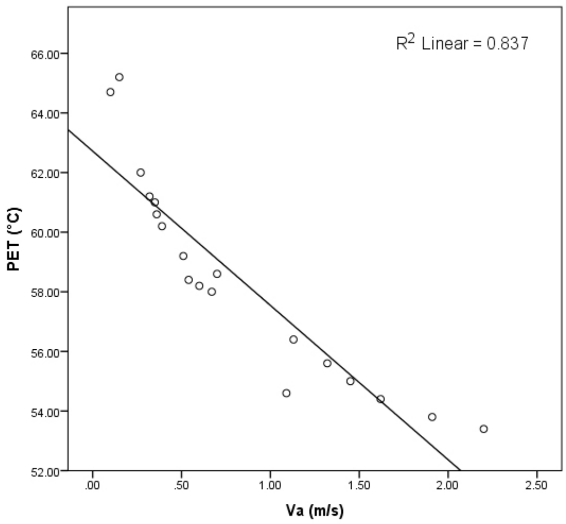
correlation could be observed between V$_a$ and PET at both sites, whereas a correlation could not be established between V$_a$ and T$_{mrt}$. The effect of V$_a$ on PET is observed in several other studies (Bhaskar and Mukherjee, 2017; Qaid et al., 2016).

Wind flow patterns can be affected by smaller changes in urban arrangements. According to (Bhaskar and Mukherjee, 2017) change in orientation affects wind patterns. Longer building facades oblique to the incoming wind flow increase the wind speed (Givoni, 1998). This phenomenon can be observed in the case of location Np2 which is oblique to the prevailing wind direction (northwest) and has longer vertical surfaces of buildings on either side of the open space resulting in the higher wind speed due to the channeling effect. On contrary, in location Np4 (also having longer vertical surfaces) wind speed is lower due to the orientation of the open space. Appropriate orientation is highlighted by other Indian subcontinent studies (Sharmin et al., 2012; Emmanuel et al., 2007), (Yahia et al., 2018) found the same for warm humid dar es salam.

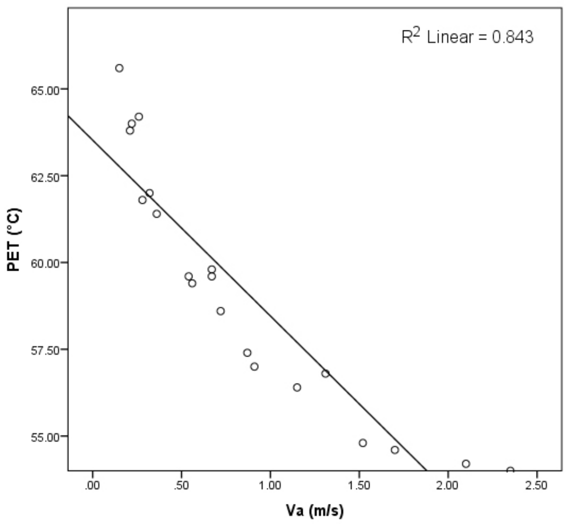
Wind speed is usually mild and reaches a maximum of up to 2 m/s. at locations, Bk1 (1.45 m/s) and Np2 (1.91 m/s) the highest V$_a$ observed from respective sites. whereas, the stagnation of wind movement observed at locations Bk4 (0.132 m/s), Bk5 (0.137 m/s) and Np3 (0.24 m/s) due to which higher PET values 69.6°C , 69.28°C, and 68°C are observed respectively. Within Bhikaji Cama Place the increase of V$_a$ by 1.32 m/s resulted in a reduction of PET by 10.82°C, whereas at Nehru Place the increase of V_a by 1.67 m/s resulted in a reduction of PET by 11°C. This is in agreement with the earlier studies (Deevi and Chundeli, 2020; Amirtham et al., 2015) done for other Indian cities which concluded that the higher wind speed significantly reduces the PET.



(a)



(b)



(c)

Figure 6.18: Correlation between V_a and PET (a) at site B (b) at site C (c) at site D

Although T_{mrt} is highly affected by solar access (Figure 6.14) and physical configuration (Figure 6.16) which affects the solar access and shade, it is not affected largely by V_a. The effect of V_a is evident on PET (Figure 6.18). The correlation between average PET values on each side of V_a is shown in Figure 6.18. The correlation between average PET and V_a at site A could not be established due to the negligible V_a at various locations of site A. For this reason, the remaining three sites are taken for analysis. A strong negative correlation could be observed which implies the importance of ventilation. An increase of V_a by 1 m/s decreased PET by 7°C. It is noteworthy that the previous analysis in this paper shows the comfort level at site A is better than the rest of the sites, even though the wind speed is negligible. It shows that the V_a alone may not help in improving the thermal comfort level whereas maximizing the shade and reducing solar access is far more important.

7

Conclusion

This study is focused on two different commercial open spaces in the composite climate of Delhi and four different residential neighborhoods in Jaisalmer and discussed the effect of vertical surfaces on human thermal comfort in an outdoor environment. Software simulations with Envi-met were performed to achieve various climatic indices such as T_a, T_{mrt}, PET, V_a, sun hours, etc. These indices were analyzed with physical parameters defined by the H/W ratio, SVF, and the orientation of vertical surfaces. Field measurements were conducted to validate the results obtained from Envi-met simulation outputs. Alongside this, a questionnaire survey was conducted to understand the subjective thermal comfort level. Results were analyzed for the summer season since winter is not dominant and lasts only for a short duration of the year. The study shows that the vertical surfaces and their geometry have high effects on outdoor thermal comfort. Complex urban geometries can result in varying thermal comfort levels. Within small proximity, the variation in thermal comfort level can be observed due to the change in the vertical surface geometries around the open spaces. The effect of solar access, shade, and wind velocity is seen in the thermal comfort level. From this study following conclusions can be made.

7.1 Objectives addressed in this study

7.1.1 Objective 1

The study begins with the objective to perform a critical review of thermal comfort studies that are conducted in the Indian context. The objective is important in a way to understand the current status of the research in the Indian context. It helped me to learn as well as to identify the gaps present. Chapter 2 highlighted the overall idea of outdoor thermal comfort around the world followed by an in-depth review of the Indian studies. The review highlighted the focus of the current studies to date, the built environment focused, the methods used and the results achieved by them. The review is performed in a comparative manner.

7.1.2 Objective 2

The objective was to study various subjective and objective parameters of thermal sensation. Subjective parameters are primarily evaluated from the on-site questionnaire survey whereas objective estimation was done with the thermal comfort indices achieved from the simulated output.

In this study, the subjective estimation is in the form of thermal sensation votes received from the users. The study suggests that there can be other ways to evaluate the subjective thermal comfort level such as visual monitoring of user patterns. Other studies have performed the photographic analysis rather than depending on the questionnaire survey. Throughout the study, it was observed that the user responses may vary due to their recent activities, the pattern of their space use, etc., because of which errors may occur while estimating the mean of the thermal sensation votes. Earlier studies are more focused on to objective estimation and numerous parameters have been developed and estimated to date. For this reason, it is recommended to give attention primarily to the subjective aspects of thermal comfort.

7.1.3 Objective 3

The objective was to study and analyze various indices that define the outdoor thermal comfort level. There are numerous indices used by the researchers to date. They vary in terms of the climatic, personal, and environmental parameters involved in their estimation.

In the Indian context PET and T_{mrt} are the popular indices. These indices are affected differently by climatic and non-climatic parameters; For example, T_{mrt} is affected more than PET due to solar access, on the contrary, wind speed has shown a more effect on PET than T_{mrt}. Because of this, it is recommended that multiple indices should be used in a single study to achieve better results.

It is possible that the different indices are suitable for different climatic zones. Future research is required to undertake the cross-climatic study to estimate the effects of various indices in a comparative manner. It is also possible that the various indices are not necessary, in that case, the researchers can also think about the standardization of the indices.

7.1.4 Objective 4

The objective was to conduct the on-site survey campaign to understand the subjective thermal comfort level. The thermal sensation of the user is usually estimated through questionnaire surveys that include questions related to personal parameters, sensation parameters, and expectancy. The major question is about the thermal sensation of the user, which is usually taken on a seven-point scale. The other questions in the questionnaire are supportive. There are certain protocols that need to be followed while conducting the survey, such as the prevailing weather conditions, recent activity of the user, character of the monitoring location, etc.

One of the critical shortcoming studies observed is that the thermal sensation scale which is usually of seven-point can be difficult to use in a composite climate and hot and dry climate of India. Because the votes received on the scale are either on the cold side of the scale or only towards the hot side of the scale from the neutral point. Out of seven points, the votes are usually received on four points (neutral, warm, hot, and very hot), and the other side of the scale (cool, cold, and very cold) is not used. For this reason, many Indian studies have modified these scales and added further points to make it nine points or eleven points (Figure 2.2). This study recommends future research to explore the possibilities to improve the scales of thermal sensation to ultimately improve the accuracy of the results of the questionnaire survey.

7.1.5 Objective 5

The objective is to make use of the simulation software to achieve the necessary depth in the study. Simulation methods are broadly used in the studies of thermal comfort. In this study, one of the objectives was to make use of the simulation software to achieve the necessary depth. Envi-met is used in this study to achieve the spatial and temporal data of various thermal parameters. The software is useful and commonly used by other researchers. Several studies have even validated the accuracy of this software.

The use of simulations has an advantage over on-site measurements. The data collected on-site is usually based on the monitoring locations whereas the thermal state at each point on the site can not be recorded, or a large number of monitoring equipment should be placed to achieve the data from various parts of the site, to overcome this issues the software simulations can be benefited from. Also, there are numerous indices that can not be measured directly on-site, those indices can be easily estimated through the software. It is very important that the simulation model is calibrated and the simulation outcome is validated before the results are used for further analysis.

One of the issues with the Envi-met is that it does not take into account the indoor- façade-outdoor interaction. The indoor activity may affect the thermal characteristics of the facades, and the then the outdoor environment. For this reason, improvement is required in the software. The author recommends future research to conduct more studies on the reliability of Envi-met based on climate classification. It is also recommended to conduct studies that involve other software that may produce more accurate results.

7.1.6 Objective 6

The objective was to make make use of various methods of data analysis for qualitative and quantitative evaluation of the thermal comfort level. After getting the necessary background from the review (chapter 2), it was decided to use the analysis methods the data collected on-site, and the data obtained from the simulation results. For the validation, R^2, RMSE, and d is used. For the analysis, bar chart, line chart, scatter plot, and linear regression with R^2 are used.

7.1.7 Objective 7

The major objective of the study was to study various physical/ geometrical parameters of the built environment that affect the thermal parameters. After getting the necessary background on the subject, the study established the relationship between physical parameters and thermal parameters. Following are some of the results obtained in the study.

- The effect of geometrical parameters is evident in the thermal sensation of the user. In the case of Delhi, a good negative correlation is observed between mTSV and the H/W ratio, whereas a moderate correlation could be seen between mTSV and SVF. It can be said that the effect of height to width ratio on thermal comfort is more prominent that the sky view factor.

- In the case of Jaisalmer, At any given time the spatial variation in T_{mrt} is much higher than T_a and PET. For this reason, it is important to analyze the thermal comfort level with T_{mrt}, which can help understand the variation observed spatially. It can also be said that the T_{mrt} is sensitive to various parameters such as hours of solar access, shade, and shadow patterns.

- Moderate to good correlation could be found between physical parameters (H/W ratio and SVF) and thermal comfort parameters (T_{mrt} and PET). Having the smaller SVF, it is possible to reduce the temperature which gives more flexibility for designers to design the streets having various orientations. Whereas the sites having higher SVF should be carefully designed in terms of H/W ratio and the orientation of vertical surfaces enclosing those open spaces.

- In the case of Delhi, vertical surfaces in the south, west, and south-west direction of the space are beneficial in maintaining the thermal comfort of that location whereas the existence of a vertical surface on the north side of the open space may not benefit. Although a higher H/W ratio will give better thermal comfort it is not always true. A higher H/W ratio with appropriate surface orientation is the key to achieving maximum comfort level for any space. In the case of Jaisalmer, The locations enclosed from NE and SW directions and locations enclosed from NW and SE are having lesser values of T_{mrt} and PET. For this reason, the open spaces and streets can be designed considering these directions.

- Shade from the vertical surfaces is the guiding factor for the users to use the space for a certain duration of time per day, maximum the duration of the shade the user spending time in the space will be higher. Vertical surfaces can so be provided that space will get the maximum shade during the harsher hours of the day. South and west directions provide the shade for maximum duration. Shading does not affect the T_a drastically but the variation in T_{mrt} and PET is observed.

- The H/W ratio along with the orientation of vertical surfaces can determine the hours of solar access to that open space. For this reason, the H/W ratio should not be seen in isolation and the orientation of the enclosing surfaces should be focused. The author also recommends future research to modify the index in such a way that the orientation is taken into account.

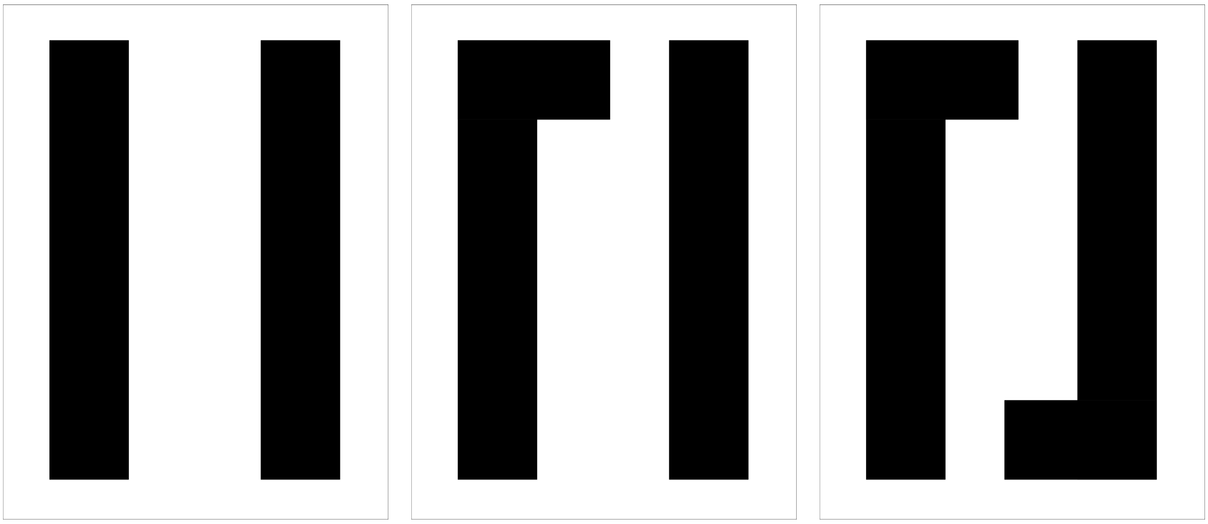
- The effect of solar access and shade is seen on T_{mrt}. Locations having solar access of fewer than 4 hours performed better than the rest of the locations. The urban areas in the hot and dry climatic zone should be designed considering the hours of solar access.

- Contrasting results can be seen in terms of the wind access to the open spaces. In the case of Delhi, it is recommended that the open spaces must be well-ventilated. The higher wind speed can reduce the PET significantly. For this reason, the open spaces can be designed in such a way that the wind channeling effect can be created by orienting the open space aligned or oblique to the prevailing wind direction. Whereas, the effect of wind on thermal parameters in hot and dry regions is negligible. It gives freedom for the designers to design the spaces having narrower lanes of high H/W ratio where there is not much concern of wind flow that also allows to have lesser hours of solar access.

The objective could estimate the important parameters of the built environment that are responsible for the changes in the thermal parameters by affecting the wind speed, solar access, shade, radiant temperatures, etc. Although there are studies conducted in the composite climates previously (section 2.4.1), those studies failed to address these issues, which are covered in this study. In the case of hot and dry regions, it was the first attempt to estimate the effect of the built environment on thermal comfort. Although the objective helped estimate the effect of physical parameters on thermal comfort, but it could not estimate the thermal neutrality. Future studies are required in these climatic zones to estimate the range of neutral values of thermal indicators.

7.2 Limitations and future directions

H/W ratio, SVF, and orientation are the typical parameters used in the studies to define the physical composition of urban open spaces. The H/W ratio is the height of the vertical surface to the horizontal space in front of that surface, whereas the adjacent vertical surface and its impact are not considered in this index.



(a) Case 1 (b) Case 2 (c) Case 3

Figure 7.1: Schematic representation of the different scenarios of the same H/W ratio

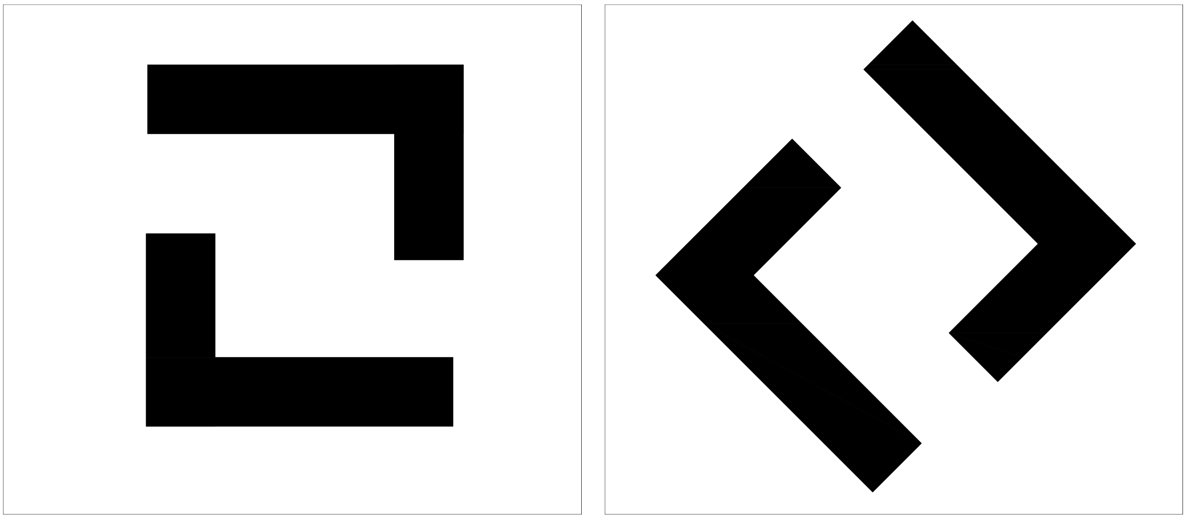
The H/W ratio between all the scenarios is equal in Figure 7.1, but the adjacent vertical surface may impact the thermal parameters in that open space, and different results may be obtained for all three cases (Figure 7.1a, Figure 7.1b, and Figure 7.1c).

Similarly, SVF between both scenarios is equal in Figure 7.2, but the directions of the vertical surface enclosures are different. When analyzing their relation with thermal parameters different results may be obtained for both cases (Figure 7.2a and Figure 7.2b).

For this reason, the author recommends future research to improve/ modify the index, so that the directions from which the vertical surfaces are enclosed can be considered in the analysis.

Most of the studies done for outdoor thermal comfort studies to date, considers the impact of building façades on outdoor areas, whereas the interaction of indoor-façade-outdoor is not yet considered by any studies. The activities and the thermal status of the indoor areas may influence the thermal state of the façade/ building skin which may ultimately impact the thermal state of an outdoor area.

Since the R_h for any specific time at all the studied locations was almost the same, the geometrical modifications in the vertical surfaces could not help in achieving the change in the level of R_h. For this reason, it was not considered for the analysis. The study focused only on the geometrical aspects of vertical surfaces, whereas, further studies on a similar topic can be



(a) Case 1 (b) Case 2

Figure 7.2: Schematic representation of the different scenarios of the same SVF

done by exploring the building materials and related technologies to achieve maximum thermal comfort due to vertical surfaces.

The thermal comfort level in Delhi is difficult to achieve due to its extreme temperature for the maximum number of days in the year. But, the improvement is possible, by working on the micro configuration of the vertical surfaces which can help improve the PET level. Although a very slight difference in the temperature is observed for varying geometries, designers can take this difference into account to improve the micro-climate of an urban neighborhood which can ultimately improve the climate of the city.

The geometrical configuration of the vertical surfaces is dependent primarily on the function of the indoor space rather than the outdoor space, for this reason, architects and urban designers have to consider outdoor space in the early stage of the design. Through this, the use of outdoor spaces can be encouraged. For the same reason, the results and conclusions achieved in this study can not be applied to the existing vertical surfaces in urban areas and neighborhoods; and they can only be implemented before the construction activity takes place.

The appropriate design of vertical surfaces will contribute to reducing the thermal impact and there will be less need for other provisions like vegetation, horizontal projections, etc. to mitigate the thermal discomfort. In the old city of Jaisalmer, strategies were developed to increase the shade for the street and reduce the heat gain to the building by designing horizontal projections which were often ornamented. The later development in the city could not follow a similar trend. This study will give flexibility to architects, urban designers, and planners to design buildings and outdoor spaces by focusing more on vertical surfaces and minimal intervention with horizontal projections.

This study is the first attempt in the hot and dry region of India, which will help guide other researchers in thermal comfort studies for other cities with similar climates. This study will also open up several directions in this field such as a focus on the material properties which was not a focus in this paper.

7.3 General research implications for future work

Some of the general directions for future research are listed below.

- **Investigation of the impact of shading devices**: Future studies can explore the effectiveness of different types of shading devices, such as awnings, pergolas, or louver systems, in enhancing outdoor thermal comfort. This research could provide valuable insights into the optimal design and placement of shading elements to mitigate heat stress in urban open spaces.

- **Integration of green infrastructure**: Investigating the role of green infrastructure, such as urban parks, green roofs, and vertical gardens, in improving outdoor thermal comfort would be valuable. Assessing the cooling effects of vegetation and exploring innovative ways to incorporate greenery in urban design can contribute to creating more comfortable outdoor environments.

- **Evaluation of building material properties**: Further research can focus on the influence of building material properties, such as thermal conductivity and emissivity, on outdoor thermal comfort. Understanding how different materials interact with solar radiation and affect the thermal environment can guide architects and designers in selecting suitable materials for vertical surfaces to enhance comfort levels

- **Long-term monitoring and evaluation**: Conducting long-term monitoring studies to assess the performance and effectiveness of different design interventions in improving outdoor thermal comfort would provide valuable data. By analyzing the real-time thermal conditions and occupants' perceptions over an extended period, researchers can validate the effectiveness of design strategies and identify any seasonal variations or long-term trends.

- **Development of predictive models**: Future research could focus on developing predictive models that consider various factors, including weather conditions, urban morphology, and human behavior, to estimate outdoor thermal comfort levels in different urban contexts. Such models could assist designers and urban planners in making informed decisions early in the design process.

- **Integration of climate change adaptation strategies**: With the increasing impact of climate change, future studies can explore adaptation strategies to mitigate the adverse effects of rising temperatures on outdoor thermal comfort. This may involve considering climate projections, urban heat island mitigation techniques, and resilient design approaches to create sustainable and comfortable outdoor environments.

Throughout the study, several positive and negative events appeared. One of the major setbacks was the outrage of COVID due to which the study got slowed down significantly. Nevertheless, the study picked up the pace thereafter, and with the support from the concerned people, it was made sure to get the best results out of it. This thesis is useful for the concerned stakeholders. The study will primarily help architects, and urban designers in the early stage of the design. It has also opened up numerous directions for future work.

Appendices

A
On site survey

A.1 Questionnaire used for Delhi study

Site		**Location**	
Time		**Activity**	

Weather Condition

Temp.		Humidity		Sky Condition	

Resident from

Delhi		Outside Delhi	

How do you feel thermally at this moment

Very Cold	Cold	Cool	Neutral	Warm	Hot	Very Hot

How is your thermal Comfort Level

Very uncomfortable	Uncomfortable	Neutral	Comfortable	Very Comfortable

When is it most Comfortable

Month		Time		Today's Time	

When is it most Uncomfortable

Month		Time		Today's Time	

What is your preferred humidity level

Very High		High		Medium		Low		Very Low	

What is the source of discomfort according to you

Solar Radiation		Wind Velocity		Humidity	

Prefered area to get refuge from the thermal discomfort

Tree Shade		Building Shde		Other	

Most comfortable location from the following -Bhikaji Kama Place

								A1	
A2		A3		A4		A5		A6	

Most comfortable location from the following -Nehru Place

								B1	
B2		B3		B4		B5		B6	

A.2 Questionnaire used for Jaisalmer study

Location		**Date**		**Time**	

Age		**Gender**		**Clothing**	

Weather Condition	Temp.		Humidity		Sky Condition	

Current/ recent physical activity

Seating		Walking		Running		Other	

What is your reason to be in outdor space right now	

How often do you visit this location

Daily		Weekly		Monthly		Annually		First time	

How much time do you usually spend in this location? (Answers from daily visitors)

Less than 10 min.		10min-30 min.		More than 30 min.	

How do you feel thermally at this moment

Very Cold	Cold	Cool	Neutral	Warm	Hot	Very Hot

How is your thermal Comfort Level

Very uncomfortable	Uncomfortable	Neutral	Comfortable	Very Comfortable

When is it most Comfortable				**When is it most Uncomfortable**			
Month		Time		Month		Time	

What is the source of discomfort according to you

Solar Radiation		Wind Velocity		Humidity		Other	

Prefered area to get refuge from the thermal discomfort

Building shade		Alteration with clothing		Tree shade	
Cover head		Avoid outdoor actvity		Other	

B
Simulated output

Table B.1: Summary of thermal parameters T_a, T_{mrt} and PET at Delhi

Time	Bk1	Bk2	Bk3	Bk4	Bk5	Bk6	Np1	Np2	Np3	Np4	Np5	Np6
07:00	30.74	30.68	30.31	30.97	31.14	31.18	31.15	30.49	31.12	30.84	31.59	31.25
08:00	31.73	31.78	31.53	31.83	31.86	31.96	32.08	31.49	32.00	31.79	32.32	32.12
09:00	32.93	33.00	32.84	32.89	32.75	32.90	33.13	32.69	33.08	32.92	33.21	33.12
10:00	34.17	34.31	34.32	34.05	33.81	33.98	34.26	34.03	34.25	34.18	34.21	34.23
11:00	35.38	35.53	35.76	35.21	34.97	35.12	35.43	35.39	35.43	35.39	35.31	35.35
12:00	36.58	36.74	37.05	36.29	36.00	36.16	36.64	36.74	36.57	36.56	36.39	36.46
13:00	37.87	38.00	38.41	37.43	36.95	37.24	37.91	38.03	37.77	37.74	37.52	37.61
14:00	39.02	39.01	39.54	38.45	37.77	38.23	39.00	39.06	38.78	38.67	38.45	38.54
15:00	39.89	39.78	40.32	39.20	38.58	39.02	39.72	39.67	39.46	39.34	39.14	39.19
16:00	40.56	40.30	40.82	39.77	39.28	39.65	40.21	40.17	40.00	39.82	39.69	39.73
17:00	40.14	40.03	40.35	39.64	39.31	39.49	39.92	39.89	39.77	39.63	39.54	39.59
18:00	39.37	39.34	39.28	39.07	38.87	39.00	39.25	39.15	39.08	39.04	38.99	39.00

(a) Simulated Ta

Time	Bk1	Bk2	Bk3	Bk4	Bk5	Bk6	Np1	Np2	Np3	Np4	Np5	Np6
07:00	28.61	55.88	27.49	26.94	26.19	27.24	29.48	28.76	29.98	56.63	57.53	29.77
08:00	35.86	63.71	34.54	33.90	32.97	34.25	65.05	64.39	65.50	64.54	65.58	65.30
09:00	67.26	66.51	40.93	65.50	38.90	65.81	67.90	67.12	68.40	67.34	68.50	68.19
10:00	67.46	66.59	66.09	65.40	63.89	65.78	67.93	66.94	68.50	67.28	68.61	68.26
11:00	65.83	64.86	64.28	63.50	61.44	63.93	66.00	64.70	66.67	65.21	66.80	66.39
12:00	65.77	64.71	64.07	63.19	60.56	63.67	65.90	64.29	66.66	64.99	66.81	66.34
13:00	72.84	71.94	71.41	70.69	68.53	71.08	73.61	72.19	74.27	72.83	74.40	73.99
14:00	77.80	77.05	76.61	76.01	55.68	76.34	78.73	77.65	79.24	78.14	79.34	79.02
15:00	79.00	56.24	77.95	77.42	53.45	77.71	79.64	56.87	80.05	79.18	80.13	79.88
16:00	75.42	51.43	74.48	50.42	49.08	74.27	52.89	52.15	76.36	52.41	53.40	76.21
17:00	44.31	43.80	63.21	43.06	42.16	43.29	44.85	44.35	64.59	44.49	45.21	64.48
18:00	35.99	35.82	35.71	35.54	35.04	35.64	36.39	36.18	36.49	36.27	36.51	36.45

(b) Simulated Tmrt

Time	Bk1	Bk2	Bk3	Bk4	Bk5	Bk6	Np1	Np2	Np3	Np4	Np5	Np6
07:00	28.59	41.49	28.05	28.98	29.35	29.41	30.14	27.85	29.87	42.14	44.14	29.76
08:00	32.50	48.15	32.11	32.83	33.18	33.30	51.53	43.70	48.99	48.86	51.56	48.28
09:00	48.97	50.59	36.11	53.53	36.80	54.93	54.07	46.34	51.34	51.06	54.03	50.51
10:00	50.41	51.97	51.55	55.00	58.38	56.53	55.35	48.19	52.62	52.25	55.34	51.68
11:00	51.13	52.48	52.29	55.73	58.03	57.74	56.01	48.90	53.20	52.45	56.30	52.21
12:00	52.04	53.19	53.01	56.93	58.51	59.03	57.01	49.91	54.18	53.22	57.27	53.14
13:00	55.48	56.79	56.53	61.54	63.47	63.95	61.45	53.20	58.04	57.01	61.68	56.89
14:00	58.30	59.68	59.37	65.25	57.17	68.04	64.80	55.84	60.96	59.92	65.06	59.75
15:00	59.69	52.88	60.68	66.92	56.73	70.03	66.03	50.60	62.08	61.07	66.34	60.91
16:00	59.12	51.92	59.92	54.49	55.17	69.03	54.55	50.03	61.18	51.77	54.63	60.13
17:00	49.09	49.43	55.58	51.51	52.09	52.92	51.34	47.95	56.53	49.28	51.42	55.76
18:00	39.81	39.44	39.42	48.28	48.87	49.36	47.45	40.13	39.53	39.35	47.50	39.41

(b) Simulated PET

Table B.2: Summary of thermal parameters V_a and R_h at Delhi

Time	Bk1	Bk2	Bk3	Bk4	Bk5	Bk6	Np1	Np2	Np3	Np4	Np5	Np6
07:00	1.41	0.75	1.05	0.48	0.09	0.28	0.70	2.13	0.97	0.81	0.56	1.19
08:00	1.38	0.74	1.04	0.45	0.09	0.26	0.67	2.11	0.94	0.80	0.52	1.16
09:00	1.35	0.72	1.02	0.42	0.09	0.24	0.64	2.09	0.91	0.80	0.48	1.13
10:00	1.31	0.70	0.99	0.38	0.09	0.22	0.61	2.07	0.88	0.79	0.44	1.10
11:00	1.24	0.67	0.95	0.32	0.09	0.17	0.55	2.00	0.82	0.77	0.36	1.03
12:00	1.26	0.69	0.95	0.28	0.09	0.14	0.52	1.97	0.79	0.77	0.34	1.00
13:00	1.27	0.70	0.96	0.26	0.09	0.13	0.51	1.97	0.78	0.77	0.33	0.99
14:00	1.27	0.70	0.96	0.25	0.08	0.12	0.50	1.97	0.78	0.76	0.32	0.98
15:00	1.26	0.69	0.96	0.24	0.08	0.10	0.50	1.96	0.78	0.76	0.31	0.96
16:00	1.25	0.69	0.96	0.22	0.08	0.09	0.49	1.95	0.77	0.76	0.30	0.95
17:00	1.25	0.69	0.96	0.21	0.08	0.08	0.48	1.95	0.76	0.76	0.29	0.94
18:00	1.25	0.69	0.96	0.20	0.08	0.07	0.48	1.94	0.76	0.76	0.29	0.93

(a) Simulated Va

Time	Bk1	Bk2	Bk3	Bk4	Bk5	Bk6	Np1	Np2	Np3	Np4	Np5	Np6
07:00	68.42	68.00	69.89	67.96	68.14	67.60	67.46	70.20	68.11	69.44	66.94	68.08
08:00	67.30	67.11	68.83	66.90	66.78	66.46	66.69	69.04	67.26	68.41	66.27	67.26
09:00	65.97	65.69	67.41	65.84	65.25	65.29	65.49	67.56	66.07	66.86	65.21	65.93
10:00	63.95	63.47	65.04	64.05	63.89	63.70	63.51	65.21	63.94	64.53	63.41	63.77
11:00	61.22	60.81	61.46	61.65	62.22	61.69	60.96	61.88	61.07	61.32	60.95	60.97
12:00	58.49	58.16	57.96	59.22	60.34	59.59	58.07	58.36	58.07	58.35	58.18	58.19
13:00	55.59	55.50	54.54	56.55	57.98	57.11	55.16	55.01	55.18	55.47	55.59	55.50
14:00	53.44	53.99	52.34	54.56	56.27	55.11	53.20	52.97	53.35	53.76	54.02	53.85
15:00	52.36	53.29	51.43	53.58	55.04	54.03	52.51	52.47	52.67	53.08	53.36	53.23
16:00	51.55	52.60	51.01	52.95	53.92	53.26	52.18	52.09	52.18	52.70	52.87	52.72
17:00	52.64	53.25	52.31	53.50	54.11	53.86	53.06	53.06	53.06	53.48	53.55	53.43
18:00	54.36	54.49	54.60	54.75	55.07	54.86	54.47	54.72	54.67	54.80	54.78	54.79

(b) Simulated Rh

Table B.3: Simulated T_a at Jaisalmer

Time	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
07:00	28.55	28.80	28.56	28.58	28.34	27.59	22.96	28.67	28.41	27.83	28.17	28.56
08:00	29.73	29.88	29.71	29.75	29.51	28.76	23.97	29.80	29.55	28.99	29.35	29.72
09:00	31.06	31.12	31.01	31.08	30.84	30.15	25.37	31.08	30.86	30.29	30.72	31.00
10:00	32.57	32.52	32.54	32.59	32.35	31.68	27.42	32.55	32.30	31.77	32.22	32.44
11:00	34.13	33.99	34.10	34.17	33.88	33.26	30.37	34.06	33.78	33.35	33.72	33.91
12:00	35.61	35.63	35.61	35.68	35.57	34.99	32.86	35.60	35.31	34.85	35.21	35.45
13:00	37.19	36.86	36.67	36.95	36.86	36.63	34.77	36.73	36.78	36.30	36.69	36.69
14:00	38.60	38.09	37.87	38.11	38.03	37.73	36.28	37.91	38.11	37.63	37.83	37.96
15:00	39.71	39.17	38.93	39.17	39.04	38.97	37.66	38.94	39.10	38.82	38.98	38.94
16:00	40.58	40.00	39.93	40.13	40.06	40.04	38.77	39.89	40.14	39.85	40.00	39.93
17:00	40.05	39.67	39.69	39.81	39.75	39.59	38.15	39.67	39.81	39.52	39.69	39.71
18:00	39.11	38.94	38.96	39.02	38.98	38.72	37.08	38.96	39.01	38.72	38.90	38.97

Time	B1	B2	B3	B4	B5	B6	B7
07:00	28.65	28.73	28.66	28.96	28.88	28.60	28.53
08:00	29.79	29.91	29.85	30.05	29.99	29.77	29.79
09:00	31.06	31.22	31.17	31.28	31.24	31.07	31.18
10:00	32.46	32.64	32.61	32.64	32.60	32.52	32.68
11:00	33.85	34.04	34.04	33.99	33.96	33.99	34.17
12:00	35.25	35.42	35.50	35.34	35.27	35.53	35.66
13:00	36.67	36.91	36.98	36.80	36.71	36.96	37.26
14:00	37.99	38.31	38.24	38.24	38.06	38.28	38.80
15:00	39.19	39.42	39.31	39.32	39.09	39.44	39.97
16:00	40.25	40.32	40.25	40.25	40.07	40.48	40.89
17:00	39.94	39.92	39.93	39.92	39.75	40.13	40.28
18:00	39.18	39.17	39.18	39.05	39.05	39.21	39.36

Time	C1	C2	C3	C4
07:00	28.37	27.41	28.38	28.17
08:00	29.63	28.82	29.62	29.47
09:00	31.07	30.59	31.05	30.92
10:00	32.71	32.72	32.68	32.57
11:00	34.43	34.95	34.32	34.22
12:00	36.23	37.06	36.08	35.90
13:00	37.86	38.52	37.69	37.41
14:00	39.14	39.60	38.97	38.63
15:00	40.15	40.45	39.92	39.62
16:00	40.94	41.06	40.63	40.39
17:00	40.37	40.39	40.17	40.01
18:00	39.28	39.29	39.16	39.13

Time	D1	D2	D3	D4	D5	D6
07:00	28.39	27.93	28.54	27.91	28.03	27.17
08:00	29.70	29.36	29.77	29.33	29.51	29.03
09:00	31.18	31.02	31.18	30.96	31.14	31.01
10:00	32.83	32.88	32.77	32.83	32.95	33.19
11:00	34.58	34.84	34.41	34.80	34.86	35.50
12:00	36.42	36.82	36.11	36.80	36.82	37.61
13:00	38.17	38.46	37.76	38.46	38.68	39.37
14:00	39.50	39.66	39.04	39.67	40.06	40.75
15:00	40.50	40.61	40.02	40.63	41.09	41.90
16:00	41.31	41.34	40.82	41.38	41.93	42.87
17:00	40.67	40.65	40.36	40.68	41.10	41.68
18:00	39.45	39.50	39.33	39.51	39.77	40.12

Table B.4: Simulated T_{mrt} at Jaisalmer

Time	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
07:00	22.55	21.86	20.22	20.89	19.93	19.71	19.73	20.77	20.42	19.72	19.90	20.57
08:00	61.74	28.79	26.57	27.52	26.14	25.80	25.83	27.36	26.89	25.79	26.08	27.10
09:00	65.70	64.83	32.81	63.71	32.16	31.59	31.64	33.90	33.29	31.55	32.04	33.59
10:00	67.01	65.91	63.14	64.57	38.22	37.27	37.37	40.75	39.94	37.20	38.01	40.37
11:00	65.91	64.52	60.87	62.89	43.30	58.46	42.05	62.62	61.73	41.79	42.99	62.22
12:00	63.40	61.65	56.85	59.63	55.10	53.33	53.53	59.27	58.06	53.19	54.71	58.75
13:00	69.28	67.55	62.81	65.60	61.04	48.14	48.36	65.24	64.03	47.98	49.69	64.72
14:00	76.38	74.93	53.22	73.30	69.60	49.84	50.03	73.00	54.39	49.70	51.16	55.05
15:00	80.09	78.86	52.24	54.51	74.49	49.45	49.60	54.21	53.22	49.33	50.53	53.77
16:00	79.99	52.80	49.47	51.29	75.51	47.33	47.45	51.04	50.23	47.26	48.16	50.67
17:00	47.42	46.49	44.10	45.34	43.41	42.74	42.81	45.16	44.59	42.70	43.27	44.89
18:00	40.76	40.12	38.46	39.29	38.00	37.57	37.61	39.17	38.78	37.54	37.91	38.97

Time	B1	B2	B3	B4	B5	B6	B7
07:00	22.60	23.28	22.62	22.71	22.88	22.52	23.08
08:00	30.27	62.70	30.29	30.38	30.55	30.24	30.77
09:00	37.02	66.67	65.95	66.08	37.40	36.70	37.68
10:00	43.55	67.70	66.59	66.87	67.08	65.93	67.40
11:00	64.69	66.17	64.62	65.06	65.34	63.45	65.77
12:00	61.56	63.47	61.44	62.07	62.40	59.70	62.97
13:00	67.61	69.46	67.50	68.12	68.43	65.74	68.98
14:00	58.40	76.96	75.36	75.87	76.12	56.65	76.56
15:00	57.41	80.99	57.32	80.14	58.01	56.10	80.68
16:00	53.99	55.06	53.94	80.13	54.45	53.16	54.77
17:00	47.87	48.59	47.85	74.45	48.17	47.45	48.38
18:00	41.63	42.06	41.62	63.39	41.80	41.44	41.93

Time	C1	C2	C3	C4
07:00	53.95	24.07	23.90	23.60
08:00	64.70	32.20	63.39	31.59
09:00	69.59	68.05	67.91	39.06
10:00	71.64	69.50	69.39	68.72
11:00	71.19	68.42	68.34	67.42
12:00	69.43	65.98	65.93	64.72
13:00	74.21	70.90	70.86	69.70
14:00	80.72	78.01	77.97	77.04
15:00	83.99	59.79	81.76	58.85
16:00	83.35	56.15	81.60	55.40
17:00	76.81	49.37	75.47	48.78
18:00	64.82	42.36	63.94	41.99

Time	D1	D2	D3	D4	D5	D6
07:00	54.35	25.34	54.13	25.36	54.66	54.97
08:00	65.38	64.95	65.01	34.08	65.72	66.16
09:00	70.25	69.54	69.61	69.54	70.57	71.18
10:00	72.08	71.02	71.09	71.00	72.34	73.15
11:00	71.56	70.17	70.24	70.12	71.74	72.73
12:00	69.36	67.63	67.70	67.56	69.45	70.63
13:00	74.91	73.21	73.27	73.14	74.95	76.09
14:00	81.54	80.12	80.18	80.07	81.59	82.55
15:00	84.86	83.74	83.79	83.70	84.95	85.73
16:00	84.56	58.74	83.77	83.70	84.70	85.31
17:00	77.84	51.66	77.36	77.32	77.99	78.40
18:00	44.35	44.01	65.33	65.30	65.71	65.96

Table B.5: Simulated PET at Jaisalmer

Time	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
07:00	24.73	25.35	24.73	24.58	24.55	24.27	22.17	24.52	24.35	24.28	24.43	24.72
08:00	45.44	29.34	45.44	28.46	28.36	28.01	25.93	28.42	28.25	27.98	28.10	28.72
09:00	48.40	51.24	48.40	50.08	32.28	31.77	29.73	32.57	32.39	31.70	31.84	32.96
10:00	49.20	52.14	49.20	51.87	36.50	35.62	33.84	37.33	37.12	35.52	35.68	37.24
11:00	49.40	52.25	49.40	52.24	54.89	55.05	37.74	54.96	55.36	38.83	52.49	53.87
12:00	49.20	54.45	49.20	50.96	53.38	52.78	51.50	49.28	49.85	51.77	51.37	50.82
13:00	52.60	58.94	52.60	54.51	57.66	50.59	49.43	52.20	52.88	49.42	49.29	53.75
14:00	57.00	64.17	57.00	59.15	63.16	51.40	50.16	56.80	47.59	50.72	50.62	49.37
15:00	59.60	67.19	59.60	49.48	51.67	51.51	50.40	47.42	47.30	50.85	51.07	49.07
16:00	60.00	51.52	60.00	46.45	50.48	50.60	49.63	46.12	46.04	50.01	50.30	46.08
17:00	56.60	46.57	56.60	42.94	42.23	43.22	41.11	42.78	42.69	41.55	41.85	42.69
18:00	40.22	39.78	40.22	39.28	38.71	38.27	37.68	39.28	39.16	38.24	38.45	39.13

Time	B1	B2	B3	B4	B5	B6	B7
07:00	23.60	24.67	25.13	25.29	25.20	25.47	25.06
08:00	27.20	44.63	29.54	29.60	29.47	29.94	29.51
09:00	31.20	47.96	49.20	48.80	33.65	34.01	33.86
10:00	35.40	48.80	50.60	49.60	49.40	52.29	50.00
11:00	46.38	49.00	50.80	49.60	49.40	51.81	50.20
12:00	46.27	48.80	50.23	49.00	49.00	50.79	49.60
13:00	49.20	50.80	54.00	53.00	52.80	54.57	53.60
14:00	47.41	55.20	58.80	58.00	57.80	50.29	58.40
15:00	48.06	58.00	49.35	61.00	49.00	50.38	61.40
16:00	47.49	48.29	47.95	61.40	48.05	49.26	48.65
17:00	44.54	44.71	44.38	58.00	44.44	44.32	44.84
18:00	41.21	41.00	40.65	51.80	40.69	40.56	40.92

Time	C1	C2	C3	C4
07:00	36.68	22.80	24.80	23.60
08:00	43.30	26.60	45.11	28.00
09:00	47.26	43.84	48.40	32.48
10:00	49.00	46.90	49.40	48.27
11:00	49.60	48.45	49.80	48.60
12:00	49.80	48.80	49.80	48.60
13:00	51.60	50.60	52.20	50.40
14:00	54.00	52.60	56.40	52.60
15:00	56.00	49.20	58.80	48.80
16:00	56.20	48.80	59.20	48.31
17:00	53.20	45.69	55.80	44.91
18:00	50.00	41.76	50.20	41.20

Time	D1	D2	D3	D4	D5	D6
07:00	38.69	23.20	39.40	23.40	37.60	33.07
08:00	45.80	39.90	46.40	28.00	44.67	40.28
09:00	48.80	44.08	49.00	44.96	48.40	44.97
10:00	50.00	47.06	50.00	47.82	49.60	48.32
11:00	50.60	48.46	50.60	48.80	50.20	49.20
12:00	50.40	48.80	50.20	49.00	50.20	49.80
13:00	53.00	50.80	53.20	51.00	52.20	51.60
14:00	56.80	52.80	57.40	53.00	55.60	53.60
15:00	59.00	54.00	60.00	54.20	57.80	54.80
16:00	59.20	49.40	60.40	54.60	58.00	55.20
17:00	55.40	46.99	56.80	52.80	54.60	53.20
18:00	42.40	42.77	50.60	49.80	50.40	50.00

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Related Academic Publications

Author has published four articles (Khaire et al., 2023a,b,c,d) related to the thesis topic, the outcome of these research is not used in the thesis.

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